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Optimization of Diesel Engine Fueled With Diesel-Mahua Biodiesel-Diethyl Ether Blend to Improve Engine Performance by RSM

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ABSTRACT

In this paper, optimize direct injection single cylinder diesel engine with respect to brake power, fuel economy and exhaust emissions through experimental investigation and response surface methodology (RSM). As far as the application in rural agricultural sector of a developing nation in concerned, such engines should preferable utilize alternative fuels of bio-origin. In this test the mahua biodiesel and diesel blending with diethyl ether (DEE) in the ratio of 0:100:0, 20:80:0, 30:70:0, 40:60:0, 15:80:5, 25:70:5 and 35:60:5 by volume were tested in CI Engine. The results shows that compared with neat diesel, there is slightly lower brake specific fuel consumption (BSFC) for diesel-biodiesel-DEE blend. Strong reduction in emission is observed with diesel-biodiesel-DEE at various engine loads. Methyl ester of Mahua biodiesel at 25% and DEE 5% blend with diesel gave best performance in terms of low smoke intensity, emission of HC, CO, CO_2, and NO_x.

KEY WORDS: Diesel engine, Mahua biodiesel, DEE, Optimization, Response surface methodology.

1. INTRODUCTION

Many alternative fuels have been studied to either substitute the diesel fuels partially or completely. Alternative fuels derived from biological sources provide a means for sustainable development, energy conservation, energy efficiency and environmental protection (Sivalakshmi and Balusamy, 2013; Soo-Young,2011). Some of the alternative fuels explored are biogas, ethanol, vegetable oils etc. The high viscosity of vegetable oils and their low volatility affects the atomization and spray model of fuel, leading to incomplete combustion and severe carbon deposits, injector choking and piston ring sticking (Peterson, 1991). In particular, biodiesel has received broad attention as an alternate for diesel fuel because it is biodegradable, nontoxic and can significantly reduce exhaust emissions from the engine when burned as a fuel (Blin, 2013; Balakrishnan, 2012). Many researches show that using biodiesel in diesel engines can reduce hydrocarbon (HC), carbon monoxide (CO) and opacity emissions, but nitrogen oxide (NOx) emission may increase (Erdi Tosun, 2014). Biodiesel can be used in the existing engines without any modifications and the biodiesel obtained from vegetable sources does not contain any metals, aromatic hydrocarbons and sulfur or crude oil residues. Biodiesel is an oxyfuel; emissions of carbon monoxide and soot tend to reduce. The oxygen content of biodiesel is an important factor in the NOx formation, because it causes to high local temperatures due to excess hydrocarbon oxidation (Ramadhas, 2005). The use of vegetable oils as an alternative fuels for internal combustion engines is limited by some unfavorable fuel properties, mainly their high viscosity and density, which cause problems in poor fuel atomization, incomplete combustion and ring carbonization in the combustion chamber. These problems can be overcome by four methods: blending, micro emulsion, trans-esterifaction and pyrolysis (Soo-Young, 2011). Additional research needs to develop diesel specific additives for better performance, combustion and emissions of diesel engines. DEE has required characteristics and projected to improve low temperature flow properties. Earlier studies have recommended that the weight percent of oxygen content in the fuel is the most important factor for opacity reduction (Obed, 2013; Rejeev and Anil, 1995; Peterson, 1991).

The most extensive applications of RSM are in those situations where several input variables potentially influence some performance measure or the quality characteristics of the process. RSM has been applied for optimization of several chemical and physical processes (Jagannath and Atul, 2014; Abdullah, 2013). Initially, RSM was developed to model experimental responses and then migrated into the modeling of numerical experiments (Jagannath, 2014). The nonlinear optimization techniques such as RSM, artificial neural network, genetic algorithm fuzzy logic and Taguchi method were used for optimizing the performance and emission characteristics of diesel engine (Alpaslan, 2015; Zhenbin, 2015). Studies regarding the investigation of optimum blend ratios for vegetable oil blends were reported by researchers. But, the current literature concerning the investigation of the optimum diesel- SVO-DEE oil ternary blend ratio at which there is high fuel conversion efficiency and low exhaust emissions are absent (Katarina and Jelena, 2013; Purnanand, 2009). The main technical advantage of optimization for percentage of bio-origin components in diesel fuel is improving engine performance and exhaust emissions and utilizing optimization blends in a diesel engine without any engine modification such as injector pressure nozzle diameter or injection time (Murat Karabektas, 2012; Ohta and Takahashi, 1983).

