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To Study the Influence of Ethanol and EGR on Engine Performance and Emissions by the Integration of Taguchi and RSM for an Engine Fuelled with CAOME

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Abstract

With the rise in fossil fuel consumption rate, depletion in reserves and stringent pollution norms resulted in search of renewable and carbon neutral fuel. Ethanol is one such fuel 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. Even castor oil methyl esters which is non-edible in nature also fulfils the requirement of fuel for internal combustion engine. The traditional experimental scheme requires more time for optimization and extensive experiments need to perform as it is possible to vary only one parameter at a time. This also result in increase in cost and it doesn't provide interactive effect among the chosen variables. Mathematical models of Taguchi method using design of experiments (DOE) provide good results. By using DOE, Taguchi L27 orthogonal array is considered. Analysis of variance (ANOVA), Regression Equation and signal-to-noise (S/N) ratio are obtained to predict the optimal parameters and to evaluate the influence of significant conditions on performance, emission and combustion characteristics. It is observed from the experiments that ethanol blend percentage and EGR influences on the output parameters.

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

1.0 Introduction

The development of any nation predominantly rests on the available energy reserves. With gradual rise in energy consumption, stringent pollution rules and exhaustion of fossil fuels resulted in massive outlay in energy division to satisfy the necessity and also to find eco-friendly energy resources. The primary motive of the researchers and engine designers is to enhance the performance with reduced emissions.

Human welfare, economic and industrial growth is influenced by a critical parameter namely energy sustainability. Even today fossil fuels are the major energy source, and their utilization rate is increasing at a faster rate [1, 2, 3]. To meet the demand, all developing nations import crude oil which results in a burden on the economy of the nation [3].

The traditional experimental scheme requires more time for optimization and extensive experiments need to perform as it is possible to vary only one parameter at a time. Traditional experimental scheme is expensive and it doesn't provide an interactive effect among the chosen variables. The integration of mathematical models of Taguchi method and RSM using design of experiments (DOE) provide good results. The Taguchi experimental design integrated with RSM method minimizes cost of experimentation and also results in

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interactive correlations.

The Taguchi method has a limitation wherein it can identify only linear effects, it does not consider quadratic and interaction effects. As per Taguchi design L27 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 expressed like equation 1.

$$Y = f(X_1, X_2, X_3, \ldots \ldots X_n) \quad \ldots (1)$$

Where, f is response function, Y is the response and X_1, X_2, X_3, ... X_n are the independent variables.

Analysis of variance (ANOVA), regression equation and signal-to-noise (S/N) ratio are obtained to predict optimal parameters and to assess the influence of significant conditions on performance, emission and combustion characteristics. It is observed from the experiments that ethanol blend percentage and EGR influences on the output parameters.

2.0 Materials and Methods

Experiments 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 equipped with nozzle having 6 holes each of 0.1mm 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 [4] and mentioned in Table 1.

The experiments are carried on 4-stroke diesel engine shown in Figure 1 and engine specifications are mentioned in Table 2.

Ethanol

Ethanol is a renewable biofuel since it is obtained from biomass. Ethanol can be obtained from various feedstock's including grains and green matter with high starch and sugar

F_1	Fuel flow rate sensor	T_3	Temperature of the calorimeter water inlet
F_2	Air flow rate measuring sensor	T_4	Temperature of calorimeter outlet
F_3	Flow rate to the jacket water measurement	T_5	Temperature of exhaust gas before calorimeter
F_4	Water flow inlet to the calorimeter	T_6	Temperature of exhaust gas after calorimeter
T_1	Water jacket inlet temperature	PT	Pressure sensor at combustion chamber
T_2	Water jacket outlet temperature	Wt	Weight

