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Performance, Combustion and Emission Characteristics Improvements of Rapeseed Methyl Ester using Surface Response Methodology

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Abstract:

The main aim of the present study is to improve the performance of Rapeseed Methyl Ester (RME) and to reduce the emissions in 4-stroke, single cylinder, water cooled, variable compression ratio (VCR) engine by using surface response methodology. The performance factors used in this study are brake thermal efficiency, brake specific fuel consumption, the combustion factors are maximum pressure and net heat release rate and the emission factors used in this study are hydro carbons, carbon monoxide, carbon di-oxide, nitric oxides and INDUS smoke number. Experiments are carried out at 20%, 40%, and 100% of RME-Diesel blends by volume. Derringers Desirability approach is used for optimization of the VCR engine factors. RME-Diesel blends (%) and brake power of the engine are used as the main operational factors for optimization of the VCR diesel engine using response surface method (RSM). At a compression ratio of 18, 24.96% RME-Diesel blend, 1.893 kW Brake power, engine has the optimized performance and minimum emissions. It is observed that the experimental results and mathematical results are in good agreement with each other. At these optimized input factors, the error in percentage for output responses i.e. brake thermal efficiency, brake specific fuel consumption, Hydro carbons, Carbon monoxide, Carbon di-oxide, Nitric oxides, INDUS smoke number are found as 1.85%, 16.42%, 21.3%, 13.16%, 14.87%, 7.36%, 3.26% respectively.

***Keywords* — VCR Diesel Engine, RME, Optimization, Response Surface Methodology.**

I. INTRODUCTION

Petroleum oils are frequently used in engines, gear boxes, turbines and various industries for lubrication purpose etc. The environmental pollution is caused mainly due to frequent usage of petroleum based oils in the engines [1]. The main focus is concentrated on environmental friendly bio-fuels due to increase in fuel prices, reduce pollution in the atmosphere and reduction in fossil fuels [2]. Biodiesels are easy to produce, renewable in nature, used in agriculture sectors, good in emission characteristics when compared to petroleum based fuels [3].Vivek Lande [4] studied the performance and emission characteristics of Waste Fried Oil Methyl Ester-diesel blends in VCR diesel engine. The brake thermal efficiency (Bth), brake specific fuel consumption (Bsfc) and exhaust gas temperature (EGT) are found as 27.12%, 0.313 kg/kW h, 278.93 31 ºC respectively, at input optimum parameters of 20% biodiesel, 23.31ºBTDC Injection timing and 17.23 Compression ratio. With increase in compression ratio, increase in BTH and decrease in BSFC and increase in EGT observed in the study. In (5), RSM is used for optimization of operating parameters, when the VCR engine is fuelled with-fish oil and diesel oil blends. ANOVA model is used in the validation. Optimization of input responses and corresponding output responses is made by using desirability approach. Increase in Injection timing and Fish oil blend (upto 30%), the emission parameters viz. HC, CO, CO_2, NO_X are reduced. The optimum input parameters are found to be 15:1 compression ratio, 21 ºBTDC Injection timing, 3kg load, 22.5% fish blend. Confidence level in the experiments is found to be 95%.

Saumil C. Patel and Pragnesh K. Brahmbhatt [6] used the approach of RSM to find out the Specific fuel consumption as response. The response highly depends on compression ratio and injection pressure. Quadratic model is selected for significance of fit in the statistical analysis. It is also found that the RSM is very much useful in optimization of response. Abdullah Abuhabaya Three, John Fieldhouse and Rob Brown [7] optimized the biodiesel productions by using Response surface method. To maximize the biodiesel yield, the parameters are taken as rate of mixing, reaction time, NAOH catalyst concentration, reaction temperature. The most influential parameters for conversion to biodiesel are molar ratio of methanol to sunflower oil and catalyst concentration.

K. Prasada Rao, B.V. Appa Rao [8] reported that the optimization of performance and exhaust emissions of indirect injection diesel engine fuelled with mahua biodiesel blends. The input parameters are selected as load and fuel blend. Grey rational analysis was applied to experimental results to find out the optimal combination of input parameters by converting multi response problem to single response problem with the aid of grey rational grade. Air pollution from the atmosphere in Europe countries can be reduced by usage of bio-diesels like Rapeseed methyl esters. 25 to 30 % RME and diesel blends are conventionally used in various countries like Crench, Italy, France, Spain, Swedan & Europe. Due to high viscosity, density, low volatility and poor filtration, it is scarcely suggested to use pure rapeseed oil as substitute in diesel engines even though it is economical [9].

