Environmental Science and Pollution Research (2018) 25:29115–29128
https://doi.org/10.1007/s11356-018-2867-4

RESEARCH ARTICLE

Optimization in the performance and emission parameters of a DI diesel engine fuelled with pentanol added *Calophyllum inophyllum*/diesel blends using response surface methodology

Purnachandran Ramakrishnan[1,2] · **Ramesh Kasimani**[3] · **Mohamed Shameer Peer**[4]

Received: 9 April 2018 / Accepted: 27 July 2018 / Published online: 15 August 2018

Abstract

The primary objective of this work was to enhance the performance and emission of the computerized variable compression ratio (VCR) diesel engine fuelled with pentanol/*Calophyllum inophyllum* (CI)/diesel fuel blends. Based on the prerequisite for the current research, response surface methodology (RSM), an optimization technique, was adopted for the process parameters compression ratio (CR), load and fuel blends, and the optimized responses like brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC), and smoke were revealed with the help of Derringer's desirability approach. From the results, it is notified that pentanol-fuelled engine showed better performance and emissions at 17.5 CR, P20C20 (pentanol 20%+*Calophyllum inophyllum* 20%+diesel 60%) blend and 2.5 bmep (brake mean effective pressure) load conditions. The observed mathematical models and validation experiments show that the VCR diesel engine exhibits maximum efficiency and minimum emissions at the optimized input parameters.

Keywords Pentanol · *Calophyllum inophyllum* · Performance · Emission · Combustion · Compression ratio
Response surface methodology

Nomenclature

CI	*Calophyllum inophyllum*
DI	Direct injection
CO	Carbon monoxide
CO_2	Carbon dioxide
NO_x	Oxides of nitrogen
NO	Nitric oxide
HC	Hydrocarbon
VCR	Variable compression ratio
P10C20	Pentanol 10%+*Calophyllum inophyllum* 20%+diesel 70%
P15C20	Pentanol 15%+*Calophyllum inophyllum* 20%+diesel 65%
P20C20	Pentanol 20%+*Calophyllum inophyllum* 20%+diesel 60%
CI20	*Calophyllum inophyllum* 20%+diesel 80%
BTE	Brake thermal efficiency
BSFC	Brake specific fuel consumption
bmep	Brake mean effective pressure
CR	Compression ratio
MDS	Modular diagnostic system
RSM	Response surface methodology
ANN	Artificial neural network
DOE	Design of experiments

Responsible editor: Philippe Garrigues

✉ Purnachandran Ramakrishnan

Ramesh Kasimani
kramesh@gct.ac.in

Mohamed Shameer Peer
pmohamedshameer@gmail.com

[1] Department of Mechanical Engineering, Research Scholar, Government College of Technology, Coimbatore 641013, India

[2] Dindigul, India

[3] Department of Mechanical Engineering, Faculty of Engineering, Government College of Technology, Coimbatore 641013, India

[4] Department of Mechanical Engineering, Faculty of Engineering, VV College of Engineering, Tirunelveli 627657, India

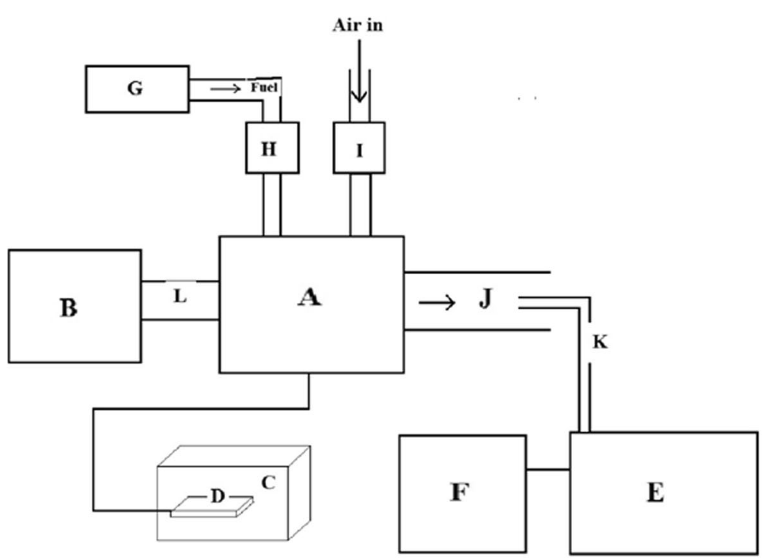
Introduction

The requirement of fossil fuel is increasing day by day, which is used for both domestic and commercial purposes. The increase in the use of fossil fuels results in the depletion of its existence. This induced the interest among researchers to search for an alternate fuel. Many such alternate solutions were achieved in the form of bio-oils. Using transesterification process, these bio-oils were converted into biodiesels. These biodiesels were used as straight fuels or blended with conventional diesel fuel. The biodiesels are limited as an alternative fuel to use in diesel engine because of its high density and viscosity, which resulted in low fuel atomization and the formation of unburnt fuels in the combustion chamber (Kocak et al. 2007; Shameer and Ramesh 2017a). *Calophyllum inophyllum* (CI) biodiesel has been proposed as a superior source due to its higher oil yield and heating value than other biodiesel sources like karanja, neem, and jatropha (Shameer and Ramesh 2017b).

On the other hand, alcohols exhibit lower exhaust emissions in engines while using as additives with diesel fuel due mainly by the oxygen in their composition (Lapuerta et al. 2008). The low sulfur content and higher oxygen content in the alcohols attribute the lower emissions of alcohol added diesel fuel. Still, the lower alcohols show some disadvantages such as phase separation on blending with diesel and reduced lower heating value (Eugene et al. 1984). The lower alcohols also show poor soluble and miscible properties on blending with diesel fuel. These problems were overcome by the use of higher alcohols as additives with diesel fuel, which shows better solubility (Yilmaz et al. 2017). Among such higher alcohols, n-pentanol possesses superior qualities like higher cetane number and latent heat of evaporation compared to other higher alcohols such as butanol and lower alcohols (Yilmaz and Atmanli 2017 and Lapuerta et al. 2010).

Many types of research were carried out using alcohol/biodiesel/diesel blends in various proportions and were tested in diesel engines with varying parameters such as injection timing, load, and compression ratio. However, it was difficult to find out the proportion of blend at which it gives better results. So the optimization techniques which give better performance and emission characteristics were utilized by the researchers efficiently and effectively.

Kesgin 2004 used Genetic algorithm and neural network in the prediction of operational parameters, load, and speed, in the engine efficiency and NO_x emissions with the help of a natural gas engine. Increase in efficiency of the engine was achieved and the NO_x emissions were maintained under 250 mg/Nm^3. The effects of speed, load, and injection timing on the performance and pollution of the engine were studied by Win et al. 2005. The input parameters were varied as 4 × 4 × 3 full factorial design array. Performance and emission results were captured and taken as output responses. Using response surface methodology (RSM) the input and output parameters were related and the objective functions were arrived (Shameer and Ramesh 2017c). Artificial neural network (ANN) modeling has been handled by Sayin et al. 2007 to predict the



A : Single Cylinder Four Stroke Variable Compression Ratio Diesel Engine
B : Eddy Current Dynamometer
C : Computer with IC Engine Soft Software
D : DAQ Card
E : AVL MDS 250 Gas Analyser
F : Computer Connected with Gas Analyser
G : Fuel Tank
H : Fuel Flow Meter
I : Air Flow Meter
J : Exhaust Gas
K : Gas Analyser Tailpipe Probe
L : Coupling

Fig. 1 Layout of the experimental test bed of the variable compression ratio single cylinder computerized diesel engine

Table 1 Engine specifications

Manufacturer	Kirloskar
Model	PSP 240PE research engine
Type	4 stroke, direct injection, single cylinder, constant speed, variable compression ratio
Loading device	Eddy current dynamometer
No. of cylinders	1
Rated power	3.5 kW @ 1500 rpm
Bore diameter	87.5 mm
Stroke length	110 mm
Connecting rod length	234 mm
Method of cooling	Water cooled
Nozzle hole diameter	0.3 mm

performance, emission, and exhaust gas temperature of a gasoline engine at different engine speeds. The predicted ANN results were compared with the experimental results and the correlation coefficients were in the range of 0.983–0.996 with a low root mean square errors. It was shown that the ANN approach accurately predicts the performance and emissions of IC engines. Xu et al. 2017 experimented on a diesel engine fueled with diesel-*Jatropha curcas* blended with diesel fuel. The experiments were conducted in the order designed with the help of design of experiments. The design was formulated on the basis of the fractional factorial design of RSM (response surface methodology). The study results show that for optimal input parameters, the performance and emission values were achieved at a high desirability. Choudhary et al. 2015 investigated the combustion and performance of bioethanol blended with diesel in a diesel engine using RSM and compared the results with the experimental results. At higher compression ratio, the fuel injection pressure and engine loads, higher combustion pressure were produced by bioethanol diesel blends.

