Performance Optimization of Variable Compression Ratio Diesel engine fuelled with Waste Fried Oil Methyl Ester-diesel blends using Respose Surface Methodology

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***Abstract*—**This article investigates the effect of compression ratio & injection timing on the performance characteristics (brake thermal efficiency, brake specific fuel consumption) and emission characteristics (Exhaust gas temperature, Smoke opacity) of single-cylinder direct injection variable compression ratio diesel engine fuelled with various blends of waste fried oil methyl ester and mineral diesel. The statistical tool like response surface methodology is used to design experiment. A single cylinder 3.5 kW engine was selected for this experimentation. Optimization of compression ratio and injection timing was performed using desirability approach of RSM. The analysis of variance was performed to check the adequacy of the proposed model. A CR of 17.23, BX of 20%, and IT of 23.31^{0}BTDC were found to be optimal values for the Waste Fried Oil Methyl Esters (WFOME) blended with diesel fuel operation in the test engine of 3.5kW at 1500 rpm. The results of this study revealed that at optimal input parameters, the values of the BTE, BSFC, EGT and smoke opacity were found to be 27.12%, 0.313 kg/kW h, 278.93^{0}C and 66.86 HSU respectively.

Keywords- *Injection timing, Optimization, Performance, waste fried oil methyl ester(WFOME), Response surface methodolog.*

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I. INTRODUCTION

The alternate fuels have gained popularity over petroleum-based fuels in recent times due to depletion of world petroleum reserves and increased environmental concerns. Biodiesel produced from vegetable oil or animal fats by transesterification with alcohol like methanol and ethanol is recommended for use as a substitute for petroleum-based diesel mainly because biodiesel is an oxygenated, renewable, biodegradable and environmentally friendly bio-fuel with similar flow and combustion properties and low emission profile [1,2].

Alternative fuels for the diesel engines are becoming increasingly important due to the diminishing petroleum reserves and environmental consequences of the exhaust gases from petroleum fuelled engines. Biomass sources, particularly vegetable oils have attracted much attention as an alternative energy source. It is renewable, available everywhere and has proved to be a cleaner fuel and more environment friendly than the fossil fuels [3]. Direct synthesis via transesterification of vegetable oils will yield biodiesel [4]. One of the advantages of these fuels is reduced exhaust gas emissions. Experience has shown that vegetable oil based fuels can significantly reduce exhaust gas emissions, including carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter (PM) [5,6]. Because of their insignificant sulfur content, the sulfur dioxide (SO_2) emissions are low [7].

Waste frying oil transesterification was studied by Felizardo et al. [8] with the purpose of achieving the best conditions for biodiesel production. Zhang et al. [9] reported that the acid-catalyzed process using waste cooking oil has proved to be technically feasible with less complexity than the alkali-catalyzed process using waste cooking oil. Al-Widyan Mohammad et al. studied the use of ethyl ester of waste vegetable oil and diesel blends in proportions of 75/25, 50/50, and 25/75 as fuel in a naturally aspirated direct injection diesel engine tested at different speeds. The fuel economy was observed to be better. They concluded that the 75/25 blend of the esters of waste cooking oil and diesel gives the best performance [10]. Puhan et al. evaluated the performance of mahua biodiesel in a 3.7 kW Kirloskar make, single cylinder, four stroke, direct injection, constant speed diesel engine. The specific fuel consumption and thermal efficiency were 20% higher and 13% lower respectively than that of diesel [11]. Reefat et al. tested a 40% blend of biodiesel from WFO with mineral diesel, they observed BTE of 28%, BSFC of 0.31 kg/kWh and EGT of 500 °C. BTE was lower by 8% while BSFC and EGT were higher by 9% and 7% respectively compared to petroleum diesel [12].

The RSM is most applicable to processes where several variable potentially influence some performance characteristics or quality characteristics of the process. RSM has been applied for optimization of several chemical and physical processes [13-15]. Initially, RSM was developed to model experimental responses and then migrated into the modeling of numerical experiments [16]. Win et al. optimized parameters like load, speed and static injection timing of a diesel fueled CI engine to reduce noise, fuel consumption and exhaust emissions by using RSM [17]. Lee and Reitz used RSM to optimize a high speed DI diesel engine equipped with a common rail injection system neglecting the interactive effects of the parameters [18]. Satake et al. performed optimization of the fuel injection control of diesel engines using RSM [19]. Hirkude et al. optimized performance of the CI engine using RSM considering 40% biodiesel blended fuel[20].

