ISSN 2395-1621

Effect of Compression Ratio and Injection Timing on Performance and Emission of Biodiesel-diesel blend fuelled Diesel engine

#1Vivek Lande, #2Atul Elgandelwar

1viveklande808@gmail.com

2atul.elgandelawr@mitpune.edu.in

#12Mechanical Department, Maharashtra Institute of Technology
Pune, Maharashtra, India

ABSTRACT

The present work is set to explore the effect of compression ratio (CR) and injection timing (IT) on performance characteristics, emissions and thermodynamic potential of Waste fried oil methyl ester (WFOME)-diesel blends run diesel engine. Parameters considered to optimize the diesel engine are brake thermal efficiency (BTE), Brake specific fuel consumption (BSFC), smoke opacity (OP) and exhaust gas temperature (EGT). Side by side thermodynamic analysis is also carried out to derive energy and exergy potential of the various Biodiesel-diesel blends. Experiments are carried out in water cooled, single cylinder variable compression ratio diesel engine at constant speed of 1500 rpm under full load of 3.5 kW. The study involves three different CRs of 16, 17 and 18; and three different ITs of 20, 23 and 250 BTDC; and three different biodiesel-diesel blends of B20, B40 and B60 (BX% where X is volumetric percentage of biodiesel in blend). Here the CR of 18 and IT of 23^0 BTDC are the standard values. To design experiment and to optimize, desirability approach of statistical tool like RSM is used. 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 0BTDC were found to be optimal values for the biodiesel-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 OP were found to be 27.12%, 0.313 kg/kW h, 278.93 0C and 66.86 HSU respectively. It shows that higher values of CR increase the shaft availability and cooling water availability, however, they decrease the exhaust flow availability. The entropy generation is also reduced for the similar CR and IT modifications.

***Keywords*— Analysis of Variance, Energy, Exergy, Optimization, Thermodynamic analysis, Waste fried oil methyl ester, Response surface methodology.**

ARTICLE INFO

Article History

Received :18th November 2015

Received in revised form :

19th November 2015

Accepted : 21st November , 2015

Published online :

22nd November 2015

I. INTRODUCTION

Now a-days not only conventional fuels power IC engine, but also various renewable alternative fuels viz. biofuels, biogas, natural gas, hydrogen etc. are also made use of fuel. Biofuels, especially the methyl and ethyl esters of vegetable oils, popularly known as 'biodiesels', have an important contribution. This is because of the need to reduce the use of fossil fuels in diesel engines without modifying them [1, 2]. Biodiesels are oxygenated fuels and can be used in diesel engines to improve combustion efficiency. The internal combustion (IC) engines are the building blocks of modern civilization. This is because of their capability to convert chemical energy of fuel into heat and mechanical energy. 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 [3, 4].

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 [5]. Direct synthesis via transesterification of vegetable oils will yield biodiesel [6]. One of the advantages of these fuels is reduced exhaust gas emissions.

Parameters such as compression ratio (CR), Injection timing (IT), injection pressure (IP) and volumetric percentage of biodiesel in blend (BX%, where X represent biodiesel % in the blended fuel) have influence on engine performance and emission characteristics of engine. Various authors have studied their effects using different methodology and different fuel combination. Interactive effects also have been studied.

As seen in literature CR, IT and volumetric percentage of the biodiesel 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 injection parameters like IT and IP on the smoke emissions and performance of a diesel engine using Waste Fried Oil Methyl (WFOME). Response surface methodology is used to optimize engine fuelled with B40 blend of WFOME-Diesel [7]. Optimization considering different blends of biodiesel-diesel is not studied extensively. In order to study effective utilization of energy, terminologically 'thermodynamic analysis' of biodiesel run IC engines is necessary. However, biodiesels have a comparatively lesser calorific value than diesel, which causes lower power and efficiency [8]. This can be improved by raising the CR. This work optimize engine performance considering emission constraint and provide methodology for thermodynamic analysis considering optimised parameter.

