# A Taguchi Method Optimization for Engine Parameters of VCR Engine Fuelled with Xanthium strumarium L. Oil Biodiesel Blend

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**Abstract-** Climate changes such as severe storms, increased drought, increase in sea level, acid rain etc are adversely affecting animal and plant life on the earth, caused due to global warming, which is the result of harmful emissions. Biodiesel is a vital alternative fuel to diesel in heavy vehicles. In spite of a number of advantages, more Nitrogen Oxide emission is a major issue reported with biodiesel. In this paper, an attempt is made for Optimization of Engine Operating parameters like Compression Ratio, Fuel injection Pressure, Fuel injection Timing and Exhaust Gas Recirculation using Xanthium strumarium L. Seed oil Biodiesel (B20) in Variable Compression Ratio Diesel engine using Taguchi Design L9 ($3^4$) Orthogonal array for maximum Brake Thermal Efficiency, minimum Brake Specific Fuel Consumption and minimum pollutants like CO, HC, Smoke and NOx. The results are compared with diesel. By considering 50:50 weightage to thermal performance and emissions, the optimum parameters obtained for B20 are CR-18, IP-210 bar, IT-19$^0$bTDC, EGR-10% and that for Diesel are CR-18, IP-240 bar, IT-25$^0$bTDC, EGR-5%. It is observed that B20 blend can be effectively used as a fuel without any engine modifications.

**Keywords-** Xanthium strumarium L. seed oil biodiesel; Taguchi method; Exhaust gas recirculation, NOx reduction.

**Abbreviations-**

| | | | |
|---|---|---|---|
| BTE | Brake Thermal Efficiency | CR | Compression Ratio |
| BSFC | Brake Specific Fuel Consumption | IT | Injection Timing |
| IP | Fuel Injection Pressure | HC | Hydro Carbon |
| EGR | Exhaust Gas Recirculation | CO | Carbon Monoxide |
| EGT | Exhaust Gas Temperature | NOx | Oxides of Nitrogen |
| COF | Combine Objective Function | PPM | Parts Per Million |
| bTDC | Before Top Dead Center | $CO_2$ | Carbon Dioxide |
| RSM | Response Surface Method | CI | Compression Ignition |
| B20 | Biodiesel 20%+Diesel 80% | VCR | Variable Compression Ratio |
| BMEP | Brake Mean Effective Pressure | RPM | Revolutions Per Minute |
| Adj SS | Adjusted sums of squares | PM | Particulate Matter |
| S/N ratio | Signal to Noise Ratio | v/v | Volume to Volume Ratio |

## 1. Introduction

The reserves of fossil fuels are depleting due to rapid growth in industry, agriculture and transportation. The harmful emissions produced by burning of these fuels are not only affecting nature but also human health. Biodiesel has emerged as the best option. The World era is moving from the first generation to the fourth generation of biodiesel. The biodiesel can be obtained from vegetable oils, animal fats and algae. Nowadays, Biodiesel can be produced by using transesterification with some recent techniques such as use of enzymes, nano catalyst, use of ionic liquids, supercritical process, ultrasound assisted process, microwave assisted process etc [18, 20, 22]. Biodiesel has several advantages over diesel [6, 16, 36, 37]. It can be used in diesel engines without any modifications [14, 32, 33, 38]. It produces less harmful pollutants like HC, CO and PM but produces more NOx emissions [7, 8, 21]. Researchers studied causes of NOx formation and suggested several techniques such as reduced injection timing, recirculation of exhaust gases, method of water injection, use of oxygenated additives etc. for reducing NOx emissions [17]. Some of the researchers obtained results with fewer NOx emissions during experimentation [2, 23, 28, 29]. Various researchers conducted experimentation by using different biodiesel fuels on a variable compression ratio diesel engine to get best thermal performance and the least emissions by optimizing various operating parameters such as compression ratio, injection pressure, injection timing and using exhaust gas recirculation. Observations by few researchers are noted here.

