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Application of response surface methodology to optimize performance and emission characteristics of a diesel engine run on Karanja methyl ester blend with conventional diesel oil and picric acid as an additive

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ABSTRACT

A was done on diesel engine run on blend of karanja biodiesel and diesel in the ratio of 40:60 (B40) with different additive percentage (1.5%, 3% and 4.5%). In this work, Picric acid dissolved in n-butyl alcohol (nBAPA) is used as an additive. The performance and emission tests were carried for three inputs-Load, compression ratio (CR) and B40 with different percentage of nBAPA and six outputs- brake specific fuel consumption (BSFC), brake thermal efficiency (BTHE) and Hydro carbons (HC), Carbon monoxide (CO), Nitrogen oxides (NO_X) and Carbon dioxide (CO_2). A set of experiments were conducted by using central composite design of response surface methodology (RSM) through Design Expert-10. The predicted and experimental maximum BTHE of 23.52% and 23.44 % were obtained at load 9.36 kg, CR 15, B40 with 3% additive. The predicted and experimental minimum BSFC of 0.38kg/kWh and 0.37 kg/kWh were obtained load 9.36 kg, CR 15, B40 with 3% additive. The predicted and experimental minimum CO_2 of 2.13% and 2.29% were obtained at load 4 kg, CR 16, B40 with 1.5% additive. The predicted and experimental minimum HC of 3.33ppm and 4ppm were obtained at load 2.63 kg, CR 15, B40 with 3% additive. The predicted and experimental minimum CO of 0.055% and 0.056% were obtained at load 8 kg, CR 16 and B40 with 4.5% additive. The predicted and experimental minimum NO_x of 113.71ppm and 120ppm were obtained at load 2.63 kg, CR 15, B40 with 3% additive.

Keywords— *Karanja biodiesel, Optimization, RSM, nBAPA additive*

1. INTRODUCTION

Due to increase in demand and scarcity of the petroleum fuels, there is a need for an alternative fuel to replace the petroleum fuels. Rudolf diesel used peanut oil to run diesel engine designed by him in the year 1893, august 10 [1]. Vegetable oils and animal fat oils are being used in place of diesel as alternative fuel since then [2]. Biodiesel can be extracted from vegetable oil like cotton seed, palm, rapeseed, soybean and animal fat [3]. Vegetable oils cannot be directly used as replacement for conventional diesel fuel in engines due to their properties such as higher viscosity, higher flash point and fire point, longer molecule chains, lower pour point and cloud point, lower vapour pressures. These features of the Vegetable oil cause poor atomization and vapour–air mixing, low pressure, incomplete combustion of fuel and engine deposit. The viscosity of vegetable oil can be reduced to improve physical features through blending, pyrolysis, dilution, cracking, Esterification and micro-emulsification [4]. Bobade S.N et al. explained the esterification process for the production of biodiesel as follows. The vegetable oil is chemically reacted with alcohol in the presence of catalyst to produce methyl ester. Since biodiesel has more than 4% (by volume) fatty acid then two Stage process is used for the transesterification of karanja oil. In the first stage of the Esterification the FFA content is reduced by Esterification with 99% pure methanol and 98% pure sulphuric acid as catalyst in 60 minutes time at 57ºC in a closed reactor vessel. The crude vegetable oil is first heated to 50ºC and sulphuric acid of 0.5% (by wt.) is added as catalyst to crude vegetable oil then methyl alcohol of 13% (by wt.) is added. To increase the rate of reaction excess amount of Methyl alcohol is added. During the process simultaneous stirring at 700 rpm and temperature of 55-57 ºC is maintained for one and half hour the FFA of the oil is checked for every 25-30 min. When the FFA is reduced up to 1%, the reaction is stopped [5]. Biodiesel can be blended with diesel fuel in any proportion as it has similar characteristics and has lower emissions. Fuel properties of biodiesel are better compared to diesel such as no sulphur content, non-toxic, renewable and no aromatics [6, 7]. A team of researchers [8, 9] classified diesel additives as preflame additives, flame additives and post flame additives according to the purpose for which they used or designed. It was reported that magnesium (Mn) based additives may reduce emissions like particulate matter (PM), CO, HC, NO_x and they act as catalysts to enhance the oxidation process [9]. Many researchers [10] studied the effect of barium additives on soot emission. It was reported that there was 20-75% reduction in visible smoke emission in the exhaust of a diesel engine due to use of barium as fuel additive. Some researchers studied the effect of Magnalium (Al-Mg) on BSFC for variable load and constant speed condition. It was found that there was a decrease in BSFC with addition of 3% of Magnalium [11]. Experiments were conducted to study the effect of jatropha biodiesel blends with an additive Al-Mg on BTHE. It was observed that BTHE increased with 1% increase in addition of Al-Mg [12]. BTHE was also found to be increasing with addition of di-ethyl ether (DEE) as additive to plastic oil biodiesel and Mahua biodiesel [13, 14]. A number of researchers made attempts to decrease emissions like CO, CO_2 and NO_x. HC and CO emissions were found to be reduced when Al-Mg additive was added to jatropha biodiesel and cobalt oxide was added to mahua biodiesel [12]. When dimethyl carbonate was added to Mahua oil, CO emission was reduced [15]. Some of the additives like oxygenated additives, metal based additives and cetane improver additive are blended with biodiesel to reduce NO_x emissions. When Mahua biodiesel was blended with diethyl ether oxygenated additive, NO_x emission was found to be reduced at low load condition. Jatropha biodiesel was blended with cerium metal based additive, it was observed that 23.5% of NO_x was reduced [16, 17]. By blending of metal additive to biodiesel, CO_2 emission was reduced slightly [18]. A desktop study and evaluation were undertaking by a researcher to study the effectiveness of ferrous picrate catalyst additive in diesel engine and reported that fuel consumption was reduced by 1.8%, CO was reduced by 22% and soot particles in the engine exhaust were smaller of high reactivity [19].