The evaluation of multiple variables with multiple responses can also be carried out easily in an efficient manner (Ileri et al. 2013). Less consumption time in RSM (Pandian et al. 2011) and its studies on the optimization of diesel engine parameters (Namvar et al. 2008) and also the determination of improved optimized values of BTE, BSFC, NO, and HC were widely studied and depict a clear picture of the role of RSM in IC engines.

In this study, optimization was carried out using design of experiments (DOE) and the optimized values related to performance and emission were determined in a DI diesel engine fuelled with pentanol/*Calophyllum inophyllum*/diesel blends by varying the compression ratio (CR), load (in bmep), and fuel blends.

Table 3 Technical specifications of AVL MDS 250 gas analyzer

Manufacturer	AVL
Model	Modular Diagnostic System 250
Type	Online data logger
CO	0–15% vol.
CO_2	0–20% vol.
HC	0–30,000 ppm vol.
NO_x	0–5000 ppm vol.

The pentanol-biodiesel-diesel blends showed lower BSFC than CI20 (*Calophyllum inophyllum* 20%+diesel 80%) fuel blend and lower NO_x and CO emissions than pure diesel fuel and CI20 biofuel blend with the addition of pentanol (Ramakrishnan et al. 2018). The optimization of the percentage of pentanol to be mixed with the biodiesel-diesel blend is required to improve the engine performance, emission, and combustion of the diesel engine. However many optimization works have been carried out in the performance, combustion, and emission characteristics of DI diesel engine using various fuel blends with diesel fuel, so far the use of pentanol/*Calophyllum inophyllum*/diesel blend fuel has not been carried out in RSM which enhances the novelty in the paper. Also, this optimization work is the extension of the previous work Ramakrishnan et al. 2018.

Experimental set-up

The experimental work was carried out using a Kirloskar single cylinder, water-cooled, constant speed, four-stroke, direct injection, computerized VCR research test engine available in the Thermal Engineering Laboratory, Department of Mechanical Engineering, Government College of Technology. The layout of the test engine is shown in Fig. 1. The specifications of the engine are given in Table 1. The test fuels used for the preparation of the blends were neat diesel fuel, CI biodiesel, and pentanol. The diesel fuel was purchased from the commercial market. CI oil was prepared from the collected CI seeds and the biodiesel was prepared from the oil using transesterification process as carried out by Shameer

Table 2 Physico-chemical properties of the fuel blends

Parameters	Diesel	Pentanol	CI	P10C20	P15C20	P20C20
Viscosity@40 °C (cSt)	3.9	2.83	4.78	3.44	3.52	3.71
Density @ 15 °C (kg/m^3)	833	814	873	833.2	835.2	837.2
Cetane Index (CCI)	54	24.3	55.8	48.42	47.33	46.27
Calorific value (MJ/kg)	43.35	35	38.33	41.178	40.927	40.676
Flash point (°C)	63	–	140	65.4	61.6	58.9

Table 4 Technical specifications of smoke meter AVL 437C

	Opacity	Absorption	Rpm	Oil temperature
Measuring range	0–100%	0–99.99 m^{-1}	400–6000 1/min	0–150 °C
Accuracy & repeatability	± 1% of full scale	Better than ± 0.1 m−1	± 10	± 2 °C
Resolution	0.1%	0.01 m^{-1}	± 1	± 1 °C

and Ramesh 2017d. Pentanol was purchased from The Precision Scientific Co., Coimbatore, Tamilnadu, India.

The fuel blends used in the test were: (i) P10C20 (Pentanol 10%+CI 20%+diesel 70%), (ii) P15C20 (Pentanol 15%+CI 20%+diesel 65%), and (iii) P20C20 (Pentanol 20%+CI 20%+diesel 60%). The fuel properties of the fuel blends were given in Table 2.

The engine emissions CO, CO_2, HC, and NO_x were measured using AVL MDS 250 gas analyzer and the smoke emission was measured using AVL smoke meter. The specifications of the gas analyzer and smoke meter were given in Tables 3 and 4. The measurement accuracy and the maximum uncertainties of the instruments were given in Table 5.

Test method

The engine used was a constant speed engine which runs at 1500 rpm. Three blends were used namely P10C20, P15C20, and P20C20 at three compression ratios 16:1, 17:1, and 18:1. The engine was operated by fuelling with diesel fuel for 5 min in order to stabilize the engine before using each blend. The performance responses were measured using the IC Engine Soft that is connected to the engine by means of a data acquisition card. The emission responses were measured using AVL Modular Diagnostic System 350. Each blend was poured in the engine tank and test runs were conducted at compression ratios of 16:1, 17:1, and 18:1 for three varying loads (1.07, 2.15, and 4.16 bmep). The engine test run was made three times with each blend, at each compression ratio and load for statistical analysis.

Response surface methodology

The input factors considered in this work were fuel blends, compression ratio, and load. These factors affect performance factors such as brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC), and emission factors such as carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC), oxides of nitrogen (NO_x), and smoke, which were taken as output responses. The RSM analysis was carried out using "design expert" trial version 11. The experimentation was carried out with each factor varied in levels of 3 × 3 × 3 (27 runs) using full factorial design. As per the run order that arrived from the design matrix, the experimentation works were carried out. Derringer's desirability approach is the optimization technique handled in this work, where the highest desirable solution is taken as the optimum result (Hirkude and Padalkar 2014; Pandian et al. 2011). The corresponding combination of the input factors was considered as the optimized input parameters to operate the engine. The obtained solutions of input parameters were validated by performing confirmatory experiments.

Table 5 Measurement accuracy and maximum uncertainties of the instruments

Test instruments	Measured parameters	Measurement accuracy	Uncertainty (%)
Burette	Fuel flow	± 0.03 L/h	± 0.4
Thermocouple	Temperature	± 1 °C	± 0.1
Kobold ZOD flow meter	RPM of engine	± 2 rpm	± 0.2
AVL MDS 250	CO	± 0.11%	± 0.01
AVL MDS 250	HC	± 102 ppm	± 0.31
AVL MDS 250	CO_2	± 1%	± 0.08
AVL MDS 250	NO_x	± 127 ppm	± 0.08
AVL smoke meter	Smoke	± 0.1%	± 0.01
Pressure sensor	Cylinder pressure	± 0.1 bar	± 1
	BSFC	± 0.05 kg/kWh	± 1
	BTE	± 0.5%	± 0.04

Table 6 ANOVA for output parameters

Model	BSFC	BTE	CO	CO_2	HC	NO_x	Smoke
Mean	0.4933	17.03	0.3811	5.93	217.89	736.07	27.97
SD	0.0092	0.3035	0.0812	0.1991	30.05	48.21	0.6395
R^2	0.9932	0.9972	0.9466	0.9973	0.7688	0.984	0.9771
Model degree	Quadratic	Quadratic	Quadratic	Quadratic	Quadratic	Quadratic	Quadratic
Adj R^2	0.9896	0.9957	0.9184	0.9959	0.6465	0.9756	0.965
Pred R^2	0.9820	0.9932	0.8656	0.9923	0.4369	0.9577	0.9409

Results and discussions

Analysis of the model

Analysis of variance (ANOVA) was used in RSM to develop and validate the models for the output responses BSFC, BTE, CO, CO_2, HC, NO_x, and smoke. For each output response, the predicted '*p* value' is less than 0.05, which shows that the factors were having a significant effect of confidence level at 95%. The maximum difference between the 'Pred-R^2' and 'Adj-R^2' among all the output responses does not exceed 0.2, which gives the reasonable agreement between the predicted and adjusted values (Pamnani et al. 2015). The signal to noise ratio is measured as 'Adeq precision'. This value is considered desirable if it is greater than 4. The 'Adeq Precision' of all the output responses was greater than 4 and thus indicates that the model prediction is adequately accurate (Ganapathy et al. 2011). The ANOVA model evaluation of the output responses was given in Table 6.

