Performance & Emission Optimization on Emulsified Diesel with 2-Butanol of a Diesel Engine through RSM

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Abstract
Alcohol fuel such as butanol is potential to use in diesel engine. While diesel-emulsion is an alternative fuel to standard diesel fuel can significantly reduce the emission levels of engine. These alternative fuel give significant different on engine performance as well as exhaust emission. The aim of this study is to optimize the engine operating parameter of water-diesel-butanol (WDBu) on the performance and emission from a diesel engine. The three types of WDBu (W5DBu5, W5DBu10, W5DBu15) was produced subsequently the fuel was prepared in the proportion of W5DBu5 (5%-water, 88%-diesel, 5%-butanol, 2%-surfactants), W5DBu10 (5%-water, 83%-diesel, 10%-butanol, 2%-surfactants) and W5DBu15 (5%-water, 78%-diesel, 15%-butanol, 2%-surfactants) by volume with a hydrophilic-lipophilic balance of 10. An experimental investigation was conducted with respect to type of fuel injected, engine speed and engine load. The data from experimental was used to simulate the design of experiment (DOE) by using response surface method (RSM). Engine power, brake specific fuel consumption, brake thermal efficiency, carbon monoxide and nitrogen oxide have been investigated. The optimal values of the Power, BTE, BSFC, CO, NOx and CO_2 were found to be 26.2 kW, 36.8% , 227.6 g/kWhr, 1.6%, 464.9 ppm and 11.5% respectively.
Keywords: Emulsified diesel with butanol, DI diesel engine, Response surface methodology

Introduction

In order to cut the reliance on fossil fuel resources, more alternative fuels have been tested in the internal combustion engines, such as biofuel, biodiesel, algae and emulsified fuel. Alcohol fuel is one of the best alternatives to diesel fuel in internal combustion engine because of their fast ignition and ability to form homogeneous mixtures weather blend with or without diesel. Moreover, biofuel such as butanol have high hydrogen to carbon ratio compared to diesel. Butanol has a physical and chemical characteristics result to give advantages as an automotive fuel. This is definitely produces low emissions in internal combustion engines. Thus, butanol produces a less amount of NOx in emissions.

Modifying the fuel by adding water in its contain offers a simple way to control performance and emissions as many researchers reported in literatures. There are several researcher reported that water in diesel can reduce NOx and smoke simultaneously. NOx emission decreased radically due to thermal, dilution and chemical effects (improvement of OH radicals) of water (Attia & Kulchitskiy, 2014; Chang, Lee, Lin, & Wang, 2013; Debnath, Saha, & Sahoo, 2015; Yahaya Khan, Abdul Karim, Hagos, Aziz, &

Tan, 2014). There were differences regarding the percentage ratio of different water emulsion diesel as reported in the literature. Most of the study, 15% water-diesel emulsion relied best to control the NOx emissions of the engine (Nadeem et al., 2006).

The experimental work of internal combustion engine is consumed a lot of time and money. In addition, many of the causes and consequences of implicit answer in experimental results is often are difficult to interpret. On the other hand, mathematical modelling approach can reduce the error to be less accurate in predicting the results of the test. It also can isolate one variable at a time simultaneously (Kumar, Kumar Chauhan, & Varun, 2013; Liu, Strank, Werst, Hebner, & Osara, 2010; Maghbouli et al., 2013; Qi, Feng, Leng, Du, & Long, 2011). Therefore mathematical model could be used to point out cause-effect relationships more clearly, and a validated model could be a very useful tool to study new type of engines or engines running with new type of fuels. Furthermore, numerical response surface method (RSM) of the 2-butanol emulsion fuel on diesel engine is essential to be explored. The objective of the present work is to investigate appropriate input parameters (speed, load and 2-butanol %) for optimal output response parameters to design CI engines for specific blended emulsified diesel with 2-Butanol. Optimization of input parameters was performed by using desirability approach of RSM. The analysis of the performance process such as brake power, brake specific fuel consumption (BSFC), brake thermal efficiency (BTE) and emission such as carbon monoxide (CO), nitrogen oxide (NOx) were systematically evaluated.