2. MATERIALS AND METHODS

2.1 Fuel preparations: Mahua oil is obtained from the seeds of madhuca indica, a deciduous tree which can grow in semi-arid, tropical and sub-tropical areas. It grows even on rocky, sandy, dry shallow soils and tolerates water logging conditions. Mahua oil was procured from an oil mill. The oil was filtered to remove the impurities. Flash point and fire point was determined by using of fire point apparatus. The viscosity was determined at different temperatures using redwood viscometer to find the effect of temperature on the viscosity of mahua oil. The viscosity of mahua oil was found to be approximately 8 times higher than that of diesel fuel. The flash point of mahua oil was higher than diesel and hence it is safer to store. It is seen that the boiling range of mahua oil was different from that of diesel (Kannan and Marappan, 2010; Nagdeote and Deshukh, 2012).

These vegetable oils trans-esterified before it blended with diesel because of the oils have glycerol. It must extract from the bio-fuel because it will affect the engine performance. Among these, the trans-esterification is the most commonly used commercial process to produce clean and environmental friendly fuel. Methyl/ethyl/butyl esters of mahua oil have been successfully tested on C.I. engines and their performance has been studied. Trans-esterification is the process of conversion of triglyceride to glycerol and ester in the presence of alcohol and catalyst. This reaction, also known as alcoholics in whom the displacement of alcohol from an ester by another alcohol in a process similar to hydrolysis except that an alcohol is used instead of water. This reaction has been widely used to reduce the viscosity of the triglycerides (Sandip and Lawankar, 2014; Swaminathan and Sarangan, 2012). The properties of diesel, biodiesel and DEE as shown in Table 1 and blended fuel properties are shown in Table 2.

2.2 Response Surface Methodology (RSM): Response surface methodology is a collection of statistical and mathematical techniques useful for developing, improving and optimizing processes. With this technique the effect of two or more factors on quality criteria can be investigated and optimum values are obtained. In RSM design there should be at least three levels for each factor. RSM also quantifies relationships among one or more measured responses and the vital input factors. MINITAB software was used to develop the experimental plan for RSM. By conducting experiments and the posterior application of regression analysis a model of the response variable of interest is obtained. The real relationship between the response and the independent variables is unknown. For that reason, the first step in RSM is to find an approximation of the true functional relationship between the response and the independent variables. The observed response "y" can be written as a function of the independent variables $x_1, x_2, x_3, \ldots x_n$ as follows

$$y = f(x_1, x_2, x_3, \ldots x_n) + \varepsilon, \quad \text{Where } \varepsilon \text{ is random error.}$$

Plotting the expected response y a surface known as the response surface obtained. As remarked previously, the form of f is unknown and can be complicated this is why an approximation is needed. Frequently, a low order polynomial function is employed in some region. If the response is well modelled with a linear function, the approximation function is a first order model. If the system has curvature a higher order polynomial model must be used, such as a quadratic model.

$$y = \beta_0 + \sum_{i=1}^{k} \beta i x i + \sum_{i=1}^{k} \beta i \, x i^2 + \sum_{i<j} \sum \beta i j \; x i \; x j + \varepsilon$$

Almost all RSM problems use one of these models. However, it is unlikely that a polynomial model will be a good approximation of a true functional relationship over the entire space of the independent variables; but for small regions polynomial models work reasonably well. When RSM is used, the objective is not only to investigate the response over the space, but also to locate the region where the response reaches or near optimum value. By studying the response surface model, the combination of factors (i.e., the values of the independent variables) which gives the optimal response can be obtained. The same software was also used to analyse the data collected by following the steps as follows:

a. Conduct the experiment with the independent variables varying around the present operating point.
b. Obtain a fitted equation with data obtained in the experiment. Normally, regression methods are used in this step. Frequently, a linear model represents the model sufficiently well.
c. Move the experimental point in the direction of steepest ascent (or descent if a minimum is sought) and repeat the previous steps.
d. When little improvement is obtained, the optimum is near.
e. Conduct a 3- level factorial experiment around this point.
f. Obtain a fitted quadratic equation by regression methods.
g. Based on this quadratic equation, determine the optimum.
h. Conduct further experiments to verify the obtained results.