It is reported that RSM is most effective in obtaining functions between the input and the output parameters. A feasibility study was conducted to use artificial neural networks along with genetic algorithms to optimize the settings of diesel engine to decrease fuel consumption and to regulate toxic emissions [20]. Experiments were conducted on fuel consumption and NO_X emissions in a diesel engine by developing a control oriented model using RSM and concluded that the mean errors of the predicted NO_X and BSFC are 6% and 2% with a calculation time of 5.5ms[21]. An attempt has made to optimize the performance, emission and combustion characteristics of a diesel engine fuelled with jatropha biodiesel- conventional diesel oil blends using Central Composite Design (CCD) of RSM and NSGA-II and reported that optimal solution thus obtained are in good agreement with confirmatory experiments [22].

Based on the literature review, in this research an attempt has made to optimize the operating parameters of diesel engine fuelled with B40 with different nBAPA additive using CCD of RSM and to study the effect of additive on the emissions of the diesel engine.

2. MATERIAL AND METHODS

Karanja oil methyl ester was brought from PES Mandya biodiesel centre (India). B40 was prepared by mixing karanja oil methyl ester and conventional diesel oil in proportion of 40:60 volumes using a magnetic stirrer for 30 minutes and 500rpm stirrer speed. nBAPA additive is prepared by mixing picric acid of 2.355 gm. (6% weight of n-Butyl alcohol) in 39.25 gm. of n-Butyl alcohol. The percentage of picric acid to be dissolved in n-Butyl alcohol was decided based on the complete solubility of the picric acid in n-Butyl alcohol which was found using trial and error method. B40 with different additive percentages (1.5%, 3% and 4.5%) is prepared by mixing B40 with additive nBAPA using a magnetic stirrer for 20 minutes at 500rpm stirrer speed.

3. EXPERIMENTAL SETUP

Figure 1 shows the experimental setup consists of computerised single cylinder, variable injection and variable compression ratio diesel engine. HG-540 emission analyser was used to measure CO_2, HC, CO and NO_X. Table 1 and Table 2 show the specification of engine and emission analyser. For the study B40 with 1.5%, 3% and 4.5% additive are used as test fuels. A set of experiments with different combination of inputs are obtained using Design Expert software and performance parameters such as brake thermal efficiency and brake specific fuel consumption are obtained through analysis of variable compression ratio engine using IC engine software and emission parameters like CO_2, HC, CO and NO_X are measured using HG-540 emission analyser.