Material and Method

Fuel preparation

Volume ratios of water-diesel-2-butanol are used to get the three types of WDBu (W5DBu5, W5DBu10, and W5DBu15). Its subsequently the fuel was prepared in the proportion of W5DBu5 (5%-water, 88%-diesel, 5%-butanol, 2%-surfactants), W5DBu10 (%-water, 83%-diesel, 510%-butanol, 2%-surfactants) and W5DBu15 (5%-water, 78%-diesel, 15%-butanol, 2%-surfactants) by volume with a hydrophilic-lipophilic balance of 10. To ensure a homogeneous mixture the blending was done just before beginning of the experiments. The properties of the emulsified diesel with 2-butanol have been tabulated in Table 1.

Table 1: Properties of emulsified diesel with 2-butanol

Fuel Properties	Unit	W5DBu5	W5DBu10	W5DBu15
Density at 20°C	kg/m^3	828.5	828	827.5
Cetane number	-	46	45	44
Kinematic Viscosity at 40°C	mm^2/s	2.6	2.6	2.7
Lower Heating Value	MJ/kg	40.64	40.20	39.75
Specific heat capacity	J/kg°C	2001	2036	2071
Flash point	°C	49	48	47
Oxygen	%weight	48.6	47.7	46.9

Engine setup

The experimental setup consists of a four cylinder diesel engine, an engine test bed and a data acquisition system in control room. The test bed of the experimental setup is shown in Figure 1.