Optimization and validation experiment

The optimization criteria for the input and output parameters were represented in Table 7. Here for the responses BTE and CO_2, the goal was set as maximize and for remaining responses the goal was to minimize. The importance of each response was set as 3. The solution with the highest desirability was preferred as the optimized solution. The maximum desirability of 0.88 was obtained for the input engine parameters 17.5 CR, P20C20 blend, and 2.5 bmep load.

In order to validate the obtained optimized result from desirability approach, a validation experiment was carried out in the engine using the obtained optimized input parameters. Three experiments were carried out to evaluate the predicted output responses. The obtained output values from the validation experiments prove that the optimized model is correct as the experimental and predicted values agreed with each other which are given in Table 8.

Brake specific fuel consumption (BSFC)

The interaction effects of the input response compression ratio and load on the BSFC for different blends were shown in Fig. 2a–c. It is evident from the plot, as the pentanol percentage increased in the blend, the BSFC was decreased. This is because of the oxygen content in the pentanol. Though the heating or calorific value of pentanol is lower than that of diesel fuel, the calorific value of the pentanol/*Calophyllum inophyllum*/diesel blends is almost equal to the diesel fuel (Table 2). So, rather the heating value of the pentanol, the oxygen content in it influences the BSFC. As the pentanol level increases in the blend, the oxygen content also increased

Table 7 Optimization criteria

Name	Goal	Limits		Weight		Importance
		Lower	Upper	Lower	Upper	
A: Fuel blends	Is in range	10	20	1	1	3
B: Compression ratio	Is in range	16	18	1	1	3
C: Load	Is in range	1.07	4.16	1	1	3
BSFC	Minimize	0.36	0.65	1	0.1	3
BTE	Maximize	10.88	23.8	0.1	1	3
CO	Minimize	0.1	1.08	1	0.1	3
CO_2	None	1.8	10.11	0.1	1	3
HC	Minimize	126	304	1	0.1	3
NO_x	Minimize	288	1325	1	0.1	3
Smoke	Minimize	20.6	34.4	1	0.1	3

Table 8 Validation experiments

Fuel blend	CR	Load	Value	BSFC (kg/kWh)	BTE (%)	CO (%)	CO_2 (%)	HC (ppm)	NO_x (ppm)	Smoke (%)
20	17.5	2.5	Predicted	0.43	20.015	0.1	7.341	156.823	1047.553	22.169
			Actual	0.46	21.5	0.11	6.98	152.87	1092.34	24.23
			Error (%)	6.52	6.91	9.09	5.17	2.58	4.1	8.5

which attributes reduced BSFC (Imtenan et al. 2014). With the increase in compression ratio, the BSFC was reduced. As the compression ratio increases, it may enhance the evaporation rate and so the combustion process (Sharma and Murugan 2015). The higher BSFC at lower compression ratio is because of the incomplete combustion. With respect to increasing load, the BSFC was decreased due to the improved combustion efficiency (Bharadwaz et al. 2016). The highest value of BSFC is 0.65 kg/kWh at 16:1 CR, P10C20 blend, and 1.07 bmep. The lowest value of BSFC is 0.36 kg/kWh at

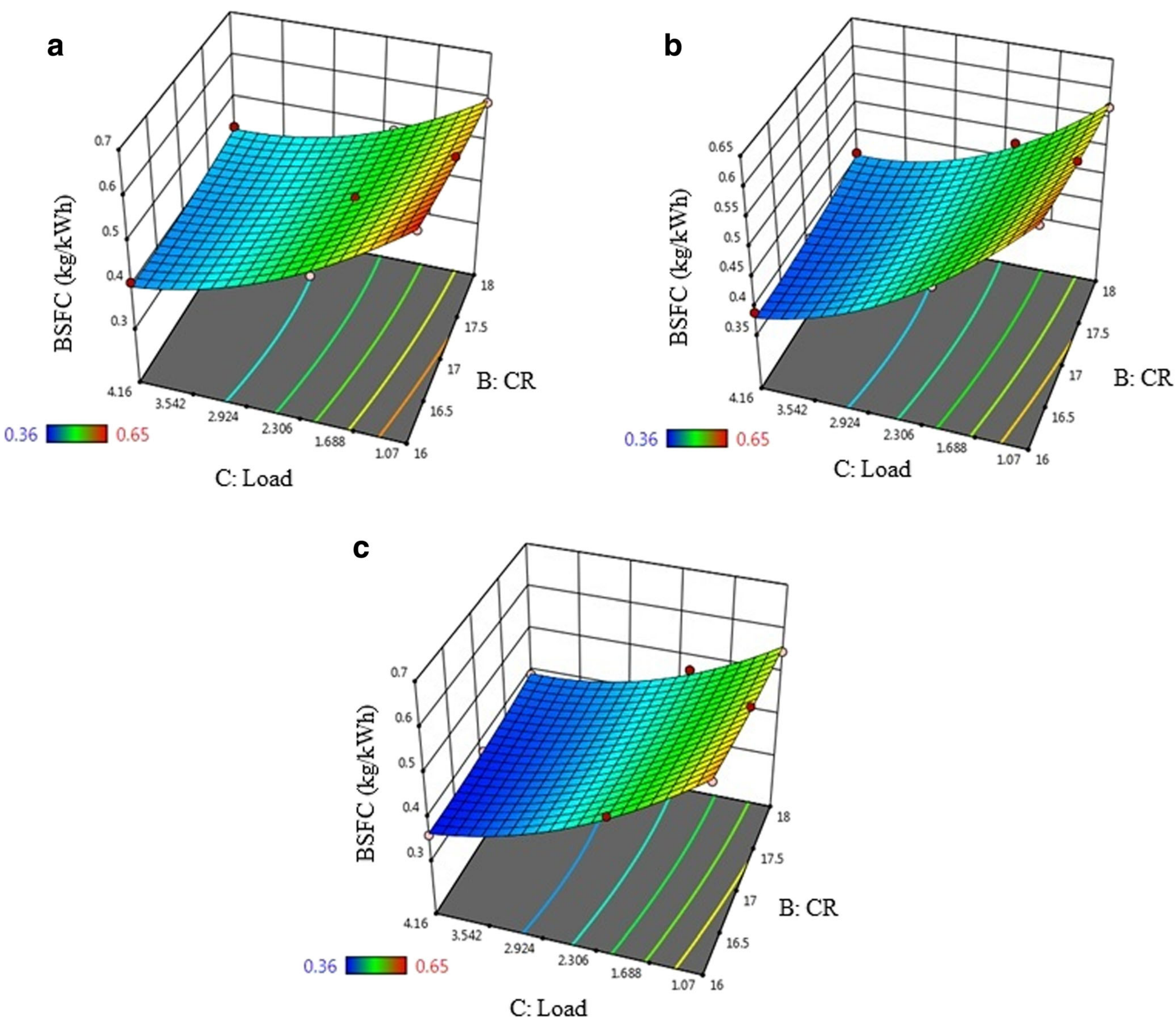


Fig. 2 Variation of brake specific fuel consumption against CR and load (**a**) at pentanol 10%, (**b**) at pentanol 15%, and (**c**) at pentanol 20%

16:1 CR, P20C20 blend, and 4.16 bmep. From this, it can be inferred that both the CR and pentanol level in the blend influence the specific fuel consumption.

The regression equation for the BSFC is generated as follows,

$$\begin{aligned}\text{BSFC (kg/kWh)} = {} & 3.99-0.0083*A-0.33*B-0.39*C \\ & +1.67e{-}4*AB+3.12e{-}05*AC+0.013*BC \\ & +6.67e{-}05*A^2+0.0083*B^2+0.019*C^2\end{aligned}$$

Brake thermal efficiency (BTE)

BTE plotted against CR and load for three blends was shown in Fig. 3a–c. It can be seen from the plot that the BTE increases with increase in the pentanol percentage in the blend. The increased oxygen content in the pentanol fuel blend resulted in the wider flame formation which attributes the increase in BTE (Yilmaz and Sanchez 2012 and Anand et al. 2011). Thermal efficiency increases with the compression ratio can be explained by the increase in temperature and pressure inside the combustion chamber. Higher cylinder temperature and pressure result in good combustion and increase the efficiency of the engine (Dhingra et al. 2014). As the load increases the BTE of all the blend increases, this is because of the reduction in BSFC as the load increases. The BTE increases with increase in engine load due to the occurrence of efficient combustion at higher engine load (Zhang and Balasubramanian 2016). The highest value of BTE (23.8%) is achieved at 18:1 CR, P20C20 blend, and 4.16 bmep. The lowest value of BTE is 10.88% which is achieved at 16:1 CR, P10C20 blend, and 1.07 bmep. Thus, the BTE value increases with increase in all input responses. The regression equation for BTE is given as follows,

$$\begin{aligned}\text{BTE (5\%)} = {} & 0.71+0.09*A+0.061*B+5.78*C-0.011*AB \\ & +0.04*AC+0.19*BC+0.003*A^2+0.004*B^2-1.14*C^2\end{aligned}$$