As seen in literature review CR, IT and volumetric percentage of the biodiesel (BX%, where X represent biodiesel % in the blended fuel) in blended fuel influences performance and exhaust emission parameters. Some researchers have studied effect of these parameters independently. Combined effects of operating parameters such as CR and injectionparameters like

IT and IP on the smoke emissions and performance of a diesel engine using Waste Fried Oil Methyl Esters (WFOME)–blended diesel fuel have not been studied in detail. Therefore this study highlights the combined effects of CR, IT and different blends of fuels (B20, B40, B60) on the engine performance and smoke emissions by using RSM. The other objective of the present work is to investigate appropriate input parameters (CR, BX and IT) for optimal output response parameters (BTE, BSFC, EGT and OP) to design CI engines for specific biodiesel. Optimization of input parameters was performed by using desirability approach of RSM.

II. EXPERIMENTAL DETAILS

A. Fuel Preparation

As seen in initial investigation optimization if the engine done considering only on proportion of blend. The biodiesel produced through transesterification process from waste fried oil was blended with diesel, procured from a commercial vendor. A volume ratio of 20:80, 40:60 and 60:40 is used to get the biodiesel–diesel blend of B20, B40 and B60 respectively. To ensure a homogeneous mixture the blending was done just before beginning of the experiments. The properties of the fuel blends (B20, B40 and B60) and diesel have been determined as per the ASTM standards in chem-tech laboratories, Pune. The properties are tabulated in Table I.

B. Engine Setup

The experiments are conducted in a single cylinder, four stroke, direct injection variable compression ratio (VCR) diesel engine (Kirloskar make, India). The engine is connected to a hydraulic cooling type eddy current dynamometer for loading. A tilting cylinder block arrangement is used to vary the CR without stopping the engine and altering the combustion chamber geometry. The brief engine specification are: bore 87.5 mm, stroke 110 mm, CR range 12–18, capacity 661 cc (at standard CR 18), IT range 0-25 ^{0}BTDC. The engine produces 3.5 kW of rated power with diesel at full load (4.24 bar BMEP) at a rated speed of 1500 rpm. The optical crank-angle sensor delivers a signal for each degree rotation of crank shaft. These signals are then interfaced to computer through engine indicator to measure rpm of the engine. A total of six thermocouples (four PT100 type and two K type) are installed at various locations of the setup for measurement of water and exhaust gas temperature. The setup has a stand-alone panel box consisting of air box, fuel tank, manometer, fuel measuring burette. The fuel measurement is performed by differential pressure transducer (Yokogawa make, Model No: EJA110A-DMS5A-92NN).

The VCR engine is first run using diesel at standard diesel specification; CR of 18 and IT of 23 ^{0}BTDC at full load (3.5kW). When the full load condition (4.24 bar BMEP) is achieved, the engine is allowed to run for few minutes and the temperatures at the outlet of cooling water and exhaust gas are monitored closely at the computer display until it reaches a steady state condition.Thereafter, the engine is brought back to no load condition slowly and allowed to run for few minutes. Later, all blends aretested in the VCR engine at various CRs and ITs.

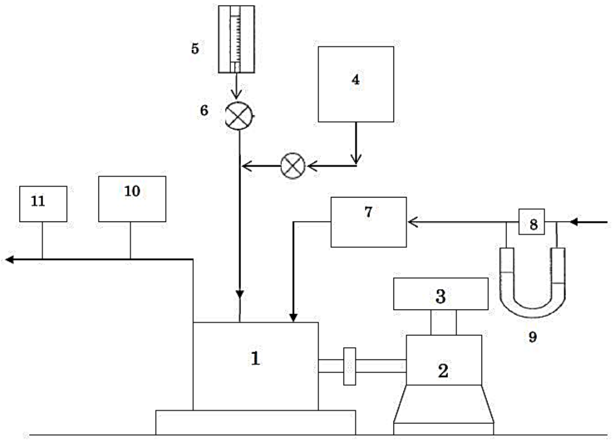


Figure 1. Schematic diagram of experimental setup (1) engine (2) alternator (3) electrical load bank (4) fuel tank (5) burette (6) two way control valve (7) air box (8) orifice plate (9) U tube manometer (10) exhaust gas thermocouple, and (11) smoke meter.