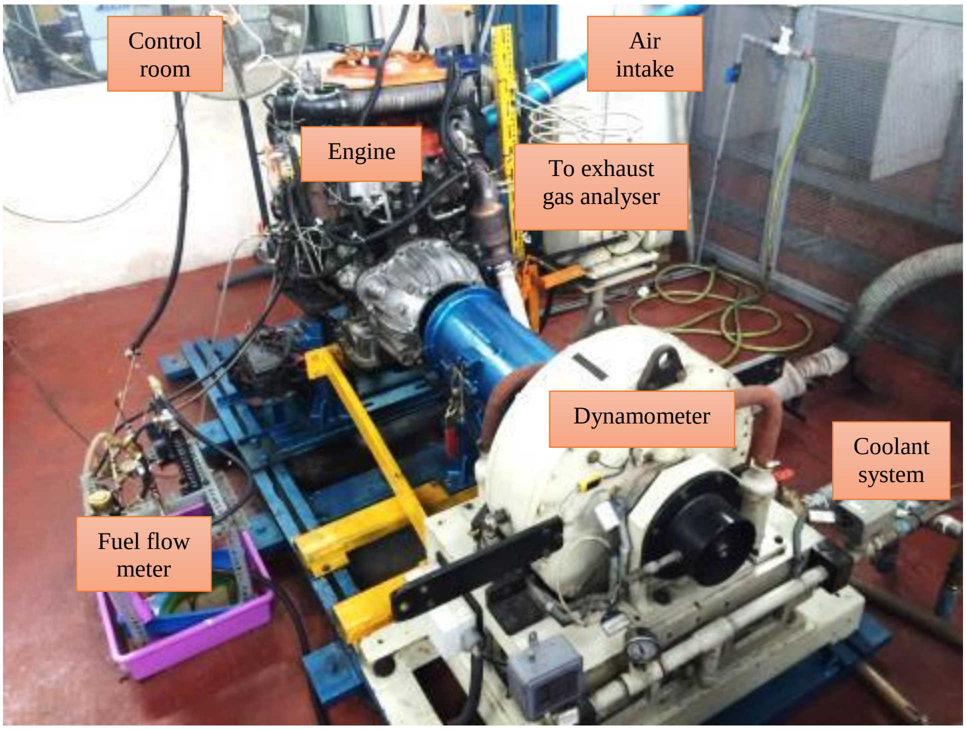


Figure 1: Engine test bed of the experimental setup

The Isuzu 4JJ1 engine as shows on

Table 2 was used in this experiment. The engine was tested at different loads and engine speeds (1000 rpm to 3000 rpm) using different percentage of Diesel with butanol (5% and 10%) blends. Researchers summarized the DBu5 (Diesel – 2-butanol 5 %) and DBu10 (Diesel – 2-butanol 10 %). At the beginning of each test, the throttle position was adjusted to give a speed of 1000 rpm at a lowest dynamometer load. In the experiments, the load was increased slowly as the engine speed increase by 500 rpm up to 3000 rpm. For each engine speed, the torque was incrementally by 30%, 35% and 50% applied while the fuel consumption rate was recorded. The engine was started with the original diesel fuel first and left to warm up for about 25 to 30 min, and then the diesel-butanol blend was gradually introduced. At the end of each test, the engine was run using original diesel fuel for about 30 to 45 min in order to flush the fueling system from any diesel-butanol blended residues.

Table 2: Specification of Isuzu Diesel engine

Engine Parameters	**Value**
Model	Isuzu 4JJ1 (Turbocharged)
Bore (mm)	95.4
Stroke (mm)	104.9
Displacement (L)	2.999 L
Number of cylinders	4 in-line
Compression ratio	17.5

Response surface methodology (RSM)

RSM was used in the present study for modeling and analysis of response parameters in order to obtain the characteristics of the engine. The ranges of the input parameters were selected based on the permissible limits within which the modifications can be made with the existing engine. Design of Experiments was applied to evaluate the performance of the engine over the entire range of variation of input parameters with minimum number of experiments. The design matrix was selected based on the historical data of RSM generated from the software "Design expert" trial version 7.0.0 of Stat ease, US. Experimental design matrix along with responses obtained is presented in Table 3. The responses such as Power, BTE, and BSFC were calculated whereas CO, NOx, and CO_2 were measured. The experimental readings were fitted to the second order polynomial equation using design expert software. A multiple regression analysis was carried out to obtain coefficients and the equations that can be used to predict the responses. Using the statistically significant model, the correlation between the operating parameters and the several responses were obtained. Finally the optimal values of engine operating parameters were evaluated by using the desirability based approach of RSM.

Table 3: Design matrix

RUN	A: Load	B: Speed	C: Butanol %	Power (kW)	BTE (%)	BSFC (g/kWhr	CO (%)	NOx (PPM)	CO2 (%)
1	20	1000	15	2.6	22.9	401.8	1.31	493	5.6
2	20	1000	5	10.3	22.5	400.4	0.96	740	9.6
3	35	2000	15	17.7	30.3	304.3	2.32	447	6.5
4	35	2000	10	18.6	30.1	302.7	2.25	465	9

RUN	A: Load	B: Speed	C: Butanol %	Power (kW)	BTE (%)	BSFC (g/kWhr	CO (%)	NOx (PPM)	CO2 (%)
5	50	2000	10	22	32.3	282.1	3.33	383	11.5
6	50	3000	5	27.6	36.6	245.7	1.23	483	10.8
7	50	1000	15	11	23.7	389.5	4.58	316	8.7
8	35	3000	10	16.1	29.5	308.9	1	489	6.5
9	35	2000	10	18.6	30.1	302.7	2.25	465	8.9
10	20	2000	10	10.3	22.3	408.1	0.95	432	5.6
11	50	1000	5	10.5	22.9	401.8	4.02	397	9.3
12	50	3000	15	28.7	38.1	242.1	1.8	455	8.5
13	35	2000	10	18.6	30.1	302.7	2.25	465	8.8
14	35	2000	10	18.6	30.1	302.7	2.25	464	8.9
15	35	2000	5	17.9	29.1	309.3	2.18	496	9.4
16	20	3000	15	3.5	13.6	676	0.35	399	1.4
17	35	1000	10	10.7	23.2	393	3.39	327	4
18	20	3000	5	4.3	17.4	516	0.48	458	2
19	35	2000	10	18.6	30.1	302.7	2.25	465	8.9

Desirability approach for optimization

The optimization analysis can be carried out using Design Expert software, where each response is transformed to a dimensionless desirability value (d) and it ranges between d = 0, which suggests that the response is completely unacceptable, and d = 1 suggests that the response is more desirable. The goal of each response can be either maximize, minimize, target, in the range and/or equal to depending on the nature of the problem. The desirability of the each response can be calculated by the following equations with respect to the goal of each response.