TABLE I
SPECIFICATIONS OF VCR ENGINE

Item	Specification
Make and Model	Kirloskar, TV1
General details	Four stroke, compression ignition, Constant speed vertical, Water cooled, Direct injection, Variable compression ratio
Number of cylinders	One
Bore X Stroke	87.5 mm X 110 mm
Swept volume	661 cc
Compression ratio	18:1
Rated speed	1500 rpm

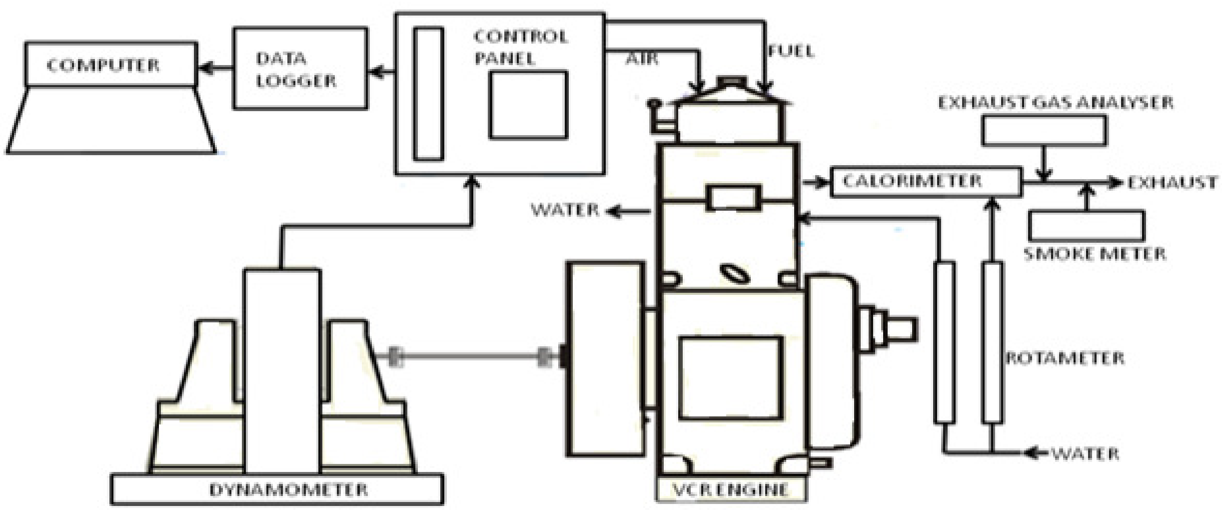

Fig. 1 Schematic Diagram of experimental engine set up.

II. EXPERIMENTAL SETUP

The schematic diagram of experimental engine setup is shown in the Fig.1. The VCR diesel engine is of water cooled type, four stroke, single cylinder and direct injection system. The detailed specifications of the engine are given in Table I. Three types of biodiesel blends are used in the experiments i.e. RME 20 (20% RME + 80% Diesel), RME 40 (40% RME + 60% Diesel), and RME 100 (100% RME). The experiments are conducted with these three biodiesel blends and the loads are varied in terms of Brake powers (i.e. 0.54, 0.93, 1.83, and 3.45). The tests are conducted at a compression ratio 18. The software used to find out the brake specific fuel consumption, brake thermal efficiency, maximum pressure, and heat release rate is "IC Engine Soft". Smoke in the exhaust pipe line is measured with the help of INDUS smoke meter. The exhaust gas emissions like NO_X, CO, HC, and CO_2 are measured by using INDUS five gas analyzer. The temperatures at different positions of the engine are measured with the help of resistance temperature detectors.

TABLE II
FUEL PROPERTIES OF RME AND ITS BLENDS WITH THE DIESEL FUEL.

Property	Gross Calorific value (Cal/g)	Kinematic Viscosity, (cSt)	Density (g/ml)
RME20	10197	2.9	0.835
RME40	9483	3.4	0.850
RME100	8726	5.0	0.890
Protocol	IS: 1448 (P 6)	IS: 1448 (P 25)	IS: 1448 (P 32)

TABLE III
SPECIFICATIONS OF FIVE GAS ANALYZER AND SMOKE METER.