The VCR engine allows online modification of CR variation. The CRs under investigation are 16 and17 along with the standard CR of 18. Initially, the engine is set at CR of 18 and IT of 23^{0}BTDC forblended fuel test. Once the data are recorded at this particular setting, the CR is changed by rotating the CR adjustor knob. Once all the CRs at 23^{0}BTDC are tested, the engine is then allowed to run at other ITs by rotating the injection point adjustment nut. Thereafter, for each IT, the engine is tested at all the CRs. The appropriate IT is confirmed from the fuel pressure data. The same process as discussed above is repeated to study other IT before complete shutdown.

The Smoke Opacity (OP) was measured by using smoke meter (make: AVL India Pvt. Ltd.; Model Name: AVL437 smoke meter). The smoke opacity was measured in Hartridge Smoke Unit (HSU).

All tests were conducted at electrical loading of 3.5 kW (full load capacity). All together 27 tests were conducted by varying CR at three levels (16, 17and 18), IT at three levels (20^{0}BTDC, 23^{0}BTDC and 25^{0}BTDC). All tests were conducted for fuel blends of B20, B40 and B60. Uncertainty analysis of measured and calculated parameters is presented in Table II.

TABLE I. PROPERTIES OF FUEL BLENDS.

Properties	B20	B40	B60	Diesel	Method
Viscosity at 40 ^{0}C (cSt)	4.94	5.56	6.18	4.320	ASTM D445
Specific gravity	0.838	0.846	0.854	0.830	ASTM D941
Calorific value (kJ/kg)	42200	41,400	40600	43,000	ASTM D240
Flash point (^{0}C)	95	120	145	70	ASTM D93

C. Response Surface Methodology

RSM was applied 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 used 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 III. The responses such as BTE, BSFC were evaluated where as EGT and OP was measured. The experimental readings were fitted to the second order polynomial equation using design expert software.A multiple regression analysis was carried out to obtaincoefficientsandthe 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.

TABLE II. ACCURACY AND UNCERTAINTY ANALYSIS

Measured quantity	Accuracy	Calculated quantity	Uncertainty
Viscosity	±0.2 cSt	Brake power	±2%
EGT	±1 C	BSFC	±2.15%
Smoke opacity	±1 HSU	Specific gravity	±1.5%
Calorific value	±0.15 MJ/ kg	–	–
Speed	±30 rpm	–	–

Finally the optimal values of engine operating parameters were evaluated by using the desirability based approach of RSM.

D. 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.

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 [21].

TABLE III. DESIGN MATRIX

Std	Run	BX (%)	CR	IT (^{0}BTDC)	BTE (%)	BSFC (kg/kW h)	OP (HSU	EGT (^{0}C)
1	1	20	16	20	24.99	0.348	73	255.64
2	2	20	16	23	26.09	0.333	70	267.16
3	3	20	16	25	25.5	0.341	68	263.11
4	4	20	17	20	25.88	0.336	71	273.11
5	5	20	17	23	27.27	0.319	68	277.11
6	6	20	17	25	25.86	0.329	66	278.24
7	7	20	18	20	26.27	0.331	68	282.47
8	8	20	18	23	27.78	0.313	65	286.37
9	9	20	18	25	26.67	0.326	63	288.44
10	10	40	16	20	24.31	0.363	75	268.91
11	11	40	16	23	25.22	0.35	72	270.65
12	12	40	16	25	24.24	0.364	70	272.38
13	13	40	17	20	25.5	0.346	72	279.34
14	14	40	17	23	26.47	0.333	69	280.44
15	15	40	17	25	25.12	0.342	67	282.67
16	16	40	18	20	26.03	0.339	69	288.64
17	17	40	18	23	27.67	0.319	66	290.18
18	18	40	18	25	26.33	0.335	64	292.64
19	19	60	16	20	23.88	0.375	76	270.11
20	20	60	16	23	24.57	0.364	73	274.16
21	21	60	16	25	24.07	0.372	71	278.4
22	22	60	17	20	24.94	0.259	73	280.64
23	23	60	17	23	25.74	0.348	70	285.22
24	24	60	17	25	24.8	0.353	68	288.84
25	25	60	18	20	25.58	0.35	70	290.12
26	26	60	18	23	26.87	0.33	67	296.48
27	27	60	18	25	26.19	0.342	65	298.33