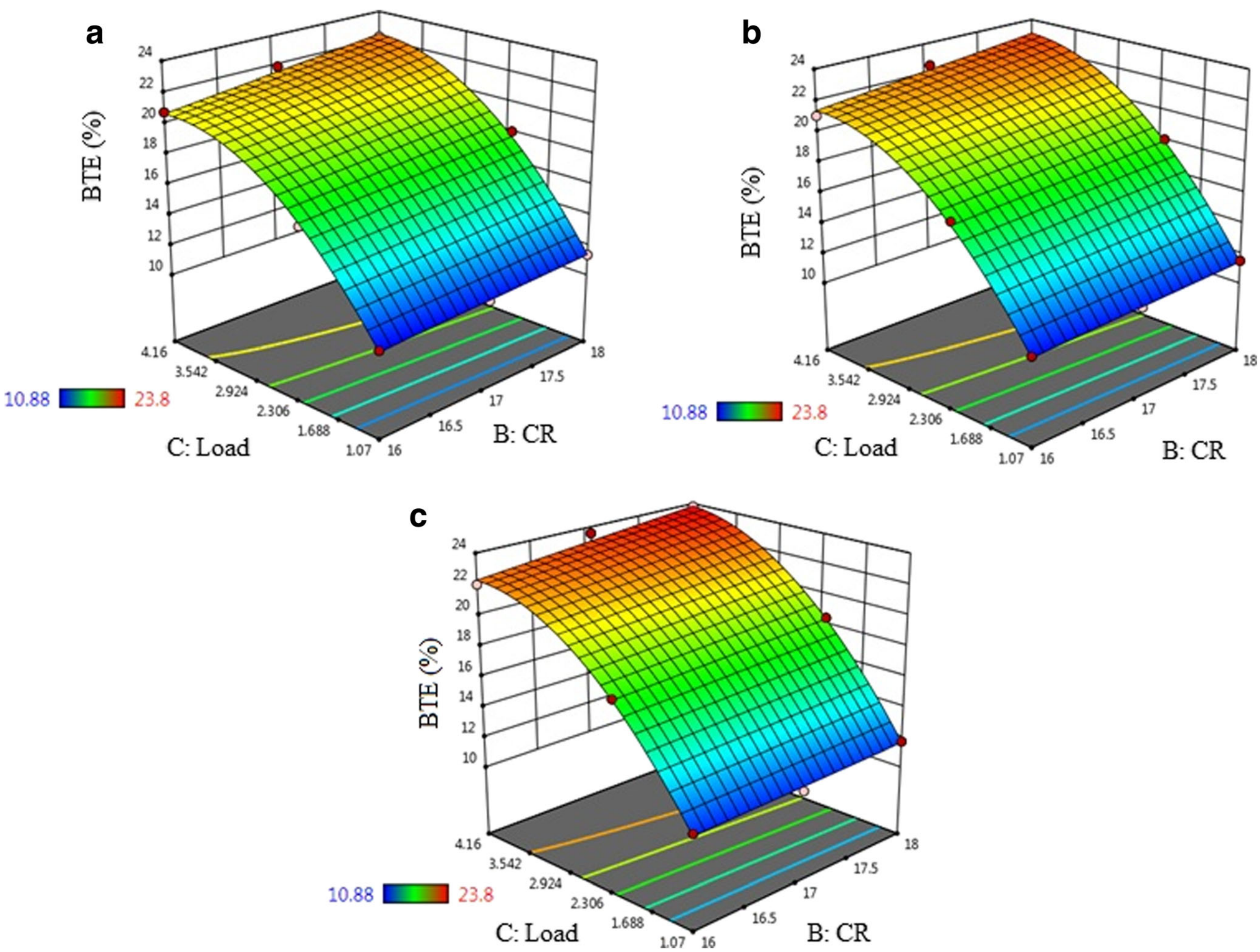


Fig. 3 Variation of brake thermal efficiency against CR and load (**a**) at pentanol 10%, (**b**) at pentanol 15%, and (**c**) at pentanol 20%

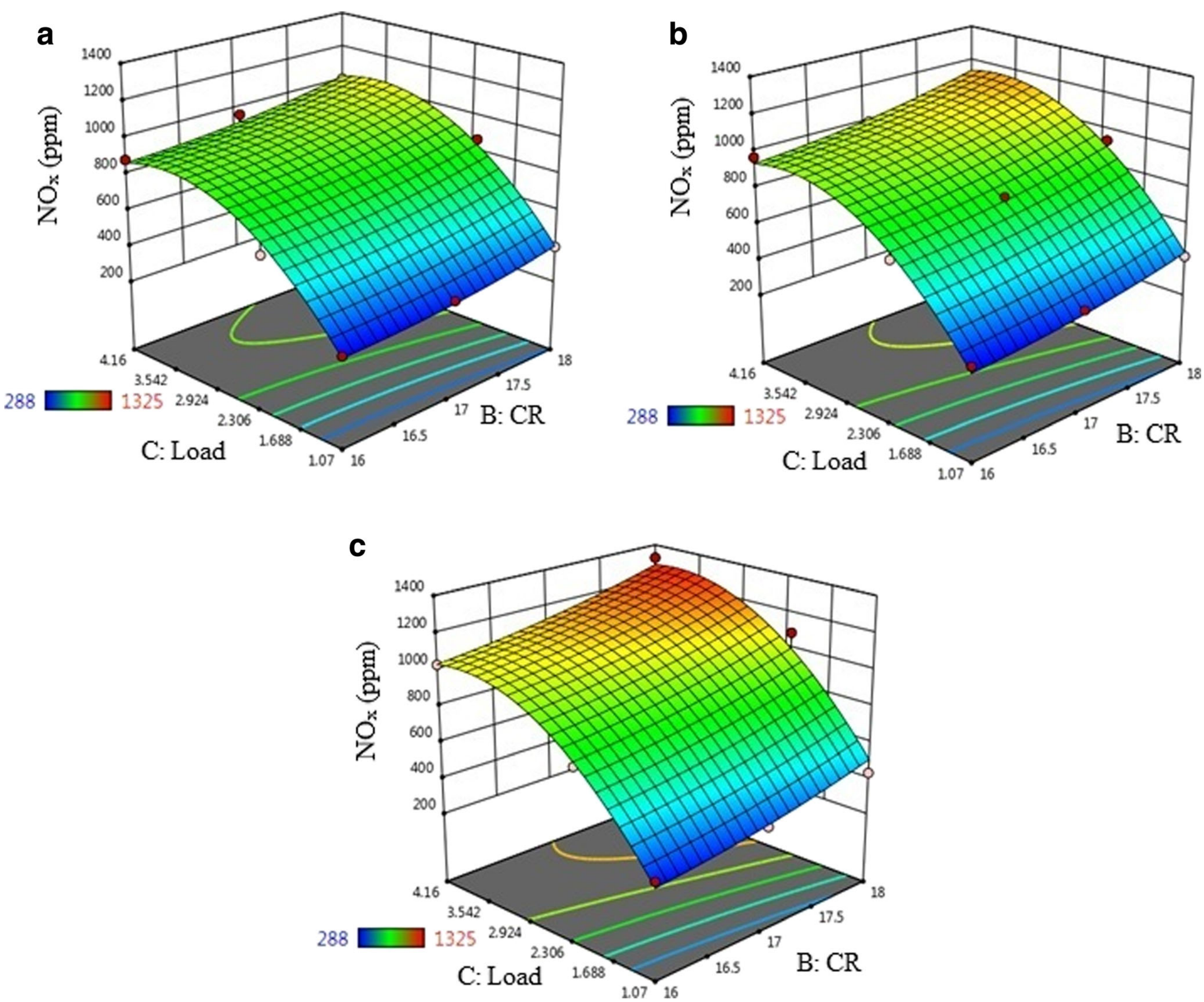


Fig. 4 Variation of NO_x against CR and load (**a**) at pentanol 10%, (**b**) at pentanol 15% (**c**), and at pentanol 20%

Emission parameters

Nitric oxide (NO_x) emissions

The NO_x emissions from the engine cylinder rely on air-fuel ratio, amount of oxygen present in the intake air and also the in-cylinder temperature. The NO_x plotted against CR and load for three blends was shown in Fig. 4a–c. It is noted from the plot that the level of NO_x emissions was inversely proportional to all the three input parameters. The NO_x emission increases with increase in pentanol percentage in the fuel blend because of the presence of the non-reactive nitrogen gas in the intake air-fuel mixture (Shameer and Ramesh 2017e), and the unburnt oxygen available in the combustion chamber reacted as per the Zeldovich mechanism forms NO_x emissions (Sakthivel and Ramesh 2018). The lower NO_x emission was observed as 288 ppm at 16:1 CR, P10C20 blend, and 1.07 bmep and higher NO_x emission as 1325 ppm at 18:1 CR, P20C20 blend, and 4.16 bmep. The NO_x formation is attributed by means of high temperature and pressure inside the engine cylinder combustion chamber which is obviously occurred at high load and CR (Sharma and Murugan 2015).