Para-meter	Measuring Range	Accuracy	Resolution
Hydro-Carbons(PPM)	0-30,000	1	2
Carbon Monoxide (%)	0-15	3	4
Nitrogen oxides(PPM)	0-5000	5	6
Oxygen (%)	0-25	0.1	0.01
Carbon di-oxide(%)	0-20	0.5	0.01
Smoke, HSU (%)	0-99.9	0.1	0.1

Table II shows the fuel properties and its blends with diesel fuel. Table III shows the various measurement parameters and its accuracies of five gas analyzer and smoke meter.

III. RESPONSE SURFACE METHODOLOGY (RSM)

The relationship between input factors and output response variables are computed with the help of RSM. In this present study, two input factors are chosen for analysis. Input factors considered in this methodology are loads in terms of brake power and different types of fuel blends. Brake specific fuel consumption, Brake thermal efficiency, CO_2, HC, NO_X, Smoke and HRR are the output response variables. "Design-Expert" software is used to get the results of the present RSM. Table IV shows experimental design Matrix for various parameters. ANOVA (Analysis of variance) was used in the present study for analysis of this model. Derringer's design approach was used to find out the optimization of the engine variables. At optimum input factors i.e. fuel blend & brake power and corresponding optimum output response parameters were obtained by this approach with highest desirability. In RSM, following steps are used for analysis to obtain optimum values (10):

- Quadratic equation of second order was selected to build up a polynomial equation.
- ANOVA for Response surface quadratic model was used to find out the relation between inputs and responses.
- From Model graphs tool, 3D Surface plots, contour plots are produced.
- Numerical optimization was done at desired goals, with high desirability.

IV. RESULTS AND DISCUSSION

A. *Model Analysis*

To estimate the numerical information regarding p value, Analysis of variance (ANOVA) is used in the present model. The maximum value of p is 0.05. The model is regarded as insignificant for the value of p more than 0.05. The present model is significant for which the value of p is less than 0.05, which is considered as reference limit.

TABLE IV
EXPERIMENTAL DESIGN MATRIX

Run Order	Fuel Blend (%)	BP (kW)	Bth (%)	BSFC (Kg/ kW hr)	HC (PPM)	CO (%)	NO_X (PPM)	Smoke (%)	CO_2 (%)	Max. Pr. (bar)	HRR (J/degree)
1	20	0.54	12.91	0.65	0.057	2	153	71.4	2.26	46.1	12.66
2	20	0.93	23.56	0.47	0.062	3	228	75	2.76	46.84	13.31
3	20	1.83	28.52	0.3	0.041	3	687	76.7	4.01	50.8	18.69
4	20	3.45	44.76	0.19	0.036	4	1128	82.5	5.94	58.32	20.61
5	40	0.54	13.65	0.66	0.032	7	37	85.4	0.92	45.33	14.6
6	40	0.93	23.32	0.54	0.02	12	96	87.4	1.29	49.01	16.33
7	40	1.83	29.56	0.41	0.035	14	178	87.7	2.46	55.7	19.12
8	40	3.45	40	0.27	0.045	16	662	81.2	4.43	62.11	25.14
9	100	0.54	14.1	0.7	0.038	6	90	83.3	2.41	46.14	15.22
10	100	0.93	18.45	0.53	0.049	8	153	86.3	2.99	51.31	19.84
11	100	1.83.	25.33	0.39	0.075	12	587	83.5	4.13	56.54	20.68
12	100	3.45	35.58	0.28	0.098	14	767	80.6	6.73	66.4	29.05

$$Bth = 28.03 - 1.58 \times a + 11.25 \times B - 0.94 \times aB - 0.30 \times a^2 - 0.96 \times B^2 \quad (1)$$

$$Bsfc = 0.35 + 0.026 \times a - 0.20 \times B + 0.11 \times B^2 \quad (2)$$

$$HC = 9.32 - 3.35 \times a + 2.51 \times B + 1.47 \times aB \quad (3)$$

$$CO = 0.033 + 0.012 \times a + 0.019 \times aB + 0.027 \times a^2 \quad (4)$$

$$NO_X = 256.51 - 84.92 \times a + 389.59 \times B - 53.60 \times aB + 335.87 \times a^2 - 58.37 \times B^2 \quad (5)$$