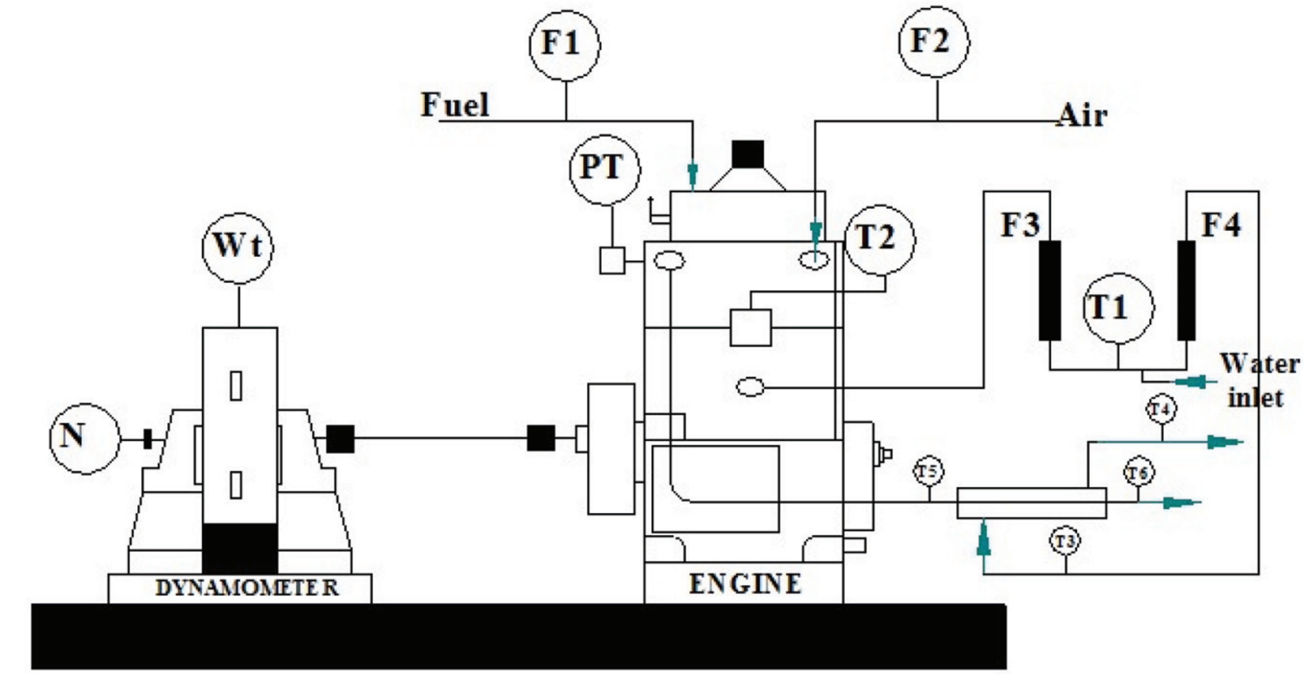

Figure 1: Schematic line diagram of engine test setup

Table 1: Properties of Fuels

Fuel	Density (kg/m^3)	Viscosity (cSt)	Calorific Value (CV) (kJ/kg)	Specific gravity	Flash point (°C)
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

content such as corn, sugar cane and sugar beets. Ethanol can also be obtained from agricultural and forestry residues such as corn cobs, rice straw, sawdust and wood chips [14, 45]. Ethanol required for present work is procured from the industry which has 99.9% quality.

3.0 Experimental Results and Discussion

The parameters and chosen levels are presented in Table 3 and layout of the experiment for the current study is presented in Table 4. Every single trial of experiment is replicated three times, the averaged value is taken as the response and are presented in Table 5. This experimental database is considered to obtain the mathematical model using Taguchi method.