For a goal of minimum,

$$d_i = 1 \; when \; Y_i \leq Low_i; \; d_i = 0 \; when \; Y_i \geq high_i; \; and$$

$$d_i = [\frac{high_i - Y_i}{high_i - low_i}]^{wti} when \; low_i < Y_i < high_i$$

For a goal of maximum,

$$d_i = 0 \; when \; Y_i \leq Low_i; \; d_i = 1 \; when \; Y_i \geq high_i; \; and$$

$$d_i = [\frac{Y_i - low_i}{high_i - low_i}]^{wti} when \; low_i < Y_i < high_i$$

For target of target,

$$d_i = 0 \; when \; Y_i \leq Low_i; \; Y_i \geq high_i$$

$$d_i = [\frac{Y_i - low_i}{T_i - low_i}]^{wt1i} when \; low_i < Y_i < T_i$$

$$d_i = [\frac{Y_i - high_i}{T_i - high_i}]^{wt2i} when\ T_i < Y_i < high_i$$

For goal within the range,

$$d_i = 1\ when\ low_i < Y_i < high_i$$

$d_i = 0$; for otherwise

Here "i" indicates the response, "Y" the value of response, "low" represents the lower limit of the response, "High" represents the upper limit of the response, "T" means the target value of the response, "wt" indicates the weight of the response. The shape of the desirability function can be changed for each response by the weight field. Weights are used to give more emphasis to the lower/upper bounds. Weights can be ranged from 0.1 to 10; a weight greater than 1 gives more emphasis to the goal, weights less than 1 give less emphasis. When the weight value is equal to one, the desirability function varies in a linear mode. Solving of multiple response optimizations using the desirability approach involves a technique of combining multiple responses into a dimensionless measure of performance called the overall desirability function, D ($0 \leq D \leq 1$), is calculated by

$$D = \left(\prod_{i=1}^{n} d_i^{ri}\right)^{1/\sum ri} \quad (1)$$

In the overall desirability objective function (D), each response can be assigned an importance (r), relative to the other responses. Importance varies from the least important value of 1, indicated by (+), the most important value of 5, indicated by (+++++). A high value of D indicates the more desirable and best functions of the system which is considered as the optimal solution. The optimum values of factors are determined from value of individual desired functions (d) that maximizes D.

Results and Discussion

Analysis and evaluation of model

The Analysis of Variance (ANOVA) was used to verify model acceptability which provides numerical data about P value. Based on the ANOVA, the models were found to be significant as the values of P were less than 0.05. The regression statistics goodness of fit (R^2) and the goodness of prediction (Adjusted R^2) indicated that the model fits the data very well.

The predicted quadratic models for the responses were developed in terms of non-dimensional coded factors and are given below as Eqs. (2) - (7). These equations are valid for input variables levels range from 20 to 50% for load, 1000 to 3000 rpm for speed and 5 to 15% for butanol. To simplify calculations and analysis, the actual variable ranges are usually transformed to non-dimensional coded variables with a range of ±1. In this analysis, the actual range of $20 \leq load \leq 50$ would translate to coded range of $-1 \leq load \leq +1$. The general equation used to translate from coded to uncoded is given below as Eq. (8).

$$Power = 18.24 + 6.88A + 3.51B - 0.71C + 4.99AB + 1.26AC + 0.94BC - 1.65A^2 - 4.40B^2 + 2.577e^{-3}C^2 \quad (2)$$

$$BTE = 29.84 + 5.49A + 2.00B + 1.e^{-2}C + 5.31AB + 0.71AC - 0.44BC - 2.22A^2 - 3.17B^2 + 0.18C^2 \quad (3)$$

$$BSFC = 300.77 - 84.11A + 0.22B + 14.05C - 86.66AB - 22.16AC + 20.91BC + 46.75A^2 + 52.60B^2 + 8.45C^2 \quad (4)$$

$$CO = 2.29 + 1.09A - 0.94B + 0.15C - 0.52AB + 0.11AC - 0.059BC - 0.20A^2 - 0.15B^2 - 0.090C^2 \quad (5)$$

$$NO_x = 454.68 - 48.80A + 1.10B - 46.40C + 75.13AB + 24.63AC + 30.13BC \quad (6)$$

$$CO_2 = 8.40 + 2.46A - 0.80B - 1.04C + 1.64AB + 0.21AC + 0.21BC + 0.78A^2 - 2.52B^2 + 0.18C^2 \quad (7)$$

$$x_{actual} = x_{min} + \left[\frac{(x_{coded} + 1)}{2} + (x_{max} - x_{min})\right] \quad (8)$$