Previously, if there are a lot of possible input factors, a screening experiment should to be conducted in order to eliminate the less important factors. Obtaining the optimal values of the independent variables can be very complicated if, instead of a simple response, more than one response is sought (multi-response). Reaching the optimum is even more difficult when the response involves several independent process variables that often are constrained to a certain range in certain parameters. For the case in which more than one response is taken into account, a surface model is built for each response. Then a set of operating parameters that optimizes all the responses within their range is selected. Finally, the contour plots of all the responses are overlaid and the best operating point or range is selected. With the increase of both the number of responses and the number of independent process variables, the search becomes more complex. In addition, the optimal values of the process variables can differ of contradict one another. A consequence of this is that the search space is even more complex with multiple constraints and many local optimal points. All these facts make it more and more difficult to apply traditional mathematical methods (such as the steepest ascent) that search for the global (or near global) optimum. In this study three parameters have been chosen for analysis. They are percentage of biodiesel, percentage of diethyl ether and applied load (kg). Several trail runs were conducted to determine the range for parameters. The levels for the parameters finally chosen are shown in the Table 3**.**

2.3. Experimental setup: Test has been conducted on a Kirloskar TV1 Engine, four strokes, single cylinder, water-cooled, direct injection and naturally aspirated diesel engine with a bowl type piston combustion chamber. Specification of test engine is shown in Table 3. For high pressure fuel injection, a high-pressure fuel pump is used and three hole in injector nozzle. The injector nozzle was located at the center of the combustion chamber and has an operating pressure of 220bar.

2.4. Experimental procedure: To estimate the performance parameters i.e operating parameters such as engine speed, power output, and fuel consumption were measured. Significant engine performance parameters such as brake specific fuel consumption and brake thermal efficiency for the test fuels were calculated.

- In the first phase experiments were conducted with neat diesel
- In the second phase of the work, the engine was operated diesel- BD blend ratio of 80: 20, 70:30 and 60:40.
- In the third phase, BD and diesel blend with DEE in the ratio of 15:80:5, 25:70:5 and 35:60:5.

3. RESULTS AND DISCUSSIONS

The principal model analysis was based on the analysis of variations which provides numerical information for the y value. The different models for the response were developed in terms of actual factors and the output parameters in experimental work as a function of biodiesel, load, diethyl ether and it can be expressed as

T=f (L,BD,DEE)

For the three factors, the full quadratic equation was developed using response surface methodology in minitab 17 as follows

Brake thermal efficiency (BTE) = 0.6630 - 0.0671 L(kg)+ 0.00012 BD (%) - 0.00150 DEE(%)+0.00241 L(kg) *L(kg) + 0.000040 BD (%)*BD (%) - 0.000154 L (kg)*BD (%) + 0.00011 L (kg) *DEE (%) +0.000183 BD (%) *DEE (%)

Brake specific fuel consumption (BSFC)=0.738+7.117L(kg)-0.0309 BD (%) - 0.030 DEE (%) - 0.4612 L (kg)*L (kg) + 0.000308 BD (%) *BD (%)- 0.00377 L (kg)*BD (%) + 0.0160 L (kg) *DEE (%) + 0.00331 BD (%)*DEE (%)

Hydrocarbon emission (HC) = 25.79 - 0.156 L (kg) + 0.003 BD (%) - 0.939 DEE (%) - 0.1186 L (kg)*L (kg) + 0.00132 BD (%)*BD (%) - 0.01123 L (kg)*BD (%) + 0.0801 L (kg)* DEE (%)+ 0.0014 BD (%)*DEE (%)

Carbon monoxide (CO) = 0.05018+0.00525 L(kg) - 0.001137 BD(%)+0.00056 DEE(%)- 0.000714 L(kg)*L (kg) + 0.000023 BD (%)*BD (%) + 0.000015 L (kg)*BD(%) - 0.000083 L (kg) *DEE (%)- 0.000055 BD (%) *DEE (%)

Oxides of nitrogen (NOx) = 83.0 - 11.35 L (kg) - 2.11 BD (%)+ 2.78 DEE (%) 6.793 L (kg) *L (kg)+ 0.0515 BD (%)*BD (%)+ 0.0120 L (kg)*BD (%) - 0.985 L (kg)*DEE (%) - 0.050 BD (%)*DEE (%)

Carbon dioxide (CO_2)= 2.038 + 0.0729 L (kg) + 0.0038 BD (%)- 0.0477 DEE (%) + 0.02423 L (kg)*L (kg) + 0.000132 BD (%)*BD (%) + 0.000256 L (kg)*BD (%) + 0.01037 L (kg) *DEE (%) - 0.00068 BD (%)*DEE (%)

Opacity = 0.881+0.489 L(kg) - 0.0281 BD(%) - 0.015 DEE (%) + 0.1105 L(Kg)*L(Kg) + 0.001042 BD(%)*BD(%) + 0.00330 L (kg)*BD (%) - 0.0649 L (kg) *DEE (%)-0.00087 BD (%) *DEE (%)

By using above quadratic equation predicted output parameters is calculated and compared with the experimental values.