Table 2: Engine specifications of tested engine

Parameters	Specifications
Engine type	TV1(Kirloskarmake)
Softwareused	Enginesoft
Injectoroperatingpressure	200to225bar
Staticinjectiontime	23°BTDC
Governortype	Centrifugaltype Mechanical
No ofcylinders	Singlecylinder
No ofstrokes	4stroke
Fuel oil	HighSpeedDiesel
Ratedpower	5.2 kWat1500rpm
Cylinderdiameter(Bore)	0.0875 m
Strokelength	0.11m
Ratio ofcompression	17.5:1

Table 3: Parameters and chosen levels

	Level 1	Level 2	Level 3
Ethanol	5	10	15
EGR	10	15	20

Table 4: Layout of the experiment

	Ethanol	EGR
1.	5	10
2.	5	10
3.	5	10
4.	5	15
5.	5	15
6.	5	15
7.	5	20
8.	5	20
9.	5	20
10.	10	10
11.	10	10
12.	10	10
13.	10	15
14.	10	15
15.	10	15
16.	10	20
17.	10	20
18.	10	20
19.	15	10
20.	15	10
21.	15	10
22.	15	15
23.	15	15
24.	15	15
25.	15	20
26.	15	20
27.	15	20

Table 5: Response values

BTE	SO	HC	CO	NOx	PP	ID	CD
29.64	47	36	0.136	1057	66	10.02	42
29.48	47	36	0.134	1056	66	10.04	42
29.47	48	36	0.137	1055	66	10.03	42
28.90	48	38	0.144	1050	64	10.12	43
28.92	48	38	0.142	1051	63	10.14	44
28.92	48	38	0.146	1049	63	10.10	44
28.60	49	40	0.158	1035	63	10.16	44
28.72	49	41	0.156	1037	62	10.14	45
28.72	49	41	0.160	1034	62	10.18	45
29.98	46	36	0.135	1075	68	9.99	41
29.92	46	36	0.132	1078	68	9.96	41
29.92	46	36	0.137	1072	68	10.02	41
29.42	47	37	0.142	1060	66	10.05	42
29.45	47	37	0.144	1063	65	10.02	43
29.46	47	37	0.140	1057	65	10.07	43
29.21	48	39	0.156	1045	64	10.09	43
29.26	48	40	0.158	1042	63	10.06	44
29.26	48	40	0.154	1048	63	10.12	44
29.90	45	33	0.132	1085	70	9.92	39
29.99	45	34	0.134	1082	70	9.94	39
29.99	45	34	0.130	1088	71	9.90	39
29.81	47	37	0.144	1078	67	10.02	39
29.69	47	35	0.143	1080	68	9.99	40
29.69	47	35	0.142	1084	69	9.97	40
29.72	48	38	0.154	1074	66	10.03	41
29.54	48	38	0.151	1076	65	10.01	41
29.53	48	38	0.155	1072	65	10.05	41

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 6-13 mentioned below provides the contribution of each parameter on the output. For reliable statistical analyses, error values must be smaller than 20% [5].

It is noted from the ANOVA that the BTE is highly influenced by ethanol percentage in the blend compared to percentage change in EGR. SO, HC and CO emissions are influenced more by EGR percentage variation compared to ethanol percentage in blend, NO_x emissions are influenced more by ethanol percentage compared to EGR and all three combustion parameters are influenced more by percentage ethanol in blend compared to EGR variation.

BTE

Table 6: ANOVA results for BTE

Source	DF	Adj SS	Adj MS	F-Value	Contribution (%)
Ethanol %	2	2.45854	1.22927	97.21	52.74
EGR %	2	1.92459	0.96229	76.09	41.29
Error	22	0.27821	0.01265		5.97
Lack-of-Fit	4	0.20735	0.05184	13.17	
Pure Error	18	0.07087	0.00394		
Total	26	4.66134			100

SO

Table 7: ANOVA results for SO

Source	DF	Adj SS	Adj MS	F-Value	Contribution (%)
Ethanol %	2	10.2963	5.1481	43.69	29.26
EGR %	2	22.2963	11.1481	94.60	63.37
Error	22	2.5926	0.1178		7.37
Lack-of-Fit	4	1.9259	0.4815	13.00	
Pure Error	18	0.6667	0.0370		
Total	26	35.1852			100