Where x_{actual} is the uncoded value, x_{min} and x_{max} are the uncoded minimum and maximum values (corresponding to -1 and +1 coded values), and x_{coded} is the coded value to be translated. It may be noted from Eq. (8) that the coded value of 0 corresponds to the actual value $\frac{(x_{max} - x_{\min})}{2}$. Thus coded value of 0 from equations given above corresponds to the following actual values; A: Load = 35%, B: Speed = 2000 rpm and C: Butanol = 10%. Hence it is expected that corresponding output gives some numerical values even when coded factors have a value of 0. Corresponding output numerical values for coded value of 0 from the above equations are Power = 18.2 kW, BTE = 29.6%, BSFC = 300.9 g/kWh, CO = 2.28%, NOx = 454.6 ppm and CO_2 = 8.4%.

Interactive effect of Load and Speed

Figure 2 shows Interactive effect of Speed and Load (a) Power, (b) BTE, (c) BSFC, (d) CO, (e) NOx and (f) CO_2 where 2-butanol were constant (10%). Power at different load and speed is depicted in a three dimension plot (Fig. 2a). As seen in figure, for all speeds, the Power increases with increase in load. Further, increase in load and speed also increasing in BTE by all way. The pattern of Power and BTE graph are almost same. This results shows between the combustion of molecules of oxygen and fuel increase when increase load and speed. The increase in the speed as well as load will decrease in ignition the delay period. The difference situation in BSFC at different load and speed is presented in Fig. 2c. As illustrated in figure the BSFC was found increase in speed but some decrease in load. The possible reason for this trend could be that, with an increase in speed, the maximum cylinder pressure increase due to the fuel injected in hotter combustion chamber and therefore, fuel consumption per output power will increase.

From load of 35% onwards minor increase in BSFC was observed. The possible reason for this trend could be incomplete combustion due to higher pressure, which slight reduction in effective power. The variation of emission (CO, NOx and CO_2) for different load and speed is shown in Fig. 2d, 2e and 2f respectively. At higher speed and low load there are low in CO and CO_2 but increase at high load and low speed. Increase in this two element were observed and the possible reason for this could be higher operating temperature at elevated load. The interactive effect of load and speed on NOx is depicted in Fig. 2e. NOx at higher load and speed were observed lesser than at lower speed and high load. This could be because of higher temperature at that situation.