3.1. Performance Characteristics

3.1.1. Brake specific fuel consumption: The BSFC variation of the test fuels with respect to load is shown in Fig. 1. The fuel mass flow rate is calculated from the respective measured volume flow rate value and the fuel density. BSFC of D80+MA20 oil blend is 5% lower than neat diesel at load 4 kg load and D80+MA20 blend is approximately same with diesel ant 6kg, 8kg load. BSFC of D80+MA15+A5 is 3.5% lower than that of neat diesel at 4kg and almost similar to neat diesel in remaining loads. D70+MA25+A5 fuel has similar BSFC values up to 4kg load and slightly higher for higher loads compared to neat diesel. The main reason may be due to the higher volatility of DEE which speeds up the mixing velocity of air/fuel mixture, improves the combustion process and increases the combustion efficiency.

3.1.2. Brake thermal efficiency: The variations of BTE at different loads for various fuel blends has been shown in Fig.2. BTE for diesel is higher than that of all other blended fuels up to 4 kg applied load. BTE for D70+MA25+A5 blend has 2%, 4% higher than neat diesel at 6kg, 8kg load. This is because of addition of DEE reduces the viscosity which in turn increases the atomization and leads to the enhancement of combustion.

3.2. Emission Characteristics

3.2.1. Opacity: The smoke is produced due to incomplete combustion of fuel. The variation of opacity with load for the fuels is shown in Fig. 3. It can seen that higher load, the smoke intensity for blended fuels lower comparing to neat diesel. D70+MA25+A5 blend has 42%, 18% lower opacity than neat diesel at 6kg, 8kg load. The improvement in spray atomization and air fuel mixing with the addition of DEE decrease the rich mixture and also smoke emission. However DEE added blends, the smoke intensity also increase but it is still lower than biodiesel-diesel, diesel. This may due to phase separation of the blends which results in incomplete combustion.

3.2.2. Carbon monoxide (CO): The variation of CO emissions with load is shown in Fig.4. At full load, the CO emission decreases by 30% for D70+MA25+A5 blend compared to neat diesel. The improvement in spray atomization and fuel air mixing reduces the rich region in cylinder and reduces the CO emission. The high temperature promotes the CO oxidation in the cylinder. Biodiesel-diesel blend has slightly higher CO emissions due to poor atomization and do not have time to undergo complete combustion.

3.2.3. Oxides of nitrogen (NOx): Nitric oxides emission is shown in Fig.5. The NOx emission is function of lean fuel with higher temperature, high peak combustion temperature and spray characteristics. A fuel with high HRR at rapid combustion and lower HRR at mixing controlled combustion will causes of NOx emission. NOx emission increases with increase in load for all experimental fuels. D70+MA25+A5 blend has 33%, 25%, 22% lower NOx emissions than neat diesel corresponding to 4, 6, 8kg loads. The addition of DEE in blends increases the evaporation and lowers the charge temperature. It makes beneficial effect on NOx emission level. In biodiesel- diesel blends, NOx emission is higher due to high HRR and excess oxygen supplied by biodiesel.

3.2.4. Hydrocarbon (HC): It can be seen that the HC emission for all the fuel blends are lower than diesel for medium and higher loads. The addition of DEE in blends, HC emission is reduced. Initially, the increase of HC may be due to higher latent heat of evaporation of DEE causes lower combustion temperature, especially the temperature near the cylinder walls during the mixture formation. In this case higher HC will be produced from the cylinder boundary. D70+MA25+A5 blend has approximately 22% lower HC emission throughout the engine operation comparing to diesel.