HC Emissions

Table 8: ANOVA results for HC

Source	DF	Adj SS	Adj MS	F-Value	Contribution (%)
Ethanol %	2	28.741	14.3704	53.35	24.76
EGR %	2	81.407	40.7037	151.11	70.13
Error	22	5.926	0.2694		5.11
Lack-of-Fit	4	1.259	0.3148	1.21	
Pure Error	18	4.667	0.2593		
Total	26	116.074			100

CO Emissions

Table 9: ANOVA results for CO

Source	DF	Adj SS	Adj MS	F-Value	Contribution (%)
Ethanol %	2	0.000044	0.000022	5.66	1.943
EGR %	2	0.002135	0.001068	276.92	94.30
Error	22	0.000085	0.000004		3.75
Lack-of-Fit	4	0.000017	0.000004	1.11	
Pure Error	18	0.000068	0.000004		
Total	26	0.002264			100

NO_x Emissions

Table 10: ANOVA results for NOx

Source	DF	Adj SS	Adj MS	F-Value	Contribution (%)
Ethanol %	2	4908.2	2454.11	135.58	67.91
EGR %	2	1921.6	960.78	53.08	26.59
Error	22	398.2	18.10		5.51
Lack-of-Fit	4	290.9	72.72	12.20	
Pure Error	18	107.3	5.96		
Total	26	7228.0			100

Peak Pressure

Table 11: ANOVA results for Peak Pressure

Source	DF	Adj SS	Adj MS	F-Value	Contribution (%)
Ethanol %	2	72.667	36.3333	94.66	42.58
EGR %	2	89.556	44.7778	116.66	52.47
Error	22	8.444	0.3838		4.95
Lack-of-Fit	4	2.444	0.6111	1.83	
Pure Error	18	6.000	0.3333		
Total	26	170.667			100

Ignition Delay

Table 12: ANOVA results for Ignition delay

Source	DF	Adj SS	Adj MS	F-Value	Contribution (%)
Ethanol %	2	0.067222	0.033611	69.91	48.97
EGR %	2	0.059467	0.029733	61.84	43.22
Error	22	0.010578	0.000481		7.71
Lack-of-Fit	4	0.001044	0.000261	0.49	
Pure Error	18	0.009533	0.000530		
Total	26	0.137267			100

Combustion duration

Table 13: ANOVA results for Combustion duration

Source	DF	Adj SS	Adj MS	F-Value	Contribution (%)
Ethanol %	2	60.519	30.2593	152.32	65.89
EGR %	2	26.963	13.4815	67.86	29.35
Error	22	4.370	0.1987		4.76
Lack-of-Fit	4	1.037	0.2593	1.40	
Pure Error	18	3.333	0.1852		
Total	26	91.852			100

Regression Equation

Taguchi based mathematical equations are obtained from regression analysis to find (predict) BTE, SO, HC, CO, NO_x, PP, ID and CD are mentioned below. These equations can be used to predict the output parameters by substituting the values of ethanol percentage and EGR percentage values in the range.

BTE = 29.4485 - 0.4074 Ethanol %_5 + 0.0937 Ethanol %_10 + 0.3137 Ethanol %_15 + 0.3615 EGR %_10 - 0.0863 EGR %_15 - 0.2752 EGR %_20

SO = 47.2593 + 0.8519 Ethanol %_5 - 0.2593 Ethanol %_10 - 0.5926 Ethanol %_15 - 1.1481 EGR %_10 + 0.0741 EGR %_15 + 1.0741 EGR %_20

HC = 37.1852 + 1.037 Ethanol %_5 + 0.370 Ethanol %_10 - 1.407 Ethanol %_15 - 1.963 EGR %_10 - 0.296 EGR %_15 + 2.259 EGR %_20

CO = 0.144296 + 0.001593 Ethanol %_5 - 0.000074 Ethanol %_10 - 0.001519 Ethanol %_15 - 0.010185 EGR %_10 - 0.001296 EGR %_15 + 0.011481 EGR %_20