The regression equation for the NO_x emission generated is as follows,

$$NO_x(\text{ppm}) = 7392.12 - 96.47{*}A - 907.18{*}B + 586.69{*}C + 4.72{*}AB + 5.05{*}AC + 5.39{*}BC + 0.56{*}A^2 + 26.94{*}B^2 - 102.01{*}C^2$$

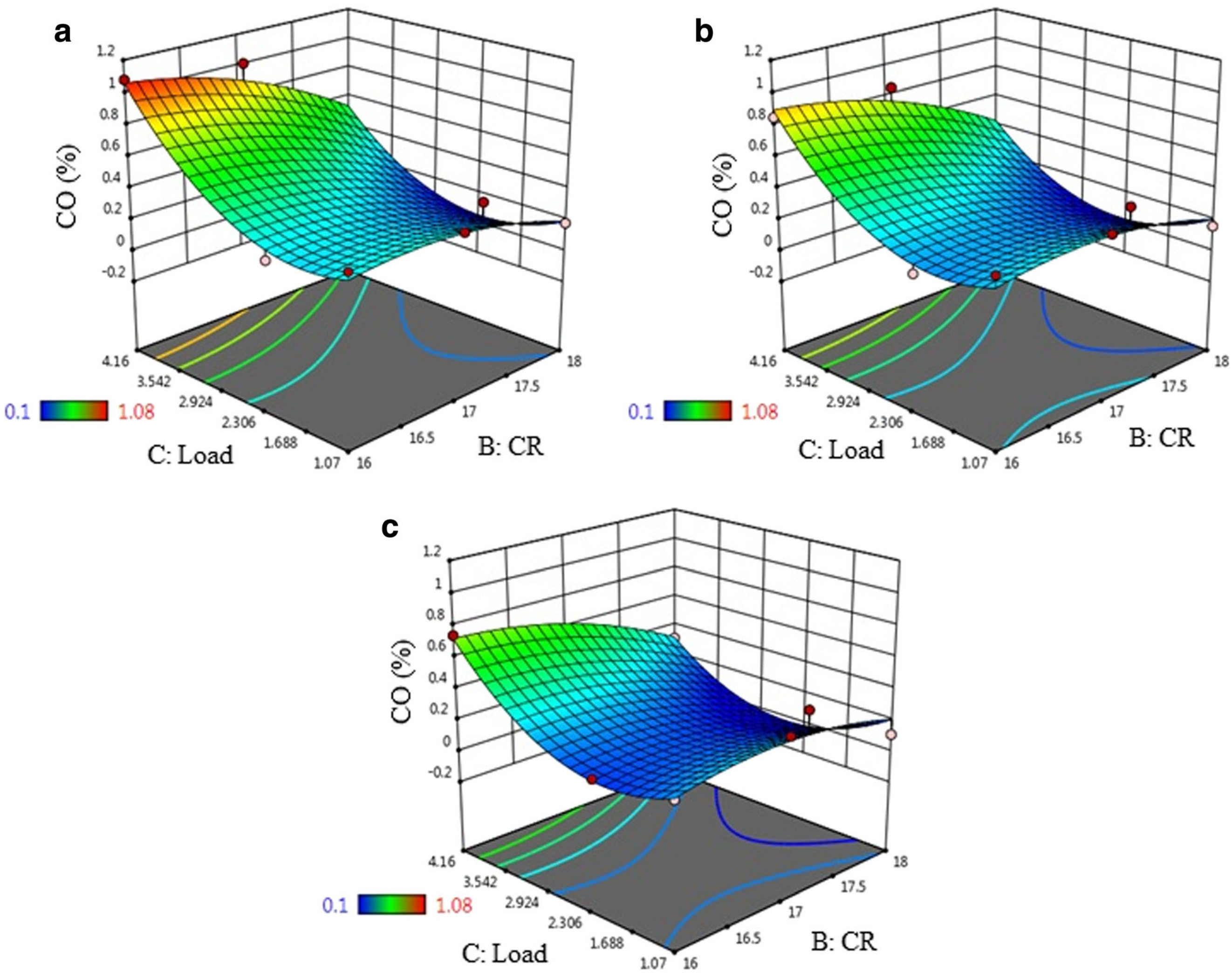


Fig. 5 Variation of CO against CR and load (**a**) at pentanol 10%, (**b**) at pentanol 15%, and (**c**) at pentanol 20%

Carbon monoxide (CO) emissions

The variation of CO plotted against the CR and load for varying pentanol blends were depicted in Fig. 5a–c. The CO emission was decreased as the pentanol ratio was increased in the fuel blend. This is because the pentanol evaporates easily in the cylinder which resulted in reduced spray atomization length. Thus with higher pentanol ratio in the blend, the CO emission is reduced (Yao et al. 2010). The presence of more number of oxygen molecules in the modified blends results in the complete combustion. This attributes the reduction in CO emission as the pentanol level increases in the blend (Fattah et al. 2014; Qi et al. 2014). At peak load, as the CR increases, a drastic reduction in CO emission can be observed. The reason is that the air temperature inside the cylinder gets increased with the increase in CR which leads to the complete combustion of the fuel and reduced CO (Sakthivel et al. 2018; Kassaby and Nemitallah 2013). The higher CO emission is observed at 16:1 CR, P10C20 blend, and 4.16 bmep loads whereas the lower CO emission is observed at 18:1 CR, P20C20 blend, and 2.15 bmep loads. The regression equation of the CO emission is as follows,

$$\mathrm{CO}\,(\%) = -25.54 - 0.091{*}A + 3.16{*}B + 0.63{*}C + 0.006{*}AB$$
$$-0.008{*}AC0.059{*}BC\text{–}2.44e-4{*}A^2 - 0.095{*}B^2 + 0.12{*}C^2$$

Carbon dioxide (CO_2) emissions

The CO_2 emission is always inversely proportional to the CO emission. This is because the O_2 molecules available in the mixture oxidize the CO molecules and