Table.1.Properties of diesel, mahua biodiesel and DEE

Property	**Diesel**	**Mahua ester**	**DEE**
Chemical structure	$C_{16}H_{34}$	$C_{17}H_{34}O_2$	$C_2H_5OC_2H_5$
Density (kg/m^3)	830	902	713
Kinematic vis. 35 ^{o} C (cS)	2.7	21.5	0.23
Auto ignition point (^{o} C)	200-400	-	160
Cetane number	48	58	>125
Boiling point (^{o} C)	180-330	-	35
Pour point (^{o} C)	-20	-	-110
Lower heating value ((MJ/kg)	42.8	37.08	33.9
Stoichiometric A/F ratio	14.9	13.5	11.1

Table.2.Properties of fuel blends

Blend	**Flash point ^{0}c**	**Fire point ^{0}c**	**Density in g/cc at 32^{0}c**	**Calorific value MJ/kg**
Diesel (100%)	68	78	0.8878	42.80
Biodiesel (100%)	135	150	0.9150	37.08
D80+MA20	71	80	0.8901	41.65
D70+MA30	75	84	0.8920	41.08
D60+MA40	82	91	0.8950	40.51
D80+MA15+A5	42	52	0.8900	41.48
D70+MA25+A5	45	53	0.8910	40.90
D60+MA35+A5	49	60	0.8923	40.33

Table.3.Specification details of kirloskar TV1 engine

Type	Vertical, water cooled
Number of cylinders/ Number of strokes	01/04
Rated power	3.7 kW/ 5 hp @ 1500rpm
Bore (m)/Stroke(m)	0.08/.11
Piston offset (m)	0.00002
Con-rod length (m)	0.235
Piston head ratio	1
Compression ratio	16.7
Speed	1500 Rev/min

Fig.1.BSFC Vs Load, BD

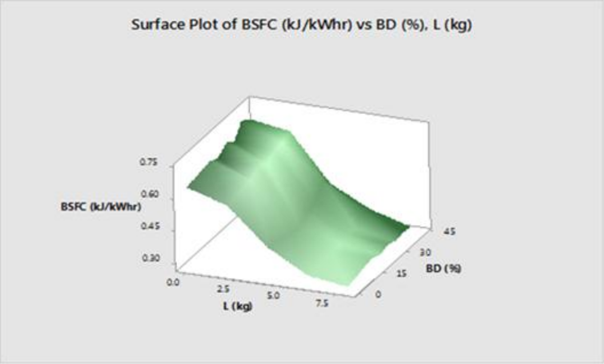

Table.3.Experimental design matrix

S.No	BD (%)	DEE (%)	BSFC (kJ/kWhr)	BTE (%)	Opacity (%)	CO (%)	CO_2 (%)	NOx (ppm)	HC (ppm)
1	20	0	0.648	0	0.8	0.03	2	60	25
2	20	0	0.634	12.9	2.9	0.06	2.2	91	28
3	20	0	0.388	21.16	5	0.04	3	111	20
4	20	0	0.3266	25.13	7	0.03	3.2	210	20
5	20	0	0.3041	27.015	12.3	0.04	4.8	425	16
6	30	0	0.659	0	0.9	0.03	2.4	70	26
7	30	0	0.64	13.07	3	0.06	2.6	86	29
8	30	0	0.428	19.56	5.6	0.04	2.8	123	22
9	30	0	0.3342	25.06	7.7	0.05	3.5	234	20
10	30	0	0.3031	27.63	13	0.05	4.6	426	16
11	40	0	0.7	0	0.9	0.04	2.6	76	27
12	40	0	0.67	13.2	3	0.06	2.7	97	30
13	40	0	0.452	19.2	6.3	0.05	3	138	21
14	40	0	0.357	24.7	9	0.04	3.6	242	18
15	40	0	0.3033	27	13.4	0.04	4.7	440	17
16	15	5	0.67	0	0.78	0.04	1.9	59	21
17	15	5	0.61	13.1	1.5	0.05	2.2	93	23.7
18	15	5	0.392	22	3	0.05	2.6	130	18.9
19	15	5	0.33	25.8	6	0.04	3.4	203	17
20	15	5	0.32	28	9.4	0.03	4.4	389	14.9
21	25	5	0.689	0	0.72	0.02	1.8	57	21.3
22	25	5	0.615	13.5	1.6	0.04	2.2	90	23.4
23	25	5	0.425	22.1	3.4	0.04	3	110	18.7
24	25	5	0.346	26	5.3	0.03	3.8	193	16.8
25	25	5	0.317	28.8	9.7	0.03	4.5	365	14.7
26	35	5	0.72	0	0.76	0.03	1.8	60	22
27	35	5	0.645	13.4	2	0.05	2.5	97	24
28	35	5	0.5	21.7	3.7	0.04	2.9	123	20
29	35	5	0.389	25.4	7	0.04	3.8	210	17.6
30	35	5	0.31	27	10.5	0.03	4.3	410	15
31	0	0	0.645	0	0.8	0.05	2	60	24
32	0	0	0.589	13.9	2	0.06	2.4	104	28
33	0	0	0.42	23	4.3	0.06	2.9	164	23
34	0	0	0.316	25.7	8.2	0.05	3.4	243	19
35	0	0	0.289	28.3	12.1	0.05	3.9	430	17.7