NOx = 1062.33 - 15.22 Ethanol %_5 - 2.33 Ethanol %_10 + 17.56 Ethanol %_15 + 9.67 EGR %_10 + 1.22 EGR %_15 - 10.89 EGR %_20

PP = 65.778 - 1.889 Ethanol %_5 - 0.222 Ethanol %_10 + 2.111 Ethanol %_15 + 2.333 EGR %_10 - 0.222 EGR %_15 - 2.111 EGR %_20

ID = 10.0422 + 0.06111 Ethanol %_5 + 0.00000 Ethanol %_10 - 0.06111 Ethanol %_15 - 0.06222 EGR %_10 + 0.01111 EGR %_15 + 0.05111 EGR %_20

CD = 41.9259 + 1.519 Ethanol %_5 + 0.519 Ethanol %_10 - 2.037 Ethanol %_15 - 1.259 EGR %_10 + 0.074 EGR %_15 + 1.185 EGR %_20

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.

BTE must be higher, the best results are obtained for 15% ethanol blend with 10% EGR. Smoke opacity. Emission of HC, CO and NO_x are less for 15% ethanol blend with 10% EGR, even the combustion parameter curves support the same and are shown in Figures 2 to 7.

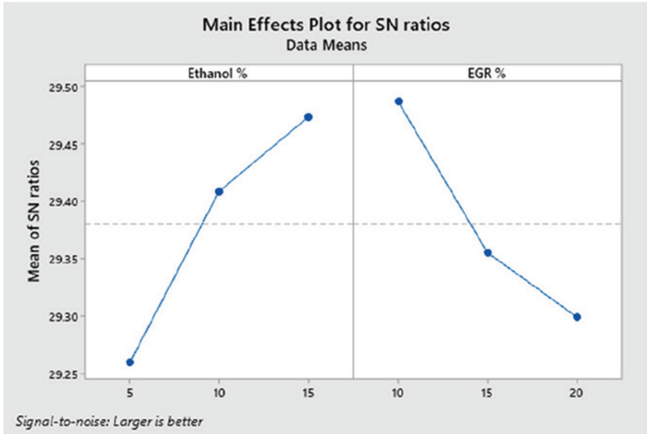

Figure 2: Mean effect plot for SN of BTE

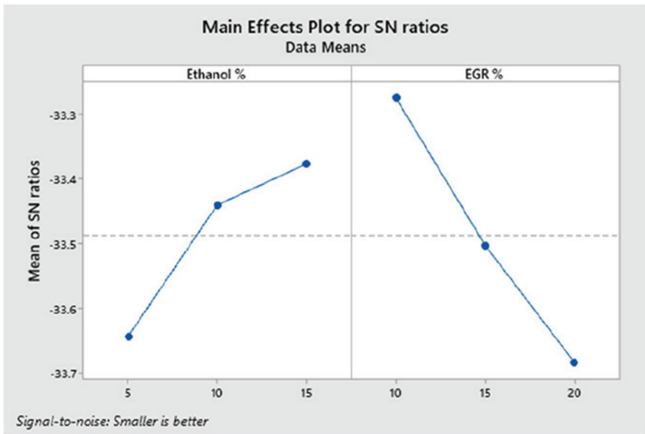