II. Objective

The optimization of diesel engine fuelled with WFOME-diesel blend using response surface methodology (RSM). Also theoretical investigation on the effective distribution of energy at various components of IC engine has been done by coupling the first and the second laws of thermodynamics together. The details study of literature unfurls the fact that the effect of engine design and operating parameters viz., CR and IT variation are not optimized considering different blends and its effects on energy and exergy distribution of a diesel engine running with WFOME-diesel blend is not clear. However, in order to establish WFOME as an alternative to diesel fuel, it is necessary to uncover the methodology to carry out optimization and the effect of engine design and operating parameters on thermo mechanical energy–exergy distribution. In this context, experiments are performed in a WFOME-diesel blends (B20, B40, B60) run diesel engine at full load condition for a set of CR and IT. The CRs of 16, 17 and 18 and ITs of 20, 23 and 25 BTDC are considered for the experimentation. The results obtained from the tests are then analyzed to explore the optimized condition for test engine. Also energy and exergy potential are explored for different processes in engine setup.

III. 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 0BTDC. The engine produces 3.5 kW of rated power with diesel at full load (12 kg) 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 0BTDC at full load (3.5kW). When the full load condition (12 kg) 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 are tested in the VCR engine at various CRs and ITs.

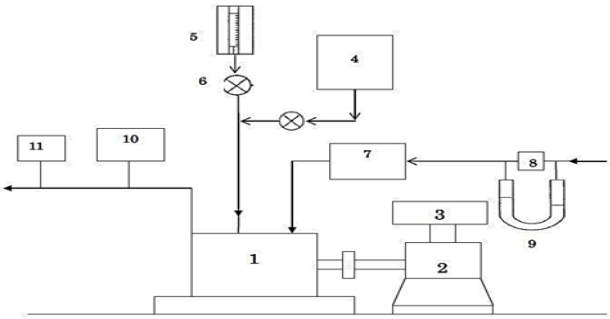


Figure 1. Schematic diagram of experimental setup (1) engine (2) alternator (3) electrical load bank (4) fuel tank (5) burette (6) two way control valve (7) air box (8) orifice plate (9) U tube manometer (10) exhaust gas thermocouple, and (11) smoke meter.

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 0BTDC for blended 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 0BTDC 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 tests were conducted by varying CR at three levels (16, 17and 18), IT at three levels (20 0BTDC, 23 0BTDC and 25 0BTDC). All tests were conducted for fuel blends of B20, B40 and B60.

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

D. Thermodynamic Analysis Methodology

The sequence of events happening in the engine operation can be identified as fuel and air entrainment, combustion, conversion of chemical energy into mechanical work, heat loss through cooling water, friction, radiation, surroundings and exhaust gas [9]. Further it is assumed that the combustion air and exhaust gases are ideal gas mixtures and their potential and kinetic energy changes are minor [10]. Reference atmospheric conditions are considered as 1 atm and 28 ^{0}C of pressure (Pamb) and temperature (Tamb). The basic equations used for performance calculations are as follows;

- Brake power (BP):

$$BP = (2 \times \pi \times N \times W \times r)/60000, kW \quad (1)$$

Where N is speed of engine in RPM, W is dynamometer load in N and r is the dynamometer arm radius in m.

- Brake thermal efficiency (BTHE):

$$BTHE = \left[\frac{BP}{\dot{m}_f \times LHV_f}\right] \times 100, \% \quad (2)$$

where BP is the brake power of the engine in kW, $\dot{m}_f$ is the mass flow rate of fuel in kg/s and LHV_f is the lower heating value of the fuel in kJ/kg.

Energy Analysis

In compression ignition (CI) engine, the fuel energy supplied per unit time (Q_{in}) is transferred in its different processes, viz. shaft power (Q_s), energy in cooling water per unit time (Q_w), energy in exhaust gas per unit time (Q_e) and uncounted energy losses per unit time (Q_u) in the form of friction, radiation, heat transfer to the surrounding, operating auxiliary equipment's, etc. These different forms of energies are calculated according to the following analytical expressions [11].