III. RESULT AND DISCUSSION

A. Analysis and Evaluation of Model

The Analysis of Variance (ANOVA) was used to verify model adequacy which provides numerical information about F 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. (1)-(4). These equations are valid for input variables levels range from 16 to 18 for CR, 24–30 BTDC for IT and 20-60% for biodiesel blend percentage. 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 16≤CR≤18 would translate to coded range of $-1 \le CR_c \le 1$. The general equation used to translate from coded to actual is given below as eq.(5)

$$BTE = +26.43 - 0.54 * A + 0.91 * B + 0.078 * C + 0.16 * A * B - 0031 * A * C + 0.071 * B * C + 0.065 * A^2 - 0.050 * B^2 - 1.09 * C^2 \quad (1)$$

$$BSFC = +0.33 + 5.899 * 10^{-3} * A - 0.012 * B + 3.167 * 10^{-3} * C - 3.083 * 10^{-3} * A * B + 9.013 * 10^{(-3)} * A * C - 8.224 * 10^{-4} * B * C - 6.278 * 10^{3} * A^2 + 0.015 * B^2 + 8.356 * 10^{-3} * C^2 \quad (2)$$

$$OP = +69.61 + 1.17 * A - 2.83 * B - 2.50 * C - 0.25 * A * B - 0.17 * A^2 - 0.17 * B^2 \quad (3)$$

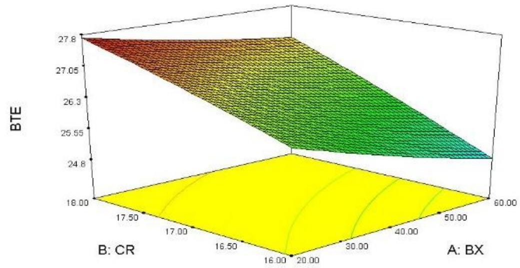
$$EGT = +281.58 + 5.01 * A + 10.74 * B + 3 * C - 0.76 * A * B + 0.42 * A * C - 0.14 * B * C - 0.99 * A^2 - 0.95 * B^2 - 0.73 * C^2 \quad (4)$$

$$X_{actual} = X_{min} + \left[\frac{X_{coded} + 1}{2} * (X_{max} - X_{min})\right] \quad (5)$$

where$x_{actual}$is the actual value, $x_{min}$and $x_{max}$are the actual minimum and maximum values (corresponding to 1 and +1 coded values), and $x_{coded}$is the coded value to be translated. A, B and C are coded values for BX, CR and IT respectively. It may be noted from Eq. (5) 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: CR = 17, BX = 40 and IT = 22.5 ^{0}BTDC. 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 BTE = 26.43%, BSFC = 0.33 kg/kW h, EGT = 281.58 ^{0}C and OP = 69.61 HSU.

B. Interactive effect of CR and BX

BTE at different CRs and BXs is depicted in a three dimension plot (Fig. 2a). As seen in figure, for all BXs, the BTE increases with increase in CR (from 16 to 18). At IT of 23 ^{0}BTDC and BX of 40% increase CR from 16 to 17 and from 17 to 18 increased BTE by 4.95%, and 4.53% respectively. Initial increase in BTE with increase in CR could be attributed to enhancement of density of intake air and reduction in ignition delay associated with it. The change in BSFC at different BXs and CRs is presented in Fig. 2b. As illustrated in figure the BSFC was found decreasing with increase in CR from 16 to 18. The possible reason for this trend could be that, with an increase in CR, the maximum cylinder pressure increases due to the fuel injected in hotter combustion chamber and this leads to higher effective power. Therefore, fuel consumption per output power will decrease. The variation of EGT for different CRs and BXs is shown in Fig. 2c. At higher CRs increase in EGT was observed and the possible reason for this could be higher operating temperature at elevated CRs. The interactive effect of CR and IP on OP is depicted in Fig. 2d. Smoke emissions at higher CRs were observed lesser than at lower CRs. This could be because of better combustion efficiency due to higher temperature and pressure at higher CRs.