Figure 3: Mean effect plot for SN of Smoke opacity

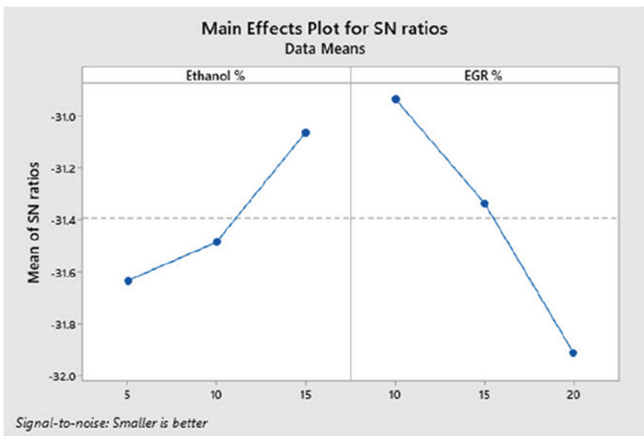

Figure 4: Mean effect plot for SN of HC emissions

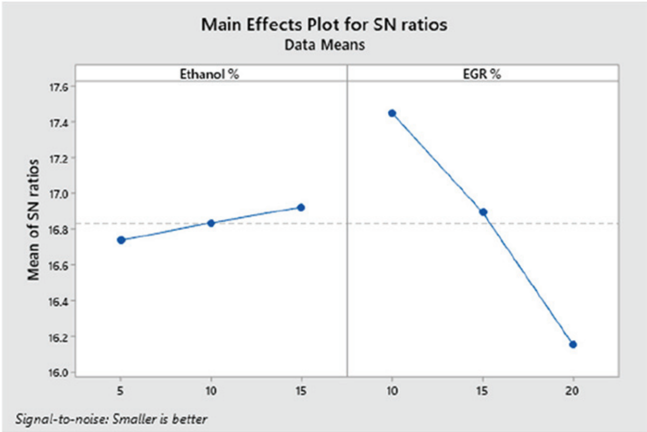

Figure 5: Mean effect plot for SN of CO emissions

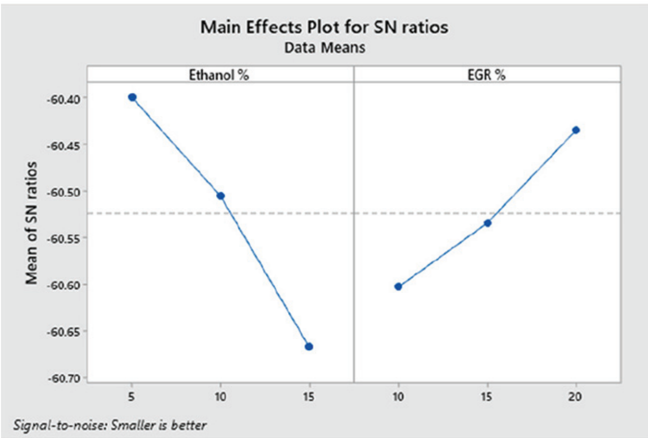

Figure 6: Mean effect plot for SN of NOx emissions

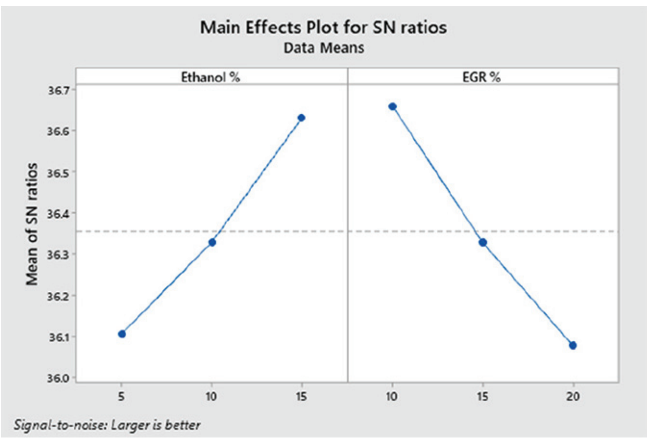

Figure 7: Mean effect plot for SN of Peak Pressure

4.0 Conclusions

1. With EGR operation, the NO_x emissions are decreased but result is slight decreased in performance and rise in smoke, CO and HC emissions. The effect of EGR is less up to 10%, but further increase has a negative effect on performance and emissions.
2. 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.
3. The mathematical model obtained by integration of Taguchi method and RSM is successfully validated with accuracy of 95%.

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