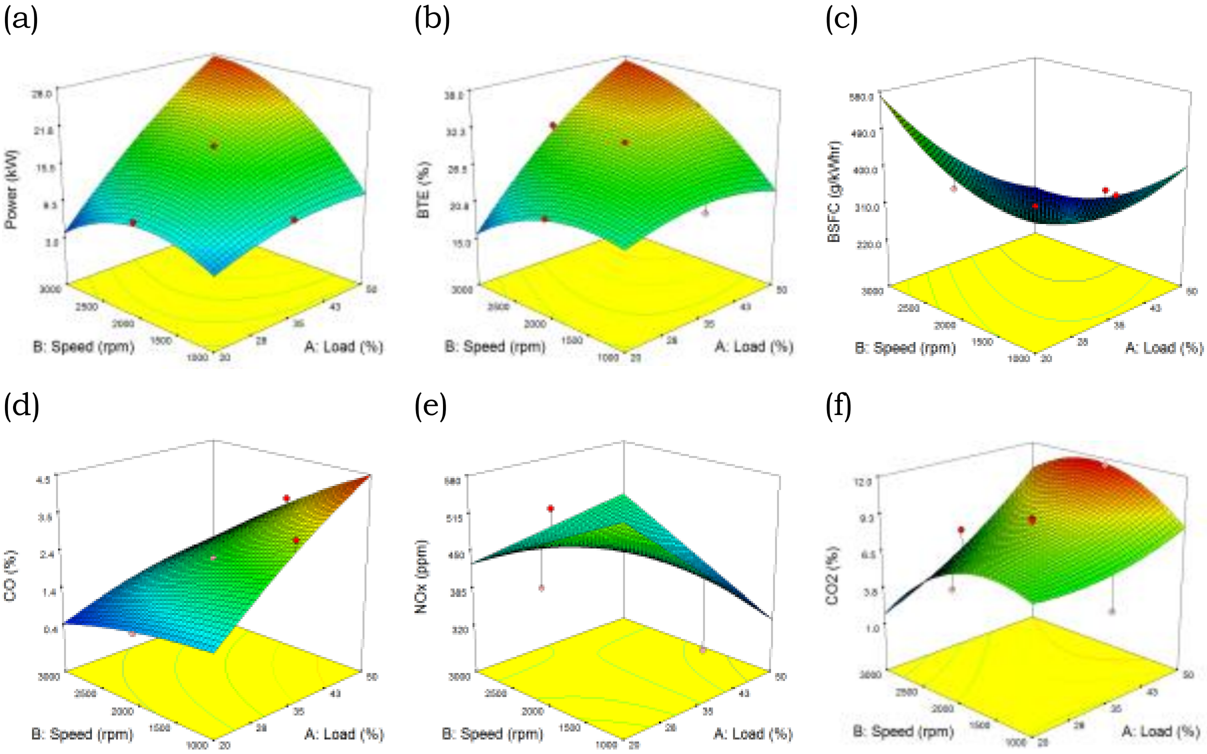


Figure 2: Interactive effect of Speed and Load (a) Power, (b) BTE, (c) BSFC, (d) CO, (e) NOx, (f) CO_2

Interactive effect of Load and 2-butanol percentages

As seen in Fig. 3a, 3b and 3c the Power and BTE increases with increase in load instead of BSFC. The change in 2-butanol percentage does not affect performance and combustion so much. Further, increase in butanol percentage from 5% to 15%, leads to decrease in BTE just by 0.8%. This is because of optimum in combustion process by oxygen content in water emulsified fuel. What interesting is, BSFC dropped suddenly by increasing load. This is because better thermal efficiency at high load. However, this good news does not benefit to the emissions. With Increasing of 2-butanol percentage, CO increase, while NOx and CO_2 slightly decrease. The most factor of the situation is rich mixture of oxygen due at high load which leads to formation of emission.