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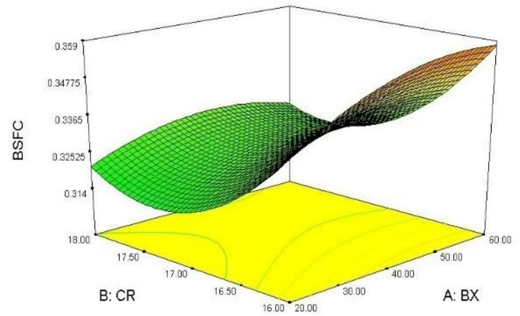

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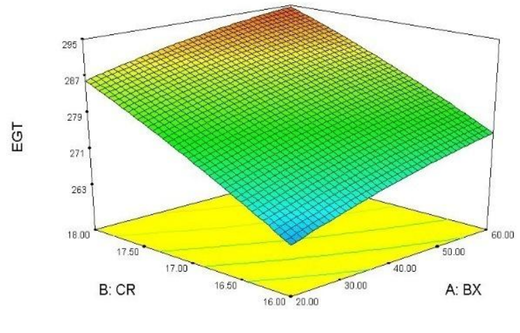

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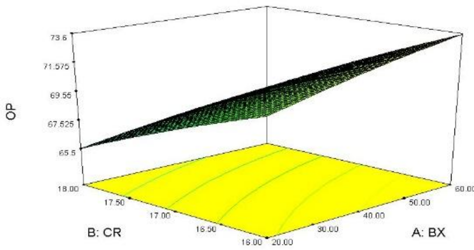


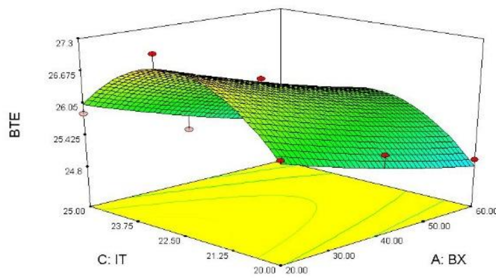
(d)

Figure 2. Interactive effects of CR and BX

C. Interacive effect of BX and IT

As seen in Fig. 3a, the BTE decreases with increase in BX. Higher fuel percentage of biodiesel in fuel blend decrease the degree of atomization as the viscosity of blend increases. The fineness of atomization is reduces and ignition delay increases, due to lower surface volume ratio. At 23 ^{0}BTDC and CR of 18 with increase in BX from 20 to 40%, average BTE decreased by 0.4%. Further, increase in BX from 40 to 60%, leads to decrease in BTE by 2.89%. This could be because of decreased spray characteristics, bad atomization and mixing with air at higher BXs. This will decrease efficiency because of less efficient combustion process. Fig. 3b demonstrates the change in BSFC at different BXs and ITs. The increased BSFC values were obtained with increase in BX (from 20 to 60 %). This could be because lower calorific value of fuel.

Variation in EGT with different IPs and ITs is shown in Fig. 3c. There was increase in EGT with increase in BX. This may be attributed to the increased cylinder pressure in latter stages of combustion due to less volatile nature of biodiesel which leads to increase in temperature. Fig. 3d explains variation in OP at different BXs and ITs. Increase in OP with increase in BX was observed. This could be, as a result of incomplete combustion due to bad atomization of blended fuel.



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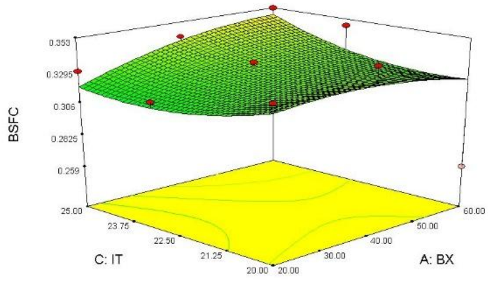

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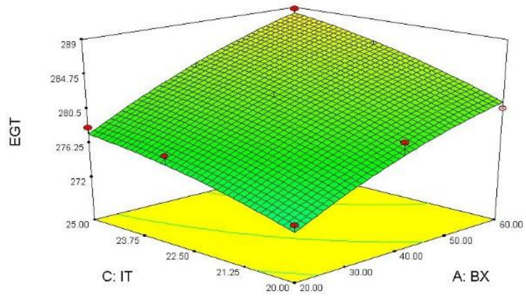

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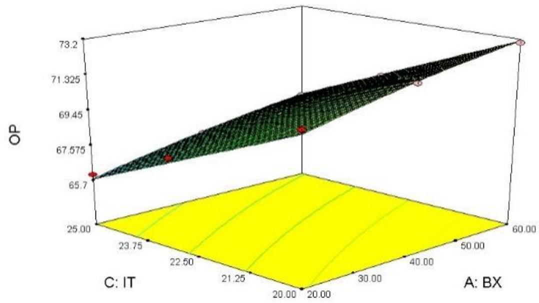