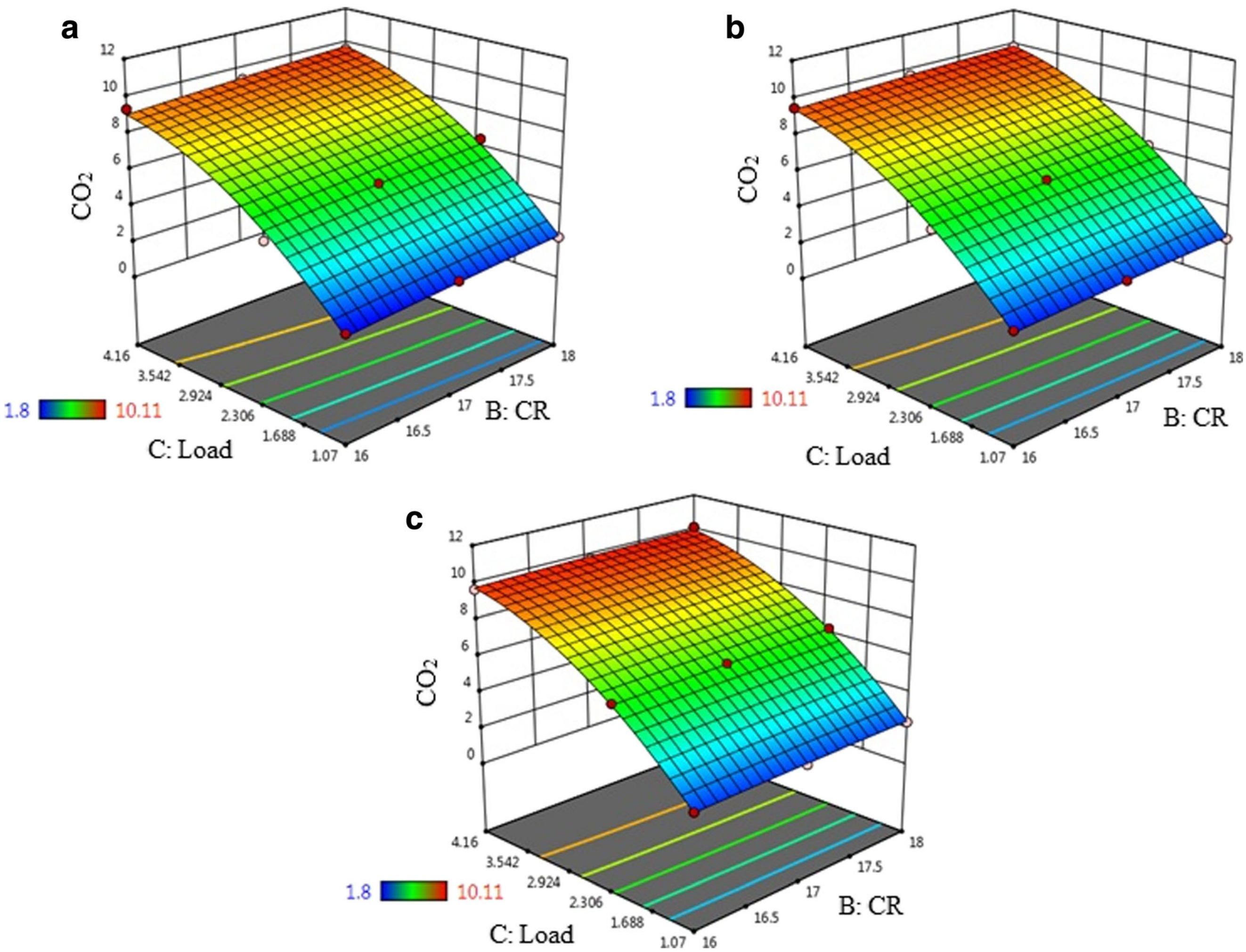


Fig. 6 Variation of CO_2 against CR and load (**a**) at pentanol 10%, (**b**) at pentanol 15%, and (**c**) at pentanol 20%

become CO_2 (http://nptel.ac.in/courses/112104033/pdf_lecture/lecture7.pdf). The plot in the Fig. 6a–c depicts the variation in CO_2 emission against CR and load for three blends. As the compression ratio increases the CO_2 emission is also increased. The complete combustion of the fuel at higher CR attributes the occurrence of CO_2 emission. The reduced clearance volume in the engine cylinder at higher CR increases the temperature and pressure in the combustion chamber which increases the CO_2 emission (Bora et al. 2014; Bora and Saha 2016). The higher CO_2 occurs at 18:1 CR, P20C20 blend, and 4.16 bmep loads whereas lower CO_2 at 16:1 CR, P10C20 blend, and 1.07 bmep. The regression equation of the CO_2 emission is as follows,

$$CO_2(\%) = -25.72 + 0.47{*}A + 2.01{*}B + 5.26{*}C - 0.025{*}AB + 0.0052{*}AC - 0.002{*}BC - 6.31e{-}04{*}A^2 - 0.041{*}B^2 - 0.55{*}C^2$$

Hydrocarbon (HC) emissions

The HC emission plot against CR and load for varying pentanol blends was shown in Fig. 7a–c. It is evident from the graph that the HC emission increases with increase in load for all percentage of blends and is decreased at moderate loads. The similar trends have been already observed in previous studies (Sahin and Aksu 2015; Chen et al. 2012b; Giakoumis et al. 2013; Rakopoulos et al. 2010). The increase in the pentanol percentage in the fuel blend also reduces the HC emission. The pentanol in the blend reduces the viscosity which improvises the spray formation and atomization of the fuel. This reduces the size of fuel droplets and leads to complete combustion of the fuel and reduced HC emissions (Chen et al. 2012a). The higher HC emission achieved was 304 ppm at 17:1 CR, P10C20 blend, and 1.07 bmep and the lower HC emission was 126 ppm at 17:1 CR, P20C20 blend, and 2.15 bmep loads.

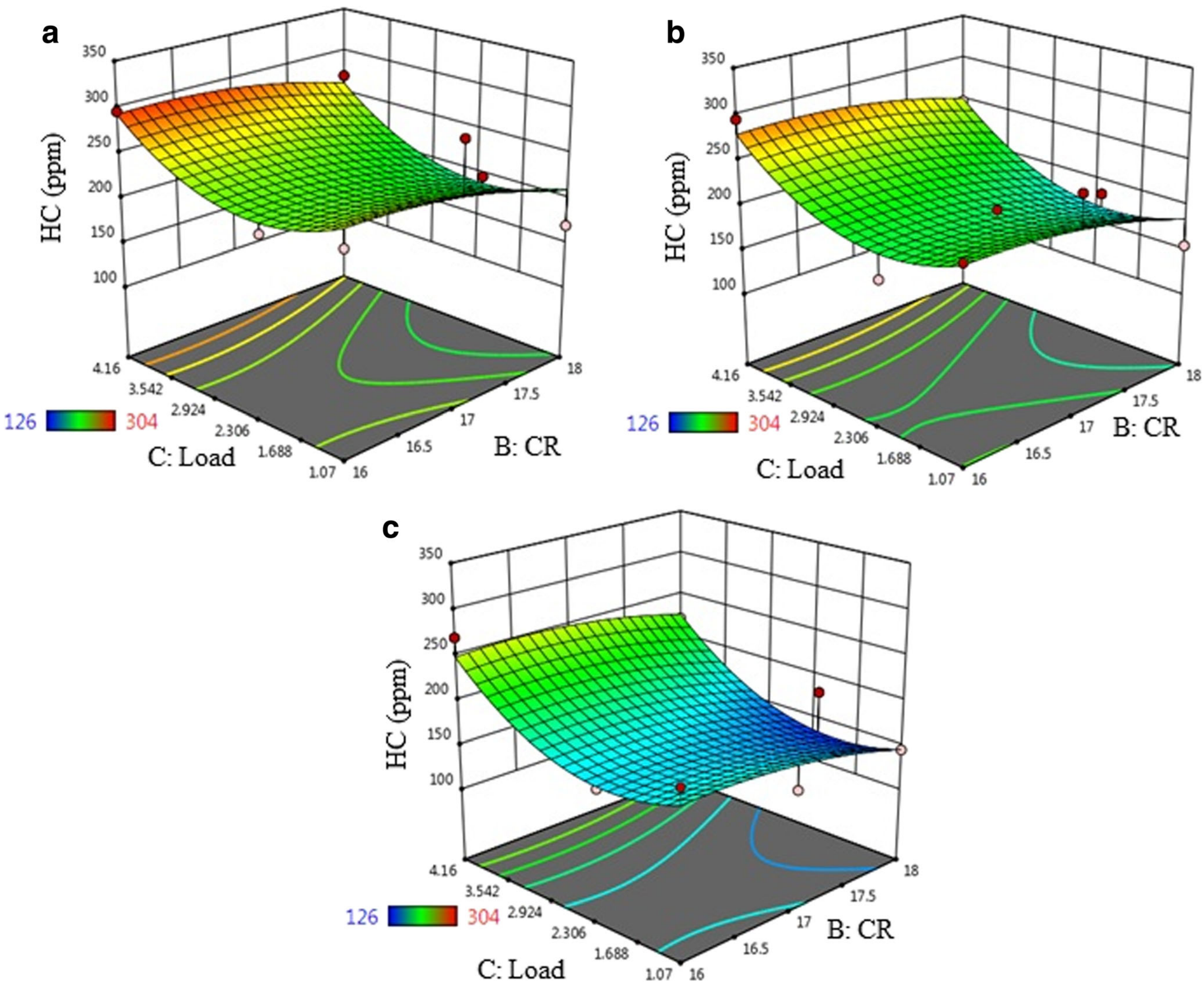


Fig. 7 Variation of HC against CR and load (**a**) at pentanol 10%, (**b**) at pentanol 15%, and (**c**) at pentanol 20%

The regression equation for HC emission is,

$$\text{HC (ppm)} = -2458.47 - 6.42*A + 356.51*B - 122.49*C + 0.45*AB + 0.96*AC + 1.97*BC - 0.31*A^2 - 11.33*B^2 + 17.93*C^2$$