Fig. 1: Engine test setup

Table 1: Specification of diesel engine

Engine Specification	
No. of cylinders	1
No. of strokes	4
Cylinder diameter	87.5mm
Stroke length	110mm
Connecting rod length	234mm
Orifice diameter	20mm
Dynamometer arm length	185mm
Fuel	Diesel
Power	3.5kW
speed	1500 RPM
CR range	12:1 to 18:1

Table 2: Specification of HG-540 emission analyser

EMISSION	MEASURING RANGE
HC	0 – 10000 ppm
CO	0-9.999%
CO_2	0-20%
NO_X	0 – 5000 ppm

3.1 Uncertainty analysis

Uncertainty analysis is generally carried out to find the accuracy of the instruments [23]. The errors and uncertainties during experimentation largely depend on type of instruments, conditions in which experiments are conducted, test planning observations and readings. Uncertainty estimates the errors and quantifies the expected accuracy but it is not the guarantee of accuracy [24]. Table 3 shows the accuracies and uncertainty of measured and calculated results. Moffat formula was used to calculate the errors.

Table 3: The accuracies and uncertainty of measured and calculated results

Measurements	Accuracy	Uncertainty (%)
Speed of engine	± 1 RPM	± 0.2
Temperature	± 1^0C	±0.1
Fuel measurement	± 2CC	±1
Crank angle encoder	± 0.5 ^{0}CA	± 0.2
Load	± 1N	± 0.2
Calculated results		
Brake power	-	± 0.2
Fuel consumption	-	± 1.5
Brake thermal efficiency	-	± 2.0

4. EXPERIMENTAL DESIGN

4.1 Parameter design and methodology

In order to optimize performance and emission parameters a five level, three factors CCD was used. The input/control parameters (load, CR and B40 with different additive percentage) have been selected for the optimization of performance and emission parameters. Each of these parameters was treated at five levels. Table 4 show the input parameter level used in CCD for combination of input/control parameters.

4.2 Design of experiments

Design Expert-10 software was used to generate design matrix which was selected based on 6 level response/output and 3 level factor/input design of RSM generated by the software. There were 20 experimental runs in design matrix. Table 5 shows experimental matrix for CCD of combination of input/control parameters.

Table 4: Independent variable or inputs and levels used for response surface design for the second combination of input

Independent variable	Units	Low	High	-Alpha	+Alpha
Load	kg	4	8	2.63641	9.36359
CR		14	16	13.3182	16.6818
B40 with % additive	%	1.5	4.5	0.47721	5.52269

5. RESULT AND DISCUSSION

5.1 Analysis of the model

Experiments with different combination of inputs generated by the software are conducted and the required performance and emission characteristics output are obtained as shown in Table 5. The experimental values were fitted to quadratic equation using design Expert software. The model analysis was done based on ANOVA (analysis of variance) which gives the p value. The ANOVA analysis was done for different output parameters BTHE (break thermal efficiency), SFC (specific fuel consumption), CO_2, HC, CO and NO_X. The p values were less than 0.05 for all parameters. The model was found to be significant as the p values were less than 0.05. Analysis was carried out to get equations and coefficients using which responses can be predicted. The software provides equation in terms of actual factors which can be used to make predictions about the response of each factor. The predicted response values of performance and emission characteristics are given in Table 6 and Table 7. The equations in terms of actual factors for the output are given below from equation 1 to 6. The software provides predicted values for each experimental test.3D surface plots of the input against output are obtained using the software and studied.