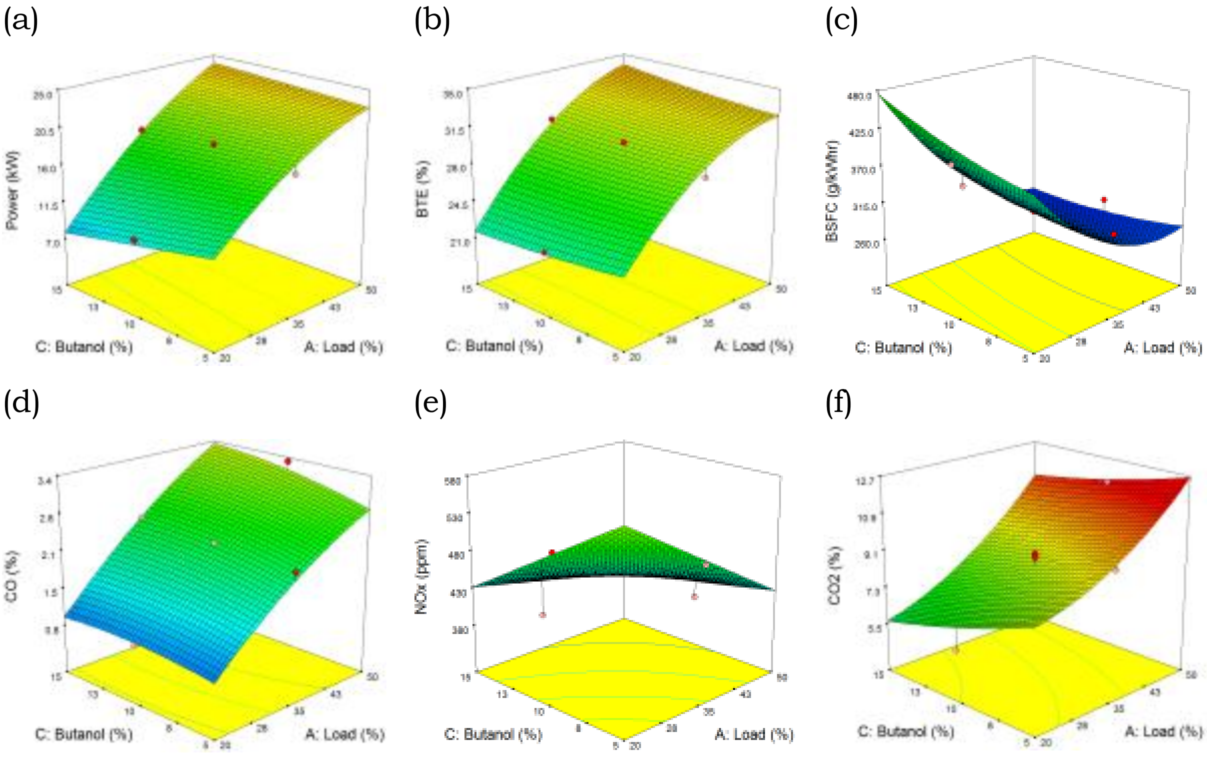
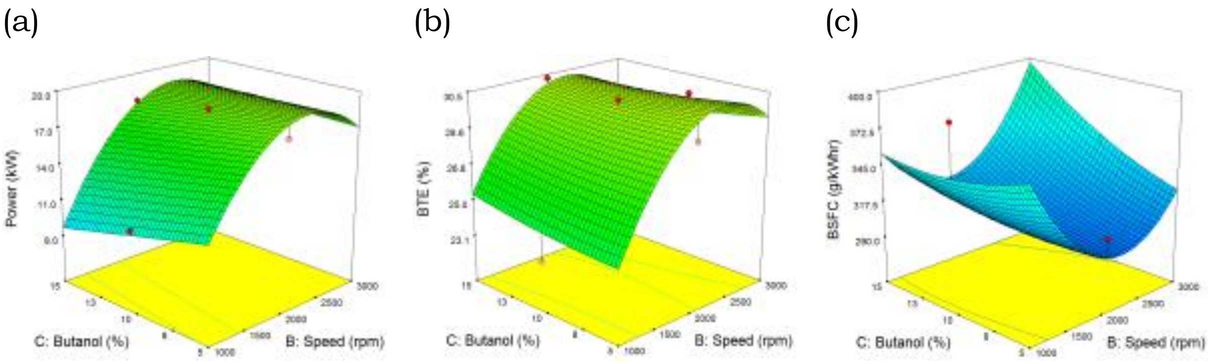


Figure 3: Interactive effect of 2-Butanol and Load (a) Power, (b) BTE, (c) BSFC, (d) CO, (e) NOx, (f) CO_2



(d) (e) (f)

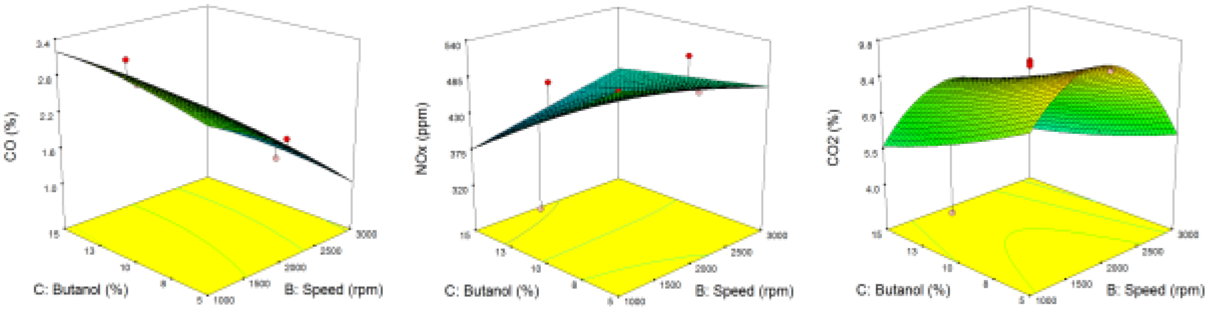


Figure 4: Interactive effect of 2-Butanol and Speed (a) Power, (b) BTE, (c) BSFC, (d) CO, (e) NOx, (f) CO_2