$$Smoke = 89.88 + 3.82 \times a - 0.080 \times B - 10.28 \times a^2 \quad (6)$$

$$CO_2 = 2.28 + 0.20 \times a + 1.96 \times B + 0.18 \times aB + 2.03 \times a^2 \quad (7)$$

$$HRR = 21.99 + 2.65 \times a + 5.42 \times B + 0.98 \times aB - 1.68 \times a^2 - 0.63 \times B^2 \quad (8)$$

$$Max.Pr. = 54.93 + 2.43 \times a + 8.20 \times B + 1.50 \times aB \quad (9)$$

TABLE V
RSM MODEL EVALUATION

Model	Bth (%)	BSFC (Kg/ kW hr)	HC (PPM)	CO (%)	NO_X (PPM)	Smoke (%)	CO_2 (%)
Mean	28.3853	0.3355	0.0430	6.3038	558.888	78.6683	3.53761
Standard Deviation	4.0913	0.0429	0.008141	4.5578	130.0153	4.04812	0.1154
R-Squared	0.98	0.98	0.91	0.96	0.94	0.64	1.0
Adj. R^2	0.94	0.96	0.80	0.93	0.83	0.34	1.0
Model	Quadratic	Modified	Modified	2FI	Quadratic	Modified	Modified

Equations (1) to (9) shows the regression equations for the present model with fuel blend and Brake power (BP) as input variables.

B. RSM Model Evaluation

ANOVA is used to find out model stability. RSM model evaluation is shown in the Table V. It is observed from the model that, difference between goodness of fit (R^2) and the goodness of predictions (Adjusted R^2) is less than 0.15. It is observed that the experimental data and model are well fitted. R^2 & adjusted R^2 describe response variability and number of predictors respectively and they are in good agreement with each other.

TABLE VI
OPTIMIZATION CRITERIA

Source	Lower Limits	Upper limits	Upper weight	Lower weight	Importance	Goal	Desirability
Fuel Blend (%)	20	100	1	1	3	Is in range	1
BP (kW)	0.54	3.45	1	1	3	Is in range	1
Bth (%)	12.91	44.76	0.1	1	5	maximize	0.9330
BSFC(Kg/ kW hr)	0.19	0.7	1	0.1	5	minimize	0.9667
CO(%)	0.02	0.098	1	0.1	5	minimize	0.9655
HC (PPM)	2	16	1	0.1	5	minimize	0.9640
NO_X (PPM)	37	1128	1	0.1	5	minimize	0.9372
Smoke (%)	71.4	87.7	1	0.1	5	minimize	0.9428
CO_2 (%)	0.92	6.73	1	0.1	5	minimize	0.9420
Combined							0.9426

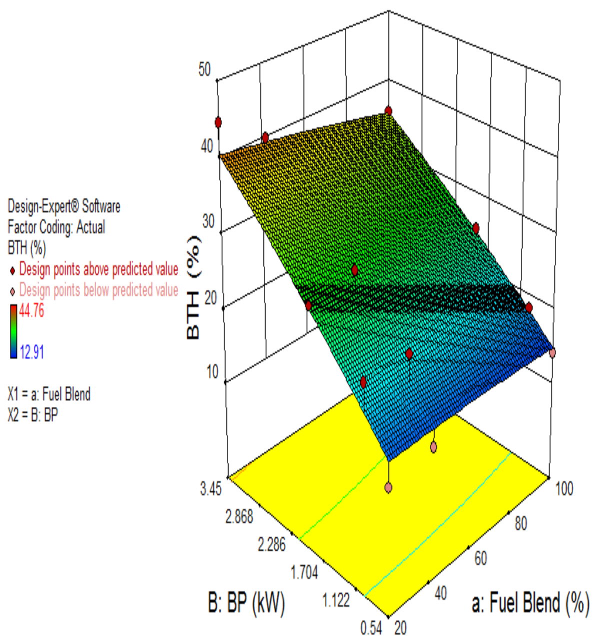

Fig. 2 Variation of BTH with Fuel blend and BP.