Table 5: Experimental Values of output for Optimization of diesel engine using B40 with different additive percentage

		Factor 1	Factor 2	Factor 3	Output 1	Output 2	Output 3	Output 4	Output 5	Output 6
Std	Run	A:LOAD	B:CR	C:B40 with additive	BSFC	BTHE	CO_2	HC	CO	NO_X
		kg		%	kg/kWh	%	%	ppm	%	ppm
17	1	6	15	3	0.46	18.62	3.37	42	0.073	797
10	2	9.363	15	3	0.37	23.44	3.85	8	0.059	1494
8	3	8	16	4.5	0.39	21.78	3	13	0.056	1329
15	4	6	15	3	0.46	18.62	16.24	42	0.079	790
18	5	6	15	3	0.45	18.5	16.2	42	0.081	794
16	6	6	15	3	0.45	18.64	16.9	42	0.081	797
1	7	4	14	1.5	0.56	16.3	2.26	15	0.061	274
2	8	8	14	1.5	0.4	20.29	3.78	30	0.056	1006
4	9	8	16	1.5	0.4	20.26	4.22	21	0.095	1431
13	10	6	15	0.477	0.45	17.73	3.44	45	0.072	807
20	11	6	15	3	0.45	18.6	15.3	43	0.078	798
19	12	6	15	3	0.45	18.59	15.8	43	0.078	794
5	13	4	14	4.5	0.58	15.06	2.92	14	0.11	234
12	14	6	16.6818	3	0.47	18.74	3.82	18	0.088	1060
14	15	6	15	5.522	0.45	17.7	3.22	40	0.077	689
11	16	6	13.31	3	0.46	18.66	3.22	19	0.073	540
9	17	2.636	15	3	0.71	14.8	2.37	4	0.091	120
6	18	8	14	4.5	0.39	22.4	3.68	28	0.06	983
7	19	4	16	4.5	0.59	15.33	3.04	21	0.083	420
3	20	4	16	1.5	0.59	17.1	2.13	27	0.086	537

The models for the responses of the optimization Table 5 are developed in terms of actual factors and are given below as equations (1-6).

BSFC = +1.57729 -0.097818 * LOAD -0.10325 * CR +0.037817 * B40 with additive -2.50000E-003 * LOAD * CR -1.66667E-003 * LOAD * B40 with additive -1.66667E-003 * CR * B40 with additive+7.69087E-003* LOAD^2+4.24699E-003* CR^2-4.69470E-004* B40 with additive^2 …..(1)

BTHE = +12.92499 +1.48733 * LOAD -0.51773 * CR +0.56462 * B40 with additive -0.10750 * LOAD * CR +0.27667 * LOAD * B40 with additive -0.093333 * CR * B40 with additive +0.04948 * LOAD^2 +0.049444 * CR^2 -0.13280 * B40 with additive^2 …… (2)

CO_2 = -853.00419+12.05569* LOAD+108.30219* CR+11.57820* B40 with additive-0.014375* LOAD * CR-0.12042* LOAD * B40 with additive-0.072500* CR * B40 with additive-0.93576* LOAD^2-3.59810* CR^2-1.62901* B40 with additive^2 ...….(3)

HC = -2247.81635+80.01720* LOAD+271.14558* CR+13.09977* B40 with additive-2.68750* LOAD * CR-0.12500* LOAD * B40 with additive-0.91667* CR * B40 with additive-3.21119* LOAD^2-8.42533* CR^2+0.026646* B40 with additive^2 ….(4)

CO = -0.047811-0.025233* LOAD -4.47062E-003* CR+0.14395* B40 with additive+2.31250E-003* LOAD * CR-3.37500E-003 * LOAD * B40 with additive-7.91667E-003* CR * B40 with additive-3.31059E-004* LOAD^2+6.20306E-004* CR^2-6.67117E-004* B40 with additive^2 …..(5)

NO_X = -1428.09355-108.92984* LOAD+66.97379* CR+212.15970* B40 with additive+20.12500* LOAD * CR+1.33333* LOAD * B40 with additive-13.00000* CR * B40 with additive+0.65742* LOAD^2+0.15483* CR^2-8.10220* B40 with additive^2 …..(6)

Table 6: Experimental and predicted response values of performance characteristics