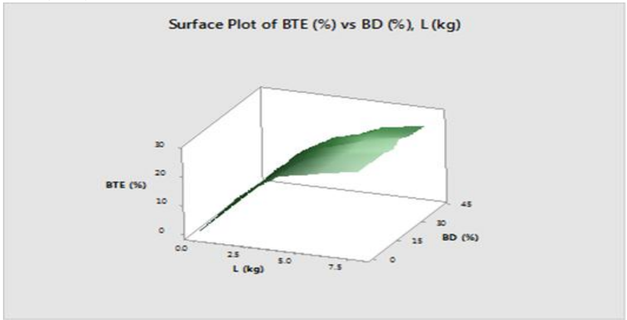

Fig.2.BTE Vs Load, BD

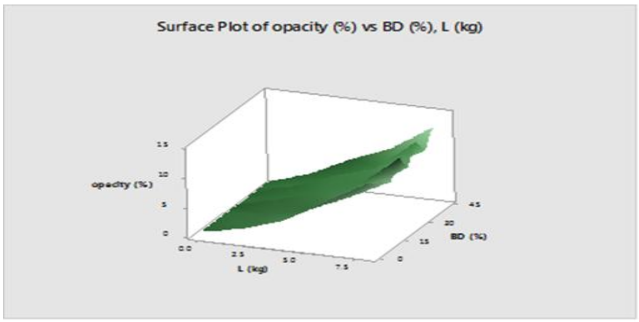

Fig.3.OPACITY Vs Load, BD

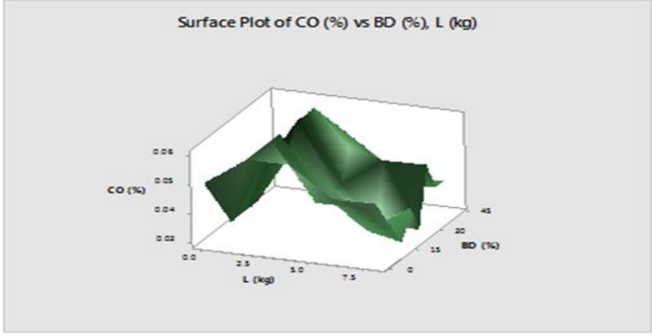

Fig.4.CO Vs Load, BD

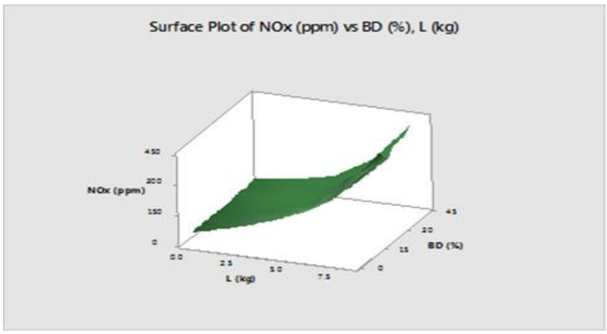

Fig.5.NOx Vs Load, BD

4. CONCLUSION

In the present study, RSM was used to investigate the optimum blend ratios of diesel fuel, biodiesel and DEE in ternary blend for the wide of operations of diesel engine. RSM powered to be a powerful tool for the optimization of biodiesel blends while used as fuel in diesel engine. The main conclusions can be summarized as in the following points:

a. RSM based design of experiments was used to design and carry out statistical analysis to determine parameters which have the most significant influence on the performance and smoke emission characteristics. Desirability approach of the RSM was used to find out optimum parameters for optimization of performance and smoke emission characteristics.

b. The optimum blend of three fuels was determined by using mathematical models of RSM as 25% BD, 5% DEE and 70% diesel.

c. Mathematical models used in this study also enable users to perform predictions for unexperimented factor levels.

d. Brake power of engine almost remains the same for all blends implemented.

e. Brake power, brake torque, BTE and BMEP of BD blends decreased, however BSFC increased due to lower heating values, related to oxygen contents of DEE and BD, compared to those of diesel fuel.

f. The formation of NOx, CO and HC emissions of BD, DEE and diesel blends drastically decreased as 22%, 40% and 21% respectively.

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