- Fuel energy supplied per unit time (Q_{in}):

$$Q_{in} = \dot{m}_f \times LHV_f, kW \quad (3)$$

- Shaft power (Q_s):

$$Q_s = Brake\ power\ of\ engine,\ kW \quad (4)$$

- Energy in cooling water per unit time (Q_w):

$$Q_w = [\dot{m}_{we} \times C_{pw} \times (T_{woe} - T_{wie})], \quad kW \qquad (5)$$

where $\dot{m}_{we}$ is the mass flow rate of cooling water in kg/s passing through engine jacket, Cpw is the specific heat of water in kJ/kg K and Twie and Twoe are the inlet and outlet temperature of cooling water passing through engine jacket.

- Energy in exhaust gas per unit time (Q_e):

$$Q_e = [(\dot{m}_f + \dot{m}_a) \times C_{pe} \times (T_{eic} - T_{eoc})], \quad kW \qquad (6)$$

Where $\dot{m}_a$ is the mass flow rate of air in kg/s, specific heat of exhaust gas (Cpe) is obtained from the energy balance of the flows passing through the calorimeter, as follows:

$$C_{pe} = \frac{[\dot{m}_{we} \times C_{pw} \times (T_{woe} - T_{wie})]}{[(\dot{m}_f + \dot{m}_a) \times (T_{eic} - T_{eoc})]}, \quad kJ/kg\ K \qquad (7)$$

where $\dot{m}_{wc}$, Twic and Twoc are the mass flow rate, inlet and outlet temperature of the cooling water passing through the calorimeter and Teic and Teic are the inlet and outlet temperatures of exhaust gas passing through calorimeter.

TABLE II. 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

- Uncounted energy losses per unit time (Q_u):

$$Q_u = [Q_{in} - (Q_s + Q_w + Q_e)], \quad kW \tag{8}$$

Exergy analysis

The availability can be described as the ability to perform useful amount of work by the supplied energy [31]. In the CI engine the availability of fuel (Ain) supplied is converted into different types of exergy, viz., shaft availability (As), cooling water availability (Aw), exhaust gas availability (Ae) and destructed availability (Ad) in the form of friction, radiation, heat transfer to the surrounding, operating auxiliary equipment's, etc. These forms of energies are calculated according to the following analytical expressions as described in the literature [12, 13].

- Input availability of fuel (A_{in}):

$$A_{in} = [\dot{m}_f \times LHV_f \times \{1.041 + 0.1728(H/C) + 0.0432(O/C) + 0.2169(S/C) \times (1 - 0.0628(H/C))\}], \tag{9}$$

where H, C, O and S are the mass fractions of hydrogen, carbon, oxygen and sulfur contents [14].

- Shaft availability (A_s):

$$A_s = Brake\ power\ of\ engine, \quad kW \tag{10}$$

- Cooling water availability (A_w):

$$A_w = Q_w - [\dot{m}_{we} \times C_{pw} \times T_{amb} \times \ln(T_{woe}/T_{wie})], \quad kW \tag{11}$$

- Exhaust gas availability (A_e):

$$A_e = Q_e + [(\dot{m}_f + \dot{m}_a) \times T_{amb} \times \{C_{pe} \ln\left(\frac{T_{amb}}{T_{eic}}\right) - R_e \times ln(P_{amb}/P_e)\}] \tag{12}$$

where Re is the specific gas constant of the exhaust gas in kJ/kg K. It is calculated from the thermodynamic relation Re = (RU/molecular weight). RU is the universal gas constant in kJ/kmol K and the molecular weight (kg/kmol) of combustion products is calculated taking into account complete combustion.

- Destructed availability (A_d):

The availabilities As, Aw and Ae are the exergies that can be recovered. Destructed availability

$$A_d = A_{in} - (A_s + A_w + A_e), \quad kW$$
(13)

- Exergy efficiency (η_{II}):

$$\eta_{II} = (1 - (A_d/A_{in}) \quad (14)$$

- Entropy generation rate:

The procedure of entropy generation is fairly a novel technique to determine perfectly, the losses in various components in an energy system and to indentify the scopes of enhancement of overall system performance [15]. The entropy generation can be expressed as

$$\dot{S} = [A_d/T_{amb}], \quad kW/K \quad (15)$$

IV. RESULT AND DISCUSSION

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. (16)-(19). 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≤ CR_c ≤1. The general equation used to translate from coded to actual is given below as eq.(5)

$$BTE = +26.43 - 0.54 * A + 0.91 * B + 0.078 * C + 0.16 * A * B - 0031 * A * C + 0.071 * B * C + 0.065 * A^2 - 0.050 * B^2 - 1.09 * C^2$$
(16)

$$BSFC = +0.33 + 5.899 * 10^{-3} * A - 0.012 * B + 3.167 * 10^{-3} * C - 3.083 * 10^{-3} * A * B + 9.013 * 10^{(-3)} * A * C - 8.224 * 10^{-4} * B * C - 6.278 * 10^{3} * A^2 + 0.015 * B^2 + 8.356 * 10^{-3} * C^2$$
(17)

$$OP = +69.61 + 1.17 * A - 2.83 * B - 2.50 * C - 0.25 * A * B - 0.17 * A^2 - 0.17 * B^2$$
(18)

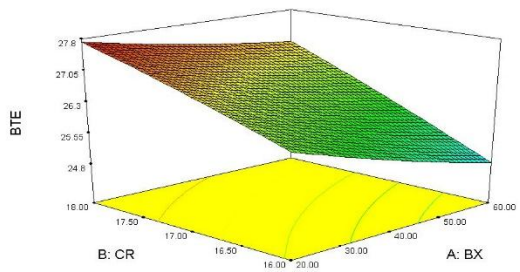
$$EGT = +281.58 + 5.01 * A + 10.74 * B + 3 * C - 0.76 * A * B + 0.42 * A * C - 0.14 * B * C - 0.99 * A^2 - 0.95 * B^2 - 0.73 * C^2$$
(19)

$$X_{actual} = X_{min} + \left[\frac{X_{coded}+1}{2} * (X_{max} - X_{min})\right] \quad (20)$$

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.

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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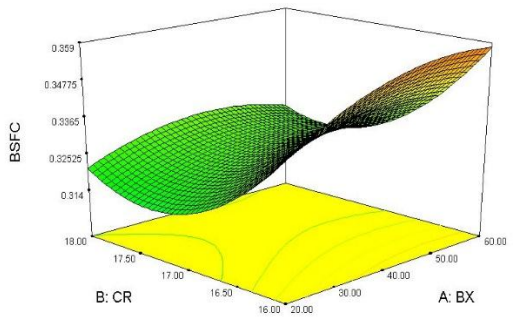

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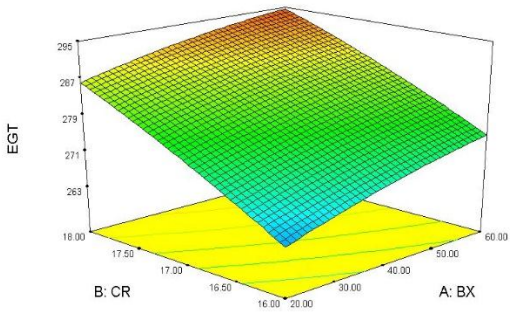

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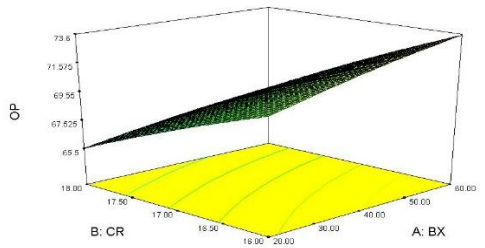


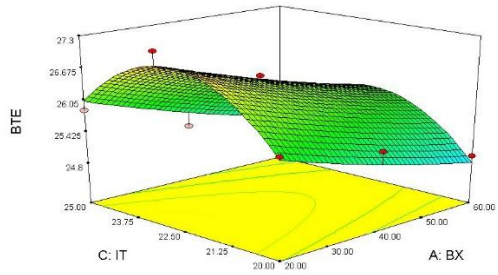
(d)

Figure 2. Interactive effects of CR and BX

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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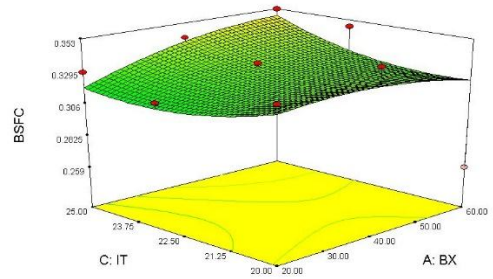