C. RSM Model Optimization

Table VI presents the criteria for optimization of the present study. The goal for the brake thermal efficiency is chosen as maximum and Brake specific fuel consumption and emission parameters like CO, HC, NO_X, Smoke, and CO_2 are selected as minimum. For all parameters (such as Bth, BSFC, HC, NO_X, Smoke and CO_2) the importance factor is taken as 5 by default. Various solutions were achieved in the present desirability based approach. The highest desirability of the solutions was regarded as the best solution. The maximum desirability of 0.9496 was obtained when the engine factors such as brake power of 1.893 kW and 24.960% fuel blend which were regarded as optimal solution of the engine having 5.2 kW rated output, 1500 rpm and at a compression ratio 18.

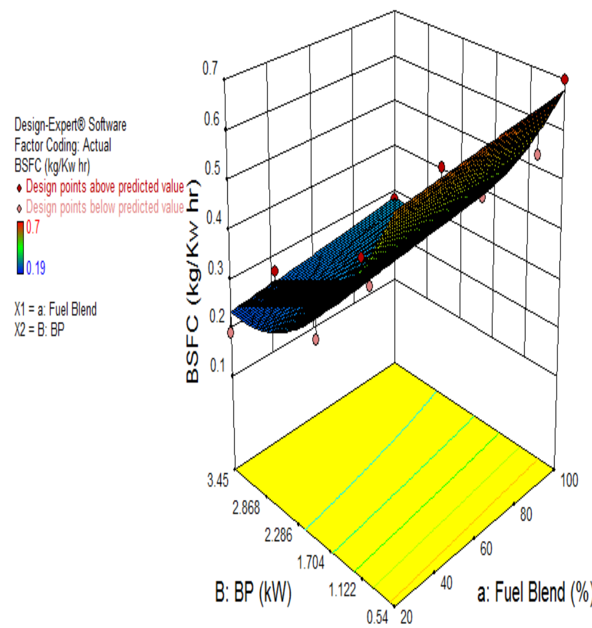

Fig. 3 Variation of BSFC with Fuel blend and BP.

The brake thermal efficiency increases with the low to high load (in terms of brake power) at all fuel blends. It is observed from fig.2, that the maximum brake thermal efficiency is observed at maximum Brake power of 3.45 kW, for the fuel blend 20% (RME 20%). It is also observed the brake thermal efficiency is reduced with the increase in fuel blend (%) at all loads. The brake thermal efficiency increases with increase in brake power (BP).

The variation of Bsfc with fuel blend (%) and load is shown in Fig. 3. It is observed that Bsfc decrease gradually with increase in brake power which depends on the fuel blend used. Due to oxygen presence in the fuel blend, lesser Bsfc values are resulted. When percentage of biodiesel in the fuel increases, Bsfc also increases.

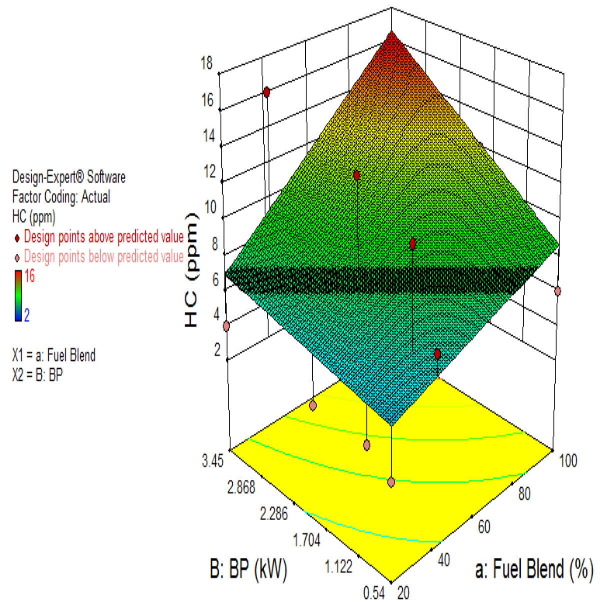

Fig. 4 Variation of HC with Fuel blend and BP

Fig. 4. represents the change in HC(ppm) emissions with BP and fuel blend. HC emissions increase with increase in load. HC emissions are mainly due to incomplete combustion which results from non-availability of sufficient oxygen, air-fuel improper mixture composition, quenching effect on wall etc.