Smoke emissions

The smoke emissions plotted against CR and load for three blends was shown in Fig. 8a–c. It can be seen from the plot that smoke emissions follow the same trend as CO and HC emissions. The smoke emission is occurred due to the soot concentration and unburned HCs available in the exhaust gases (Teoh et al. 2013). At all pentanol blends, the smoke emission is reduced with increasing CR. At lower CR the combustion will be incomplete which leads to higher smoke emissions and with an increase in CR, the in-cylinder temperature and pressure will be raised results in complete combustion and lower smoke emissions (Shameer et al. 2016). Because of the availability of the oxygen in the pentanol, with the increase in the pentanol level in the fuel blend the smoke emission is reduced (Ramakrishnan et al. 2018). The reduced smoke emission as the pentanol percentage is increased is also attributed because of the lower density and lower

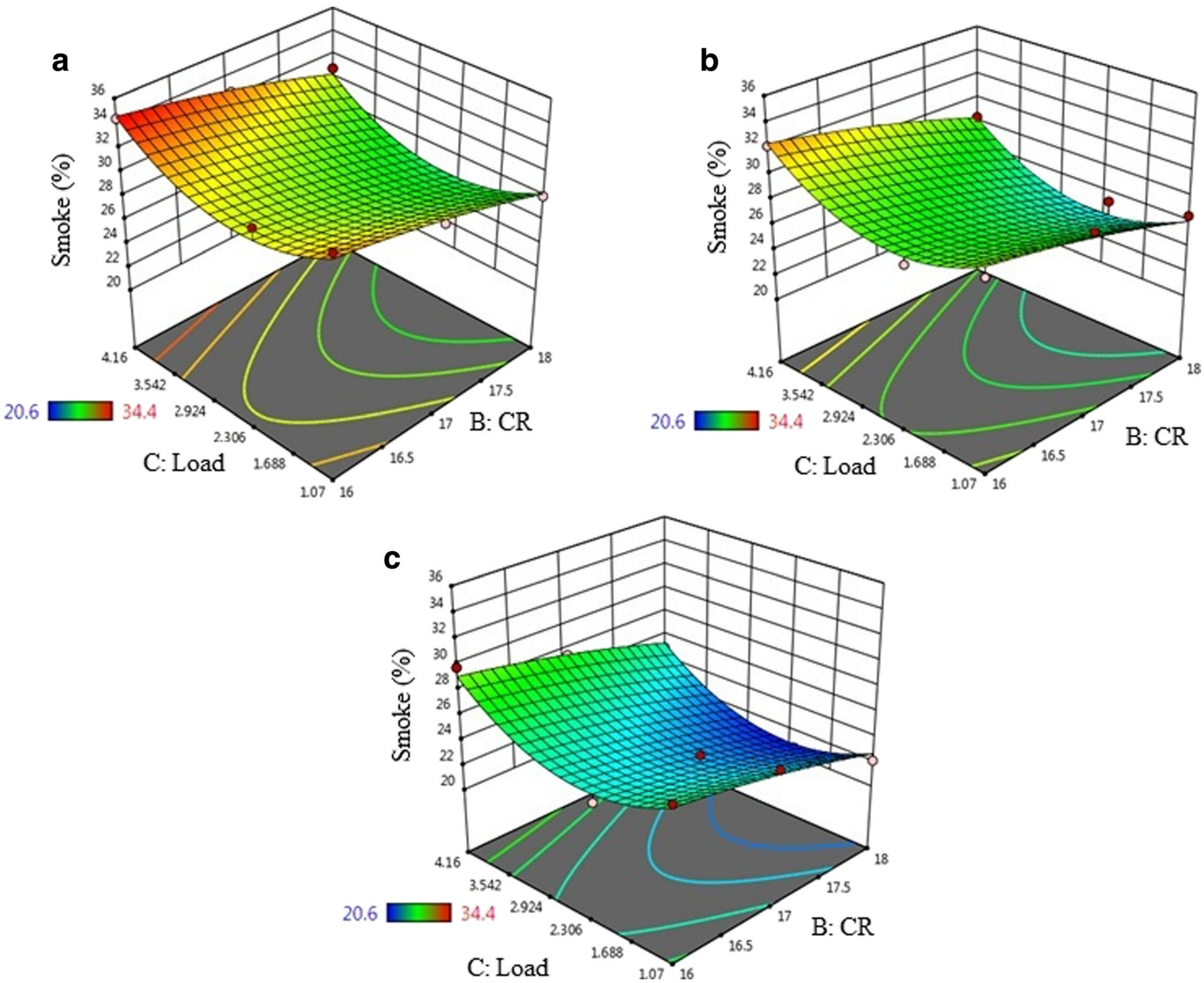


Fig. 8 Variation of smoke against CR and load (**a**) at pentanol 10%, (**b**) at pentanol 15%, and (**c**) at pentanol 20%

viscosity values of the pentanol (Qi et al. 2014). The higher smoke emission is 34.4% observed at 16:1 CR, P10C20 blend, and 4.16 bmep and the lower smoke emission are 20.6% at 18:1 CR, P20C20 blend, and 2.15 bmep loads.

The regression equation for the smoke emission is given as,

$$\text{Smoke}\ (\%) = -19.74 - 0.32*A + 9.11*B - 6.22*C + 0.023*AB + 0.021*AC + 0.0089*BC - 0.023*A^2 - 0.34*B^2 + 1.24*C^2$$

Conclusions

This study dealt with the optimization of the input parameters of a DI diesel engine with the use of pentanol/*Calophyllum inophyllum*/diesel blends as fuels to find the optimal input parameters of the engine using RSM. The optimized input parameters of the engine to get good performance and lowest emissions using pentanol/biodiesel/diesel fuel is found to be 17.5 CR, P20C20 blend, and 2.5 bmep load. The conclusions that are noted from the analysis are as follows:

1. The output responses BSFC, BTE, CO, CO_2, HC, NO_x, and smoke for this optimized input parameters are found to be 0.43 kg/kWh, 20.02%, 0.1%, 7.34%, 156.82 ppm, 1047.55 ppm, and 22.17%, respectively.
2. It is noted that the BSFC value is decreasing with increase in pentanol level in the blend whereas BTE value is increasing.
3. It is observed that the emissions CO, HC, and smoke are reducing with an increase in pentanol percentage in the blend whereas CO_2 and NO_x are increasing.

The RSM is demonstrated using design expert software to find the optimized input parameters to achieve the desired output parameters which give enhanced performance and emissions. The desired optimized input parameters were found and were used in carrying out validation experiment in the engine, which gives favorable results. Thus the RSM is found to be effective in finding optimized results in a multi-objective optimization of a diesel engine fuelled with pentanol/*Calophyllum inophyllum*/diesel blends.

References

Anand K, Sharma RP, Mehta PS (2011) Experimental investigation on combustion, performance and emission characteristics of neat karanji biodiesel and its methanol blend in a diesel engine. Biomass Bioenergy 35:533–541

Bharadwaz YD, Rao BG, Rao VD, Anusha C (2016) Improvement of biodiesel methanol blends performance in a variable compression ratio engine using response surface methodology. Alexandria Engineering Journal 55:1201–1209

Bora JB, Saha UK (2016) Optimisation of injection timing and compression ratio of a raw biogas powered dual fuel diesel engine. Appl Therm Eng 92:111–121

Bora JB, Saha UK, Chatterjee S, Veer V (2014) Effect of compression ratio on performance, combustion and emission characteristics of a dual fuel diesel engine run on raw biogas. Energy Convers Manag 87:1000–1009

Chen G, Yu W, Li Q, Huang Z (2012a) Effects of n-butanol addition on the performance and emissions of a turbocharged common-rail diesel engine. https://doi.org/10.4271/2012-01-0852

Chen Z, Liu J, Han Z, Du B, Liu Y, Lee C (2012b) Study on performance and emissions of a passenger-car diesel engine fueled with butanol/diesel blends. Energy 55:638–646

Choudhary AK, Chelladurai H, Kannan C (2015) Optimization of combustion performance of bioethanol (water hyacinth) diesel blends on diesel engine using response surface methodology. Arab J Sci Eng 40:3675–3695. https://doi.org/10.1007/s13369-015-1810-y

Dhingra S, Bhushan G, Dubey KK (2014) Multiobjective optimization of combustion, performance and emission parameters in a jatropha biodiesel engine using non dominated sorting genetic algorithm-II. Front Mech Eng 9:81–94