Load kg	CR	B40 with different additive Percentage %	BSFC kg/kWh EV*	BSFC kg/kWh PV**	BTHE % EV	BTHE % PV
6	15	3	0.46	0.45	18.62	18.59
9.36359	15	3	0.37	0.38	23.44	23.52
8	16	4.5	0.39	0.38	21.78	21.7
6	15	3	0.46	0.45	18.62	18.59

6	15	3	0.45	0.45	18.5	18.59
6	15	3	0.45	0.45	18.64	18.59
4	14	1.5	0.56	0.57	16.3	16.34
8	14	1.5	0.4	0.39	20.29	20.3
8	16	1.5	0.4	0.4	20.26	20.23
6	15	0.47731	0.45	0.45	17.73	17.68
6	15	3	0.45	0.45	18.6	18.59
6	15	3	0.45	0.45	18.59	18.59
4	14	4.5	0.58	0.58	15.06	15.04
6	16.6818	3	0.47	0.47	18.74	18.8
6	15	5.52269	0.45	0.45	17.7	17.82
6	13.3182	3	0.46	0.46	18.66	18.66
2.63641	15	3	0.71	0.7	14.8	14.78
8	14	4.5	0.39	0.39	22.4	22.33
4	16	4.5	0.59	0.59	15.33	15.27
4	16	1.5	0.59	0.59	17.1	17.13

EV* =Experimental value, PV**= Predicted value

Table 7: Experimental and predicted response values of emission characteristics

Load kg	CR	B40 with different additive percentage %	CO_2 %		HC ppm		CO %		NO_X ppm	
			EV	PV	EV	PV	EV	PV	EV	PV
6	15	3	3.37	13.95	42	42.33	0.073	0.078	797	795.25
9.36359	15	3	3.85	4.21	8	8.68	0.059	0.059	1494	1491.66
8	16	4.5	3	2.99	13	13.24	0.056	0.055	1329	1332.41
6	15	3	16.24	13.95	42	42.33	0.079	0.078	790	795.25
6	15	3	16.2	13.95	42	42.33	0.081	0.078	794	795.25
6	15	3	16.9	13.95	42	42.33	0.081	0.078	797	795.25
4	14	1.5	2.26	1.9	15	14.76	0.061	0.062	274	276.69
8	14	1.5	3.78	3.68	30	29.44	0.056	0.055	1006	1007.53
8	16	1.5	4.22	3.95	21	20.46	0.095	0.096	1431	1433.77
6	15	0.47731	3.44	3.6	45	45.63	0.072	0.072	807	802.85
6	15	3	15.3	13.95	43	42.33	0.078	0.078	798	795.25
6	15	3	15.8	13.95	43	42.33	0.078	0.078	794	795.25
4	14	4.5	2.92	2.82	14	14.54	0.11	0.11	234	237.33
6	16.6818	3	3.82	3.87	18	17.68	0.088	0.087	1060	1053.62
6	15	5.52269	3.22	3.57	40	39.37	0.077	0.077	689	684.52
6	13.3182	3	3.22	3.68	19	19.33	0.073	0.073	540	537.75
2.63641	15	3	2.37	2.53	4	3.33	0.091	0.09	120	113.71
8	14	4.5	3.68	3.16	28	27.72	0.06	0.061	983	984.17
4	16	4.5	3.04	2.78	21	21.56	0.083	0.085	420	424.57
4	16	1.5	2.13	2.29	27	27.28	0.086	0.085	537	541.93

EV =Experimental value, PV= Predicted value

5.2 Evaluation of model

The model stability is analyzed using ANOVA is shown in Table 8. The model is stable since p-value is less than 0.0001. Regression statistics like R^2 (goodness of fit) and adj. R^2 goodness of prediction shown in Table 8 are in agreement with each other.