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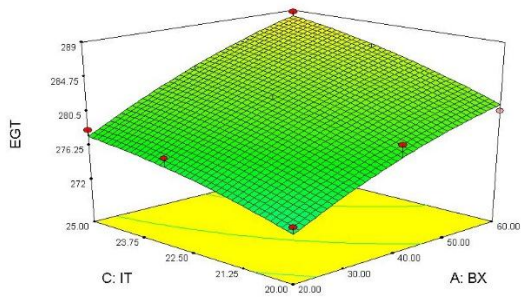

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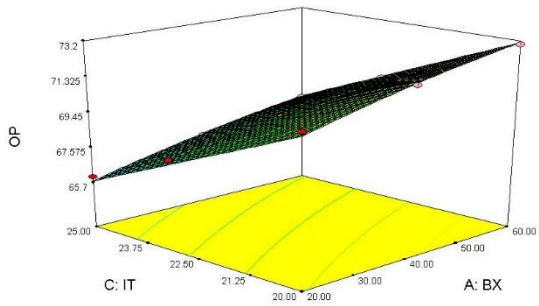


(d)

Figure 3. Interactive effects of BX and IT

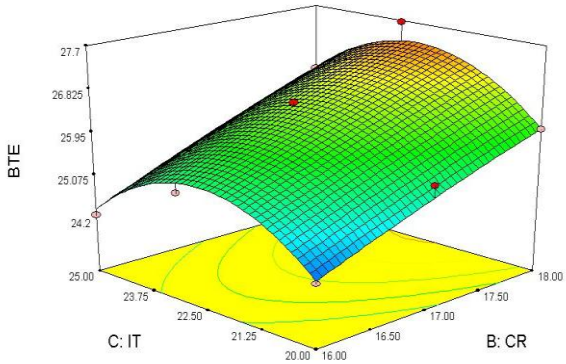
Interactive effect of CR and IT

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

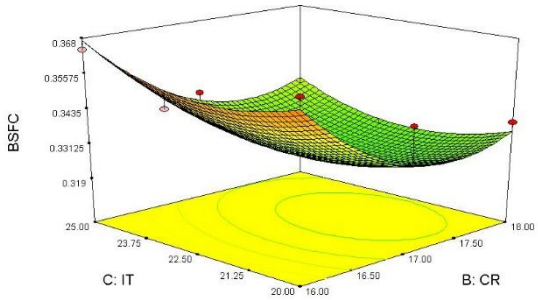
power due to burning of larger quantity of fuel during expansion.

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.



(a)



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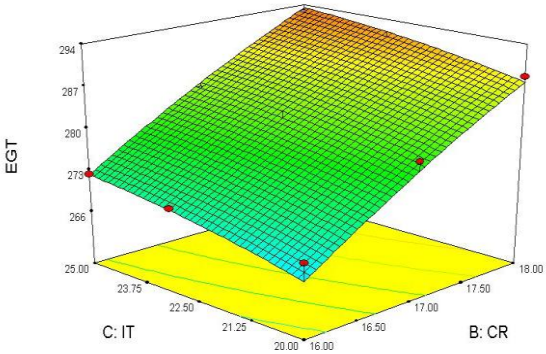

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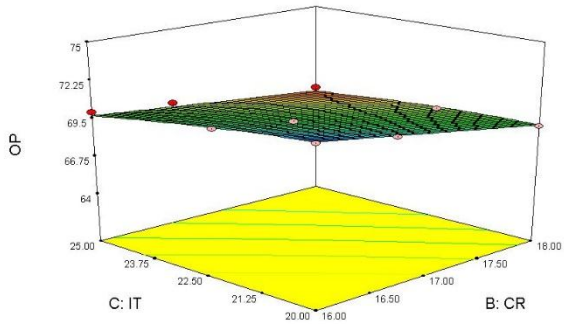

(d)

Figure 4. Interactive effects of CR and IT

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 16 resulted 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 III.