Sanjay et al., [34] suggested that energy audit for thermal performance and emission analysis of the engine fuelled with biodiesel is very important for energy conservation to improve BTE and to reduce harmful emissions like CO, HC, NOx and smoke. Campli et al. [31] performed experimentation on VCR engine with neem biodiesel blend B25 by using NiO nanoparticles as additives with variation in engine operating parameters and concluded that best thermal performance and least emissions are obtained at CR-17.25, IP-227.86 bar and IT-27$^0$bTDC with RSM method. Aparna et al., [1] conducted experimentation on a variable compression ratio diesel engine using Jatropha biodiesel diesel blend B30 and diesel with variation in compression ratio from 14 to 18, fuel injection pressure from 180 bar to 270 bar and load from 0 to 12 kg with Response Surface Methodology. The investigation revealed that CO and HC emissions were reduced by 24% and 16.7% compared to diesel. With an increase in load and compression ratio, CO and HC emissions decrease significantly but an increase in NOx and $CO_2$ is noticed. An increase in fuel injection pressure reduces CO and HC emissions but increases $CO_2$ and NOx emissions. Navdeep et al., [3] carried out research using two biodiesels, namely Jatropha and Mahua in equal volume proportion (1:1, v/v) and blended with diesel in different proportions. The experiments were conducted at constant engine speed with 50 % load and variation in compression ratio. The results show that the sample blended B10 to B40 has high brake power and mechanical efficiency as compared to diesel at 16.5:1 compression ratio. The combustion pressure and gas temperature at exhaust were also observed to be less in comparison with diesel. It is also noticed that emissions of hydrocarbons and carbon monoxide were also reduced with an increase in blend percentage, but carbon dioxide emissions were increased. It is concluded that the B20 blend is a better substitute for diesel. Sivaramakrishnan et.al., [13] investigated the effect of compression ratio on performance and emission of diesel engines using different blends of Karanja methyl ester, implementing response surface methodology. With an increase in compression ratio, the best results are obtained for brake thermal efficiency and brake specific fuel consumption with reduction in HC and CO emissions, but NOx emissions increase. Sharanappa et al., [21] used different blends of Mahua oil biodiesel with diesel fuel like B00, B20, B40, B60, B80 and B100. Engine performance parameters such as Thermal efficiency, BSFC, BSEC and EGT along with CO, HC and NOx emissions were measured to evaluate the behaviour of the engine. The results show that as the percentage of biodiesel in the blends increases, HC and CO reduce, BSFC and NOx emissions increase compared to diesel. When B20 blend is used as fuel in a diesel engine, BSFC decreases and thermal efficiency increases slightly as compared to diesel. Silitonga et al., [16] studied the performance of the engine and emission characteristics of C. pentandra biodiesel- diesel blends (B10, B20, B30 and B50) and compared with diesel. It is observed that at lower biodiesel diesel blends, there is good performance of the engine with respect to thermal efficiency and fuel consumption. However, the exhaust emissions such as HC, CO and smoke were reduced with an increase in blend percentage, but $CO_2$ and NOx have been increased compared to diesel. Ashrafur et al., [15] studied the effect of injection timing on performance of the engine and emissions in exhaust with biodiesel, diesel, alcohol and other alternative fuels. With an advancement in injection timing with diesel fuel, there is reduction in HC and CO emissions, an increase in BTE and decrease in BSFC but increase in NOx. With biodiesel-diesel fuel blends, retarding injection timing produces more CO and HC emissions but reduces NOx. Advancements in injection timing produce higher temperatures of exhaust gas with an increase in the amount of biodiesel in blends. Channapattana et al., [9] carried out testing of four different blends of Honne oil methyl ester, namely B20, B40, B60 and B80, which are found to have behavior similar to diesel at high injection pressure and high compression ratio. The percentage reduction in NOx is more for retarded injection timing than for advanced. There is an increase in smoke intensity for both advancement and retardation in injection timing. Multi-objective Optimization is carried out using GA and ANN tools. The optimum values of compression ratio, fuel injection pressure and static injection timing are found to be 18, 227 bar and 22$^0$ bTDC respectively. Datta