Table 8: Model evaluation for optimization

Model	BSFC	BTHE	CO_2	HC	CO	NO_X
Mean	0.48	18.56	6.44	27.85	0.077	784.70
SD	0.00664	0.077	3.71	0.69	0.00236	5.09
R-squared	0.9969	0.9994	0.7812	0.9987	0.9849	0.9999
Adj. R^2	0.9940	0.9989	0.5843	0.9974	0.9712	0.9998
Model degree	quadratic	quadratic	quadratic	quadratic	quadratic	quadratic
Pred. R^2	0.9815	0.9963	0.6738	0.9921	0.9530	0.9994

6. INTERACTION EFFECT

6.1 Break specific fuel consumption

Figure 2 shows the variation of BSFC against load and CR .From Figure 2 it can be seen that the maximum BSFC obtained is 0.71 kg/kW-hr for input combination of load 2.6kg, CR 15 and B40 with 3% additive .The minimum BSFC obtained is 0.37 kg/kW-hr for input combination of load 9.3kg, CR 15 and B40 with 3% additive. From Figure 2, it can be seen that the BSFC increases with the decrease in load. From Figure 2 it is also clear that compression ratio and additive percentage added to B40 does not have effect on BSFC.

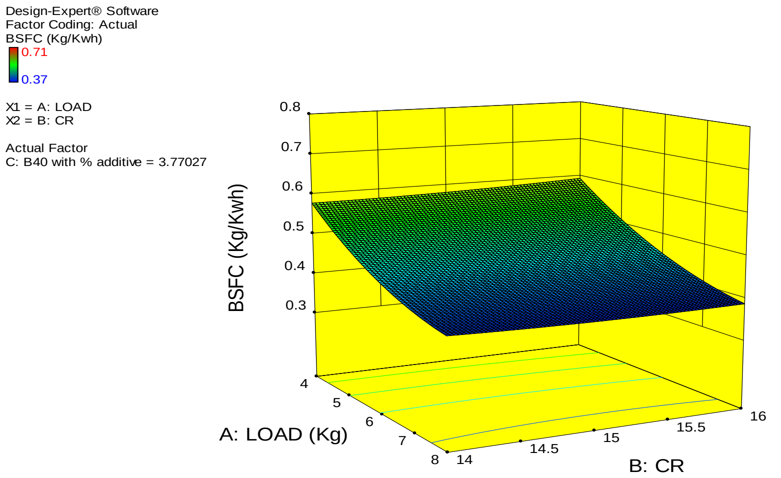

Fig. 2: 3D plot for variation of BSFC against load and CR for B40 with different additive percentage

6.2 Brake thermal efficiency

Figure 3 shows the variation of BTHE against load and CR. From Figure 3 it can be seen that the maximum BTHE obtained is 23.44% for input combination of load 9.36 kg, CR 15 and B40 with 3% additive. The minimum BTHE obtained is 14.8% for input combination of load 2.6 kg, CR 15 and B40 with 3% additive. BTHE increases with the increase in load. From Figure 3 it is also clear that compression ratio and additive percentage added to B40 does not have effect on BTHE.

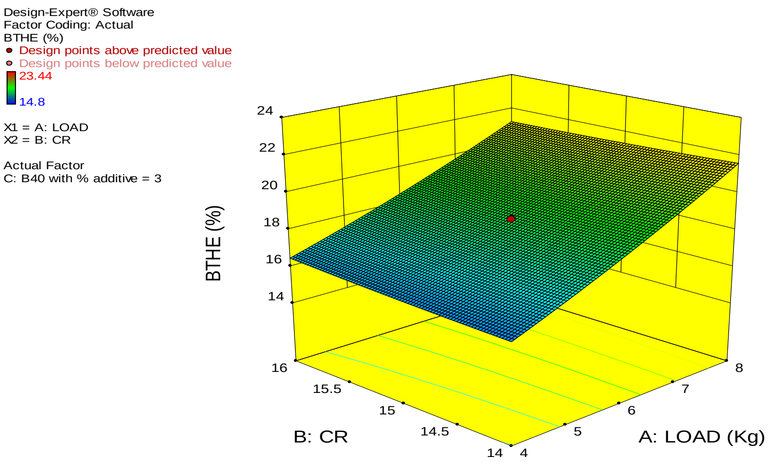

Fig. 3: 3D plot for variation of BTHE against load and CR for B40 with different additive percentage

6.3 Carbon di-oxide (CO_2)

Figure 4 shows the variation of CO_2 against load and CR. From Figure 4 it can be seen that the minimum CO_2 obtained is 2.13% for input combination of load 4 kg, compression ratio 16 and B40 with 1.5% additive. CO_2 first increases with the increase in load up to 6kg and then decreases. CO_2 first increases with the increase in CR up to 15 and then decreases. CO_2 first increases with the increase in additive percentage up to 3% and then decreases with the increase in additive percentage.