Eugene EE, Bechtold RL, Timbario TJ, McCallum PW (1984) State-of the-art report on the use of alcohols in diesel engines. SAE paper no.840118

Fattah IR, Kalam M, Masjuki H, Wakil M (2014) Biodiesel production, characterization, engine performance, and emission characteristics of Malaysian Alexandrian laurel oil. RSC Adv 4:17787–17796

Ganapathy T, Gakkhar RP, Murugesan K (2011) Optimization of performance parameters of diesel engine with Jatropha biodiesel using response surface methodology. International Journal of Sustainable Energy 30:S76–S90. https://doi.org/10.1080/14786451.2011.594889

Giakoumis EG, Rakopoulos CD, Dimaratos AM, Rakopoulos DC (2013) Exhaust emissions with ethanol or n-butanol diesel fuel blends during transient operation: a review. Renew Sust Energ Rev 17:170–190

Hirkude JB, Padalkar AS (2014) Performance optimization of CI engine fuelled with waste fried oil methyl ester-diesel blend using response surface methodology. Fuel 119:266–273

Ileri E, Karaoglan D, Atmanli A (2013) Response surface methodology based prediction of engine performance and exhaust emissions of a diesel engine fuelled with canola oil methylester. Journal of Renewable and Sustainable Energy 5(033132):1–19

Imtenan S, Masjuki H, Varman M, Kalam MA, Arbab MI, Sajjad H, Rahman SMA (2014) Impact of oxygenated additives to palm and jatropha biodiesel blends in the context of performance and emissions characteristics of a light-duty diesel engine. Energy Convers Manag 83:149–158

Kassaby MEL, Nemitallah MA (2013) Studying the effect of compression ratio on an engine fueled with waste oil produced biodiesel/diesel fuel. Alexandria Engineering Journal 52:1–13

Kesgin U (2004) Genetic algorithm and artificial neural network for engine optimization of efficiency and NOx emission. Fuel 8:885–895

Kocak MS, Ileri E, Utlu Z (2007) Experimental study of emission parameters of biodiesel fuels obtained from canola, hazelnut, and waste cooking oils. Energy Fuel 21:3622–3626

Lapuerta M, Armas O, Herreros JM (2008) Emissions from a diesel–bioethanol blend in an automotive diesel engine. Fuel 87:25–31

Lapuerta M, Contreras RG, Fernández JC, Dorado MP (2010) Stability, lubricity, viscosity, and cold-flow properties of alcohol-diesel blends. Energy Fuel 24:4497–4502

Namvar AM, Soltanieh M, Rashidi A, Irandoukht A (2008) Modeling and preparation of activated carbon for methane storage I. Modeling of activated carbon characteristics with neural networks and response surface method. Energy Convers Manag 49:2471–2477

Pamnani R, Vasudevan M, Vasantharaja P, Jayakumar T (2015) Optimization of AGTAW welding parameters for naval steel (DMR 249 A) by design of experiments approach. Proc Inst Mech Eng L J Mater Design Appl 231:320–331. https://doi.org/10.1177/1464420715596455. 12 pp

Pandian M, Sivapirakasam SP, Udayakumar M (2011) Investigation on the effect of injection system parameters on performance and emission characteristics of a twin cylinder compression ignition direct injection engine fuelled with pongamia biodiesel-diesel blend using response surface methodology. Appl Energy 88:2663–2676

Qi DH, Lee CF, Jia CC, Wang PP, Wu ST (2014) Experimental investigations of combustion and emission characteristics of rapeseed oil–diesel blends in a two cylinder agricultural diesel engine. Energy Convers Manag 77:227–232

Rakopoulos DC, Rakopoulos CD, Giakoumis EG, Dimaratos AM, Kyritsis DC (2010) Effects of butanol-diesel fuel blends on the performance and emissions of a high-speed DI diesel engine. Energy Convers Manag 5:1989–1997

Ramakrishnan P, Kasimani R, Peer MS, Rajamohan S (2018) Assessment of n-pentanol/*Calophyllum inophyllum*/diesel blends on the performance, emission, and combustion characteristics of a constant-speed variable compression ratio direct injection diesel engine. https://doi.org/10.1007/s11356-018-1566-5

Sahin Z, Aksu ON (2015) Experimental investigation of the effects of using low ratio n-butanol/diesel fuel blends on engine performance and exhaust emissions in a turbocharged DI diesel engine. Renew Energy 77:279–290

Sakthivel R, Ramesh K (2018) Analytical characterization of products obtained from slow pyrolysis of *Calophyllum inophyllum* seed cake: study on performance and emission characteristics of direct injection diesel engine fuelled with bio-oil blends. https://doi.org/10.1007/s11356-018-1241-x

Sakthivel R, Ramesh K, Purnachandran R, Shameer PM (2018) A review on the properties, performance and emission aspects of the third generation biodiesels. Renew Sust Energ Rev 82:2970–2992

Sayin C, Ertunc HM, Hosoz M, Kilicaslan I, Canakci M (2007) Performance and exhaust emissions of a gasoline engine using artificial neural network. Appl Therm Eng 27:46–54

Shameer PM, Ramesh K (2017a) Assessment on the consequences of injection timing and injection pressure on combustion characteristics of sustainable biodiesel fuelled engine. Renew Sust Energ Rev 81:45–61. https://doi.org/10.1016/j.rser.2017.07.048

Shameer PM, Ramesh K (2017b) FTIR assessment and investigation of synthetic antioxidant on the fuel stability of *Calophyllum inophyllum* biodiesel. Fuel 209:411–416. https://doi.org/10.1016/j.fuel.2017.08.006

Shameer PM, Ramesh K (2017c) Influence of antioxidants on fuel stability of *Calophyllum inophyllum* biodiesel and RSM-based optimization of engine characteristics at varying injection timing and compression ratio. Journal of Brazilian Society of Mechanical sciences and technology 39(11):4251–4273. https://doi.org/10.1007/s40430-017-0884-8

Shameer PM, Ramesh K (2017d) FTIR evaluation on the fuel stability of *calophyllum inophyllum* biodiesel: influence of tert-butyl hydroquinone (TBHQ) antioxidant. J Mech Sci Technol 31:3611–3617

Shameer PM, Ramesh K (2017e) Study on clean technology-assisted combustion behavior and NOx emission using thermal imager for alternate fuel blends. Int J Environ Sci Technol. https://doi.org/10.1007/s13762-017-1353-8

Shameer PM, Ramesh K, Sakthivel R, Purnachandran R (2016) Assessment on the influence of compression ratio on the performance, emission and combustion characteristics of diesel engine fuelled with biodiesel. Asian Journal of Research in Social Sciences and Humanities 6:344–372. https://doi.org/10.5958/2249-7315.2016.01297

Sharma A, Murugan S (2015) Potential for using a tyre pyrolysis oil-biodiesel blend in a diesel engine at different compression ratios. Energy Convers Manag 93:289–297

Teoh Y, Masjuki H, Kalam M, Amalina M, How H (2013) Impact of waste cooking oil biodiesel on performance, exhaust emission and combustion characteristics in a light-duty diesel engine. SAE Technical Paper. https://doi.org/10.4271/2013-01-2679

Win Z, Gakkhar RP, Jain SC, Bhattacharya M (2005) Parameter optimization of a diesel engine to reduce noise, fuel consumption and exhaust emissions using response surface methodology. Journal of Automobile Engineering 219:1181–1192

Xu H, Yin B, Liu S, Jia H (2017) Performance optimization of diesel engine fueled with diesel–jatropha curcas biodiesel blend using response surface methodology. J Mech Sci Technol 31:4051–4059

Yao M, Wang H, Zheng Z, Yue Y (2010) Experimental study of n-butanol additive and multi-injection on HD diesel engine performance and emissions. Fuel 89(9):2191–2201

Yilmaz N, Atmanli A (2017) Experimental evaluation of a diesel engine running on the blends of diesel and pentanol as a next generation higher alcohol. Fuel 210:75–82

Yilmaz N, Sanchez TM (2012) Analysis of operating a diesel engine on biodiesel–ethanol and biodiesel–methanol blends. Energy 46:126–129

Yilmaz N, Atmanli A, Trujillo M (2017) Influence of 1-pentanol additive on the performance of a diesel engine fueled with waste oil methyl ester and diesel fuel. Fuel 207:461–469

Zhang ZH, Balasubramanian R (2016) Investigation of particulate emission characteristics of a diesel engine fueled with higher alcohols/biodiesel blends. Appl Energy 163:71–80