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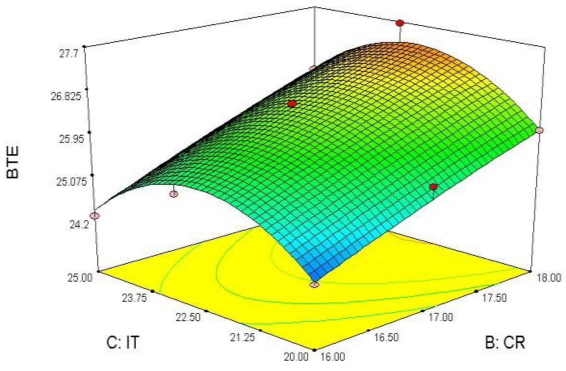
Figure 3. Interactive effects of BX and IT

D. Interactive effect of CR and IT

The change in BTE at different ITs and CRs is observed in Fig. 4a. BTE decreases with advancement of IT from 23 ^{0}BTDC to 25 ^{0}BTDC, even retardation of IT from 23 ^{0}BTDC to 20 ^{0}BTDC leads to decrease in BTE. This can be attributed to increase ignition delay associated with increase in injection time angle. Whereas retardation of injection timing by 3 (20 BTDC) decreases delay period which could lessen the brake power due to burning of larger quantity of fuel during expansion.

The variation of BSFC for different CRs and ITs is shown in Fig. 4b. At CR of 18 and BX of 40% with increase in IT from 20 to 23 ^{0}BTDC leads to decrease in average BSFC by 5.89%. While further increase in IT from 23 to 25 ^{0}BTDC resulted in increase in BSFC by 5.02%. With advancement of IT from 23 ^{0}BTDC to 25 ^{0}BTDC the ignition delay would be longer and flame speed may be lower. These cause reduction in brake power. But retardation of IT from 23 ^{0}BTDC to 20 ^{0}BTDC leads to late combustion and therefore pressure rises at a later stage of the expansion stroke. These cause reduction in effective pressure which could be responsible for reduction in brake power and reduction in BSFC.

Fig. 4c illustrates effects of IT and CR on EGT. As seen in Fig. 4c, decrease in EGT was observed with increase in IT. Advancement of injection timings may lead to an early start of combustion relative to TDC which increases chances of complete combustion and reduces the EGT [2]. Fig. 4d explains the variation of OP for different ITs and CRs. Because of advancement of injection timings from 20 ^{0}BTDC to 25 ^{0}BTDC, OP was reduced. Finer break up fuel droplets obtained with increased IP provide more surface area and better mixing with air and this effect improves combustion. As the pressure and temperature at the beginning of the injection are lower for higher ignition advance, the delay period increases with increase in injection advance. This could be attributed to the following fact: advancement of injection timing means extended ignition and decrease in charge temperature and pressure.



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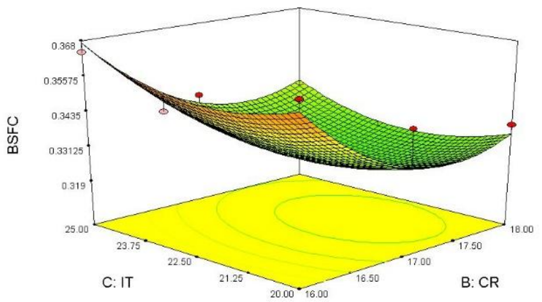

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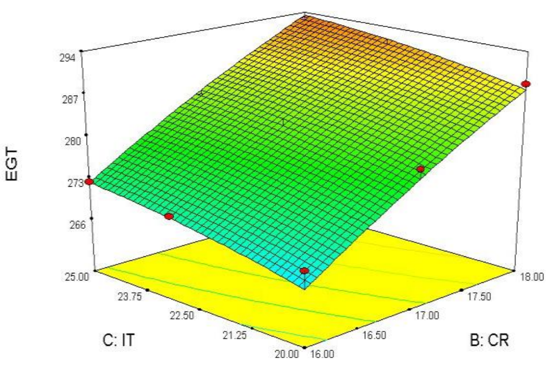

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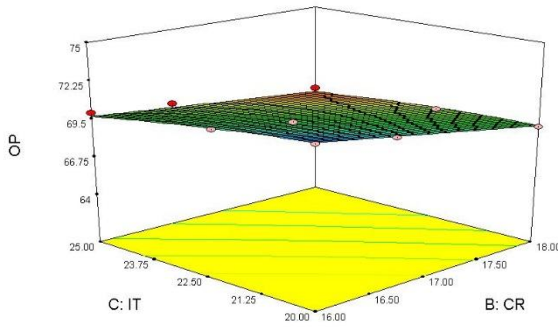

(d)

Figure 4. Interactive effects of CR and IT

E. Optimization

The comprehensive discussions on the effect of CR, BX and IT on performance and smoke emission characteristics have shown that the lowest BX of 60%, retarded IT of 20 ^{0}BTDC and CR of 16resulted in low values of BTE and EGT with high values of BSFC and OP. An BX of 60% with an IT of 23 ^{0}BTDC and CR of 18 caused higher BTE and EGT with lower values of BSFC and OP. Optimization of individual performance and emission parameters for independent input variables like CR, BX and IT are tabulated in Table IV.

As there was a trade-off between BTE, BSFC, OP and EGT, it was necessary to optimize the CR, BX and IT with the goal of minimizing smoke emission and maximizing the BTE without compromising BSFC and EGT. The criteria for the optimization such as the goal set for each response, lower and upper limits used, weights used and importance of the factors is shown in Table V. In desirability based approach the solution with high desirability was favored. Maximum desirability of 0.952 was obtained at CR of 17.23, IT of 23.31^{0}BTDC and BX of 20%, which could be considered as the optimum parameters.

TABLE IV. OPTIMIZATION OF INDIVIDUAL PARAMETER

Parameter	Optimized value	Criteria	CR	BX	IT (^{0}BTDC)	Desirability
BTE (%)	27.499	Maximize	17.65	20	22.61	0.95
BSFC (kg/kWh)	0.313	Minimize	17.33	20	23.43	0.952
EGT (^{0}C)	275.154	Minimize	16.83	20	24.42	0.948
OP (HSU)	66.41	Minimize	17.65	20	22.61	0.95

TABLE V. OPTIMIZATION CRITERIA AND DESIRABILITY OF RESPONSES FOR PERFORMANCE PARAMETERS.

Parameter	Limits		Weight		Importance	Criterion	Desirability
	Lower	*Upper*	*Lower*	*Upper*			
BX (%)	20	40	1	1	3	In range	1
CR	16	18	1	1	3	In range	1
IT (^{0}BTDC)	20	25	1	1	3	In range	1
BTE (%)	23.88	27.78	0.1	1	5	Maximize	0.993
BSFC (kg/kWh)	0.259	0.375	1	0.1	5	Minimize	0.935
EGT	255.64	298.33	1	0.1	5	Minimize	0.970
OP	63	76	1	0.1	5	Minimize	0.904
Combined	-	-	-	-	-	-	0.95

F. *Conclusions*

In this study biodiesel from waste fried oil blended with mineral diesel was used to investigate effects of significant operating parameters like CR, IT and BX on performance and emission of compression ignition engine. Based on the results of this study the following conclusion can be drawn.

1. RSM based design of experiments was used to design and carryout 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.
2. Increase in compression ratio increases brake thermal efficiency for all proportion biodiesel blend and injection timings of the engine Maximum brake thermal efficiency was observed with original engine injection timing.
3. Decrease in BSFC was observed with increase in CR (from16 to 18). Minimum BSFC was observed at original injection timing of 23 ^{0}BTDC. With increase in BX there was decrease in BSFC.
4. EGT was found to increase with increase in CR and BX, while EGTwas observed decreasing with increase in IT. OP was reduced at higher CR. It was seen that advancement in injection timing lead to reduced smoke emissions. Increasein OP with increase in BX was also observed.
5. At optimum input parameters viz. CR of 17.23, BX of 20 % with IT of 23.31^{0}BTDC, the values of the BTE, BSFC, EGT and smoke opacity were found to be 27.12%, 0.313 kg/kW h, 278.93 C and 66.86 HSU respectively.

By properly controlling CR, BX and IT, performance can beimproved and smoke emissions can be controlled by using a blend of alternate fuel like biodiesel from waste fried oil.

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