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 IV. 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

Thermodynamic analysis for B20

The energy and exergy analysis are presented only for optimized values from RSM. All the results are for B20. Fig. 5 (a) shows energy distribution for different processes in the

diesel engine for varying IT and for constant CR of 18. Here IT of 23 ^{0}BTDC is showing conformity with optimized value.

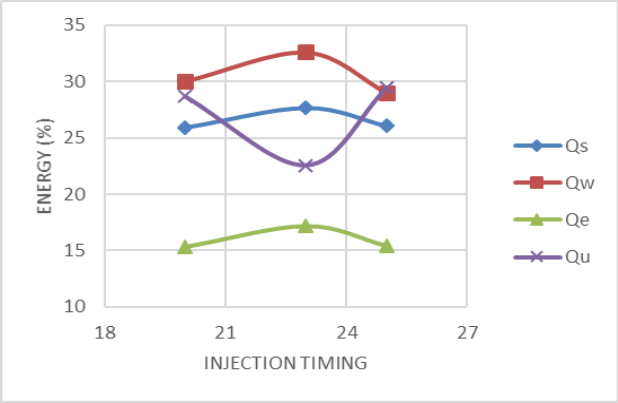

Figure 5 (a). Energy (%) distribution wit IT for constant CR of 18.

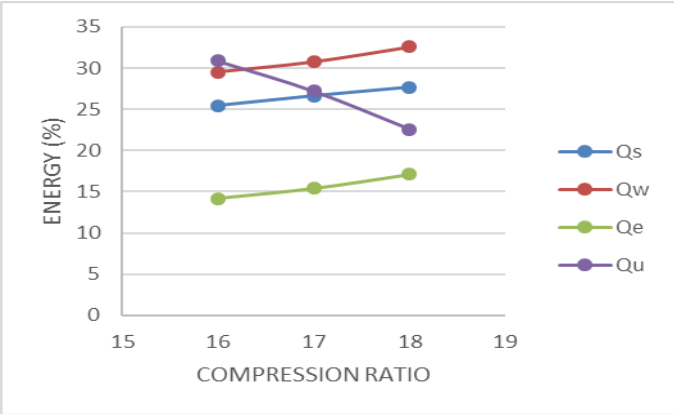

Figure 5 (b). Energy (%) distribution with CR for constant IT of 23 BTDC.

Fig. 5 (b) shows the variation of energy distribution with CR for constant IT of 23 ^{0}BTDC for different processes in engine. Energy is represented in percentage of input fuel energy.

TABLE III. 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 IV. 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

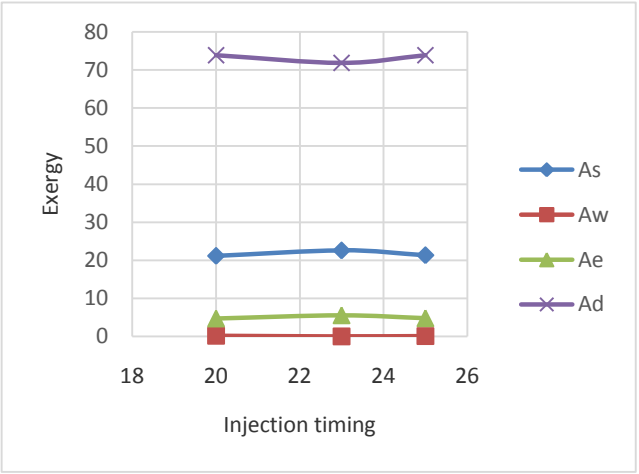

Figure 6 (a). Exergy (%) distribution wit IT for constant CR of 18

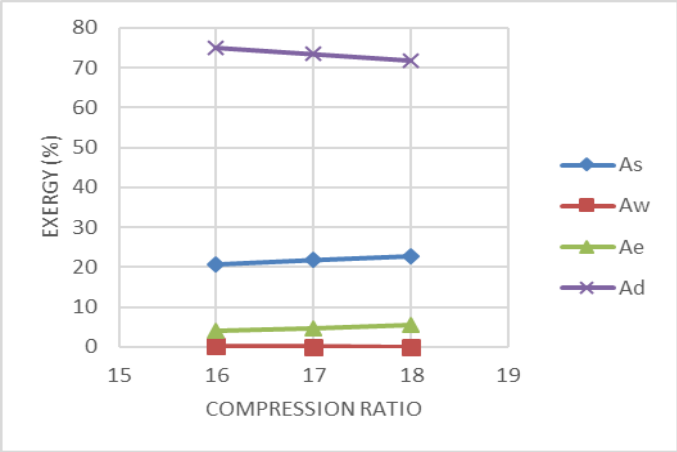

Figure 6 (b). Exergy (%) distribution with CR for constant IT of 23 BTDC.