Nitrogen oxide NO_X changes with BP and fuel blends are shown in the Fig. 5. The NO_X emissions increase with the increase in load due to higher oxygen present in the fuel. At maximum load, NO_X emissions are high for B20 fuel blend.

NO_X levels are high due to the temperature of burned gases which increase due to early start of auto-ignition. At higher gas temperatures, NO_X is formed by free atoms of oxygen and nitrogen. Lowest NO_X emissions are observed for RME 40 at all loads, when compared with RME 20 and RME 100.

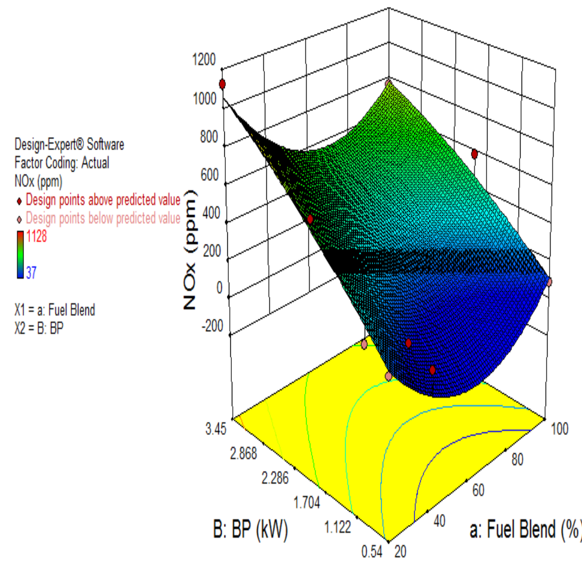

Fig. 5 Variation of NO_X with Fuel blend and BP

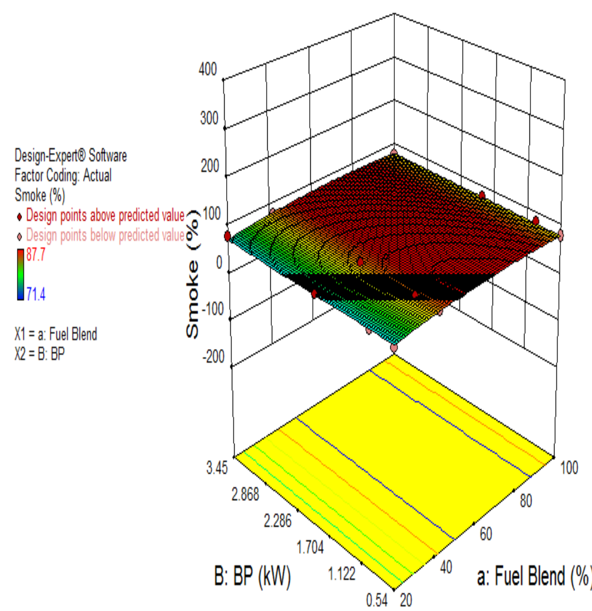

Fig. 6 Variation of Smoke with Fuel blend and BP

The variations of smoke emissions with respect to BP and fuel blend in percentage is illustrated in Fig. 6. Smoke emissions increase slightly with increase in fuel blend. Partial combustion of fuel is the main reason for the formation of smoke emissions.

TABLE VII
VALIDATION OF EXPERIMENTS

Value	Fuel Blend (%)	BP (kW)	Bth (%)	BSFC (Kg/kW hr)	CO (%)	HC (PPM)	NO_X (PPM)	Smoke (%)	CO_2 (%)
Predicted	24.96	1.893	28.336	0.336	0.043	6.296	557.672	78.648	3.533
Experimental	25	1.83	27.82	0.402	0.038	8	602	81.3	4.15
% Error	0.16	3.44	1.85	16.42	13.16	21.3	7.36	3.26	14.87