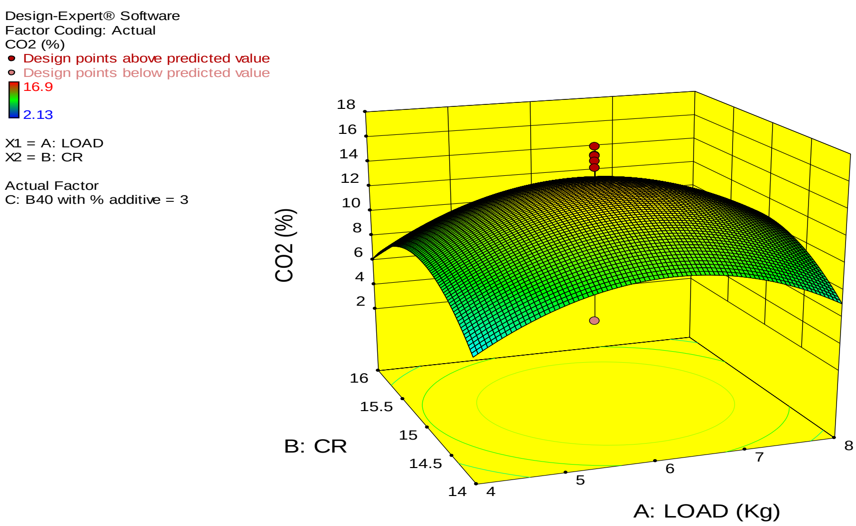

Fig. 4: 3D plot for variation of CO_2 against load and CR for B40 with different additive percentage

6.4 Hydrocarbon (HC)

Figure 5 shows the variation of HC against load and CR. From Figure 5 it can be seen that the minimum HC obtained is 4ppm for input combination of load 2.6, compression ratio 15 and B40 with 3% additive. HC first increases with the increase in load upto 6kg and then decreases with the increase in load. HC first increases with the increase in CR upto 15 and then decreases with the increase in CR. HC decreases with the increase in additive percentage.

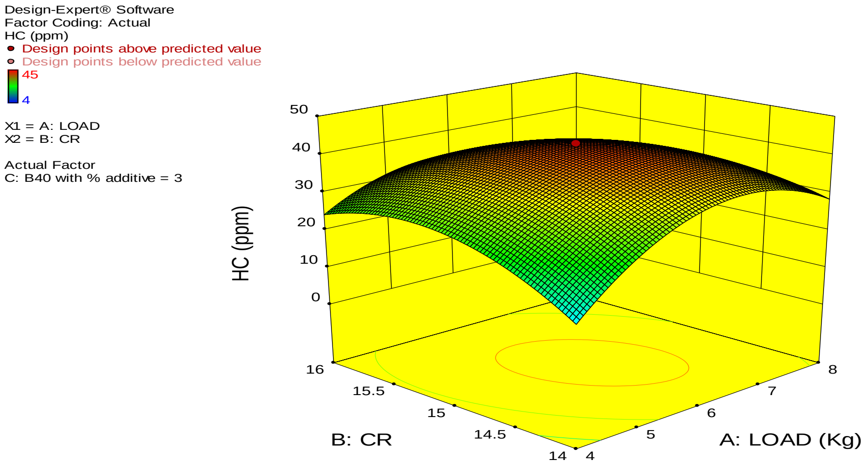

Fig. 5: 3D plot for variation of HC against load and CR for B40 with different additive percentage

6.5 Carbon monoxide (CO)

Figure 6 shows the variation of HC against load and CR. From Figure 6 it can be seen that the minimum CO_2 obtained is 0.056% for input combination of load 8 kg, compression ratio 16 and B40 with 4.5% additive. CO decreases with the increase in load. CO increases with the increase in CR and additive percentage.

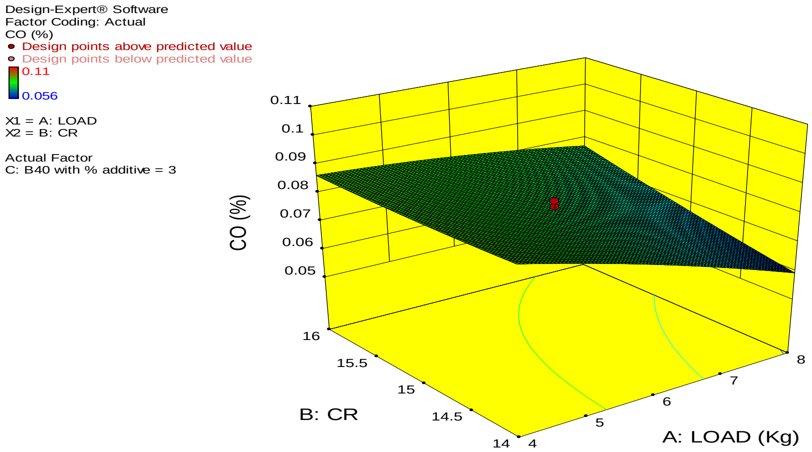

Fig. 6: 3D plot for variation of CO against load and CR for B40 with different additive percentage

6.6 Nitrogen oxide (NO_x)

Figure 7 shows the variation of NO_X against load and. From Figure 7 it can be seen that the minimum NO_X obtained is 120ppm for input combination of load 2.6 kg, compression ratio 15 and B40 with 3% additive. NO_X increases with the increase in load and CR and decreases with the increase in additive percentage.

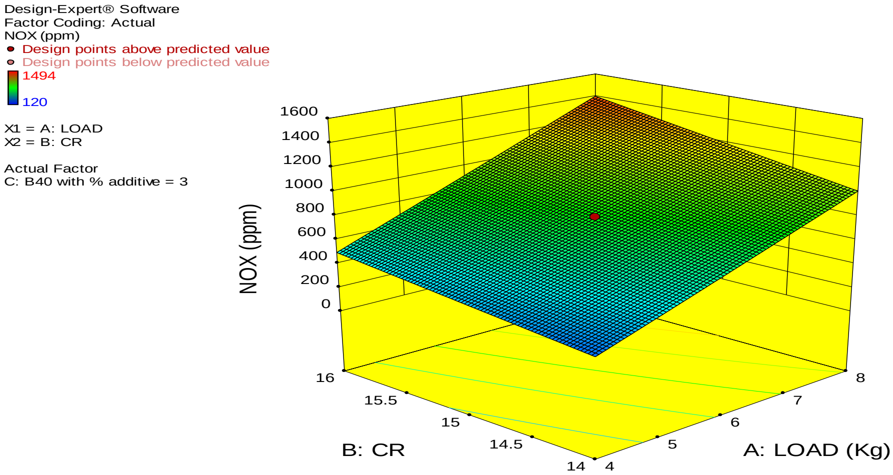

Fig. 7: 3D plot for variation of NO_X against load and CR for B40 with different additive percentage

7. CONCLUSION

It is concluded that operational parameter optimization of a diesel engine run on B40 with additive percentage 1.5%, 3% and 4.5% can be done effectively by using CCD of RSM. It can also be seen that B40 with additive percentage 1.5%, 3% and 4.5% are good in reducing the toxic gas emissions and improving the performance of the engine. With this study, it is concluded that responses such as BTHE, BSFC, CO_2, CO, HC and NO_X at optimized parameters are found to be 23.44%, 0.37kg/kWh, 2.29%, 0.056%, 4ppm and 120ppm. It is also found that the predicted and the experimental responses were almost same.

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