Interactive effect of Speed and 2-butanol percentages

The change in Power, BTE and BSFC at different 2-Butanol and Speed are observed in Fig. 4a, 4b and 4c respectively. Power and BTE increase with advancement of speed from 1000 rpm to 2500 rpm, even retardation from 2500 rpm onward. This can be attributed to increase ignition delay associated with increase in speed. Whereas retardation of Power and BTE by 2500 rpm onward decreases delay period due to burning of larger quantity of fuel during combustion. This is proven by quantity of BSFC used at 4c. At speed of 1000 rpm to 2500 rpm lead to decrease in average BSFC by 18.9%. Further increase in speed from 2500 rpm up resulted in increase in BSFC by 9.3%. For emission, the decreasing of CO will increase quantities of NOx in speed as shown in figure 4d and 4e respectively. Noticeable, CO_2 reach maximum value at 2000 rpm of speed before turning down at higher speed. What is important the level of NOx can be controlled better when using emulsified diesel with 2-Butanol because there have lower heating value while higher oxygen content that can optimize combustion parameter in the engine.

Optimization

The comprehensive discussions on the effect of Speed, Load and 2-Butanol % on the performance and emission characteristics have shown that the lowest speed of 1000 rpm, retarded load of 20% and 2-Butanol % resulted in low values of Power, BTE, CO and CO_2 with high values of BSFC and NOx. Optimization of performance and emission parameters for independent input variables like Power, BTE, BSFC, CO, NOx and CO_2 are tabulated in Table 4. In desirability based approach the solution with high desirability was favored. Maximum desirability of 0.856 was obtained at speed of 2808 rpm, load of 50% and 2-butanol of 5%, which could be considered as the optimum parameters.

Table 4: Optimization criteria and desirability of responses for performance parameters

Name	Optimized	Goal	Load	Speed	Butanol	Desirability

	value		**(%)**	**(rpm)**	**(%)**	
Power (kW)	26.20	maximize	50	2808	5	0.90
BTE (%)	36.80	maximize	50	2808	5	0.95
BSFC (g/kWhr)	227.6	minimize	50	2808	5	1.00
CO (%)	1.60	minimize	50	2808	5	0.70
NOx (ppm)	464.9	minimize	50	2808	5	0.65
CO_2 (%)	11.50	maximize	50	2808	5	0.86

Conclusion

In this study emulsified diesel with 2-Butanol was used to investigate effects of significant operating parameters like speed, load and 2-butanol % on performance and emission of compression ignition engine. Based on the results of this study the following conclusion can be listed:

1. RSM DOE based was used to design and carry out statistical analysis to determine parameters which have the most significant influence on the performance and emission characteristics. Desirability approach of the RSM was used to find out optimum parameters for optimization of performance and emission characteristics on emulsified alcohol fuel.
2. Increase in speed increases power and thermal efficiency for all load condition of the engine. Brake thermal efficiency was found to increase with increase in 2-butanol content.
3. Initial decrease in BSFC was observed with increase in load. Minimum BSFC was observed at high load and speed but maximum at high speed and 2-butanol content.
4. CO was found to increase with increase in load but decrease in higher speed. NOx was reduced at higher middle of speed-load-butanol content. Decreases in CO_2 with increase in speed but increase at high load were also observed.
5. At optimum input parameters speed of 2808 rpm, load of 50% with 2-Butanol content of 5%, the values of the Power, BTE, BSFC, CO, NOx and CO_2 were found to be 26.2 kW, 36.8% , 227.6 g/kWhr, 1.6%, 464.9 ppm and 11.5% respectively.

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