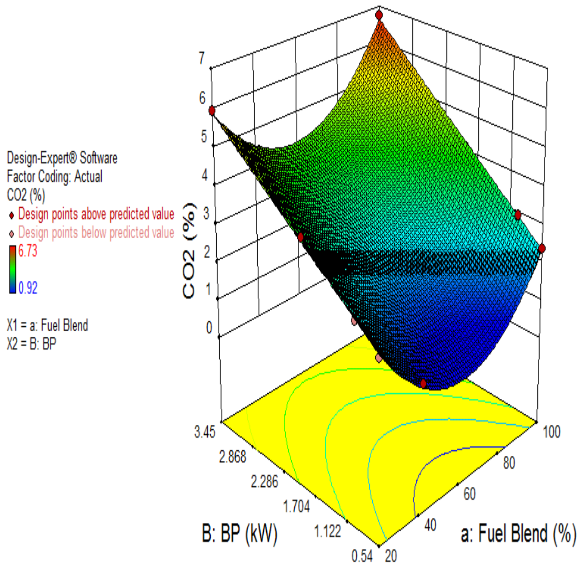

Fig. 7 Variation of CO_2 with Fuel blend and BP

The density of fuel increases with increase in percentage of biodiesel, which also leads to increase of fuel droplet size. It is observed that the, smoke emission variations are almost constant.

Fig. 7 demonstrates the CO_2 emissions. It is observed from the figure that CO_2 emissions decrease slightly and then increase with the fuel blend. The oxygen content in the fuel blend is the main cause for the formation CO_2 emissions.

Fig. 8 describes maximum net heat release rate (HRR) variations before TDC. HRR increases with the load at all fuel blends. Fuel droplets atomization and effective combustion of fuel mixture are the reasons for higher HRR at higher loads.

D. Validation of Experiments

Experiments are conducted at optimized parameter i.e. fuel blend (i.e. RME) of 24.96%, Brake power of 1.893 kW, at compression ratio of 18 for evaluating the numerical model. It is observed from Table VII that, the optimized RSM values and experimental values are good agreement with each other.

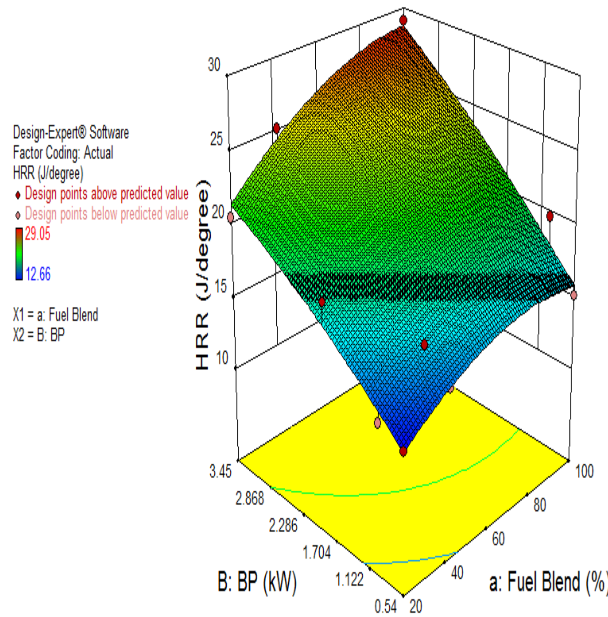

Fig. 8 Variation of HRR with Fuel blend and BP

V. CONCLUSIONS

4-stroke, single cylinder, water cooled, VCR diesel engine was operated with various Rapeseed Methyl Ester (RME) blends (RME 20, RME 40, RME 100). Response Surface Method is used as optimization tool for optimizing the RME blends as fuel when operating in DI diesel engine. The following points are drawn as major conclusions:

- "Design Expert" trail version software is used to find out the responses by using RSM technique ANOVA.
- Desirability obtained in this study is 0.9496 by using RSM based desirability approach.
- Performance characteristics such as Bth and Bsfc for different RME blends are compared.

With increase in percentage of RME, Bth decreases while BSFC increases.

- Emission parameters such as HC, Smoke, and CO_2 are found to be low for RME20 blend, except NO_X may be due to high viscosity and oxygen content in the fuel blend.
- At brake power of 1.893 kW and fuel blend RME 24.96%, the optimized values of responses by using RSM such as Bth, BSFC, HC, NO_X, Smoke, CO_2 are obtained as 28.336%, 0.336Kg/kW hr, 6.296 ppm, 557.672 ppm, 78.648%, 3.533% respectively.
- RME blended fuels can be used as best alternative for diesel fuel when operating with DI diesel engine without any alterations.

Experimental and RSM values of responses are in good agreement with each other

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