Fig. 7 and fig. 8 shows variation of exrgetic efficiency or second law efficiency and entropy generation respectively.

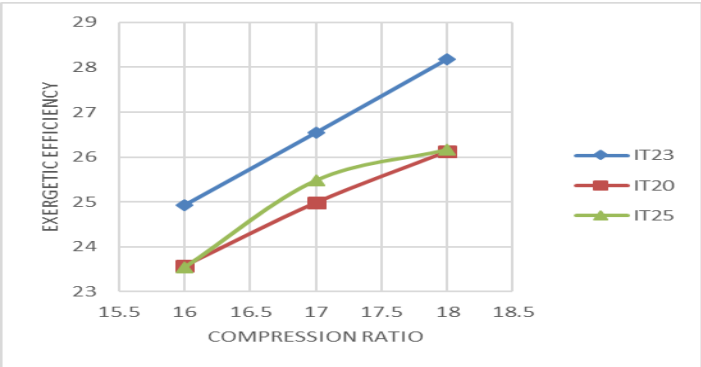

Figure 7. Exergetic efficiency (η_{II}) for different combination of CR and IT.

IT of 23 BTDC and CR of 18 shows high exegetic efficiency and low entropy generation which is in conformity with experimental and optimized values.

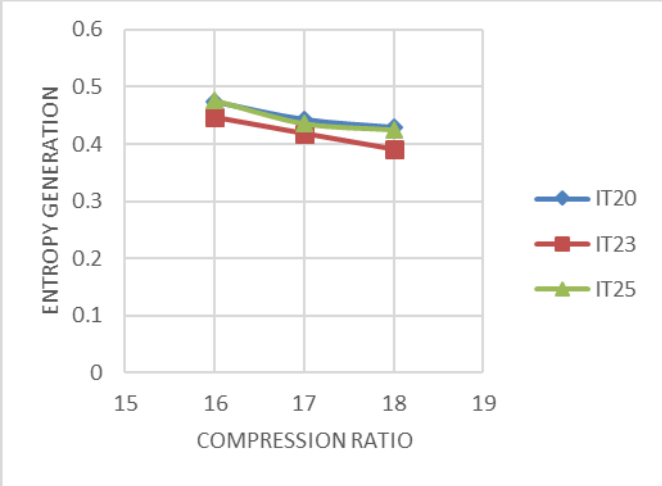

Figure 8. Entropy generation (S) for different combination of CR and IT.

V. CONCLUSION

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.

- 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.
- 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.
- 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.EGT was found to increase with increase in CR and BX, while EGT was 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. Increase in OP with increase in BX was also observed.
- 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.
- Results from thermodynamic analysis are in close conformity with experimental and optimized values. Exergetic efficiency is 28.43 % which is for IT of 23

BTDC and CR of 18.By properly controlling CR, BX and IT, performance can be improved and smoke emissions can be controlled by using a blend of alternate fuel like biodiesel from waste fried oil. Thermodynamic analysis provides modes of improvement by providing ways to reduce unnecessary heat losses.

ACHNOLAGEMENT

I express our deepest appreciation and sincere gratitude to Prof. A. M. Elgandelwar for his valuable guidance and timely suggestions during the entire duration of this project work, without which this work would not have been possible. I am thankful to Dr. Prof. M. M. Lele and Prof. Anita A. Nene for their valuable guidance & sharing resource as and when required. I am thankful to Maharashtra Institute of Technology, Pune for providing research engine test rig over which performance test will be carried on and also people those who are associated and helped in completion of my work without which it would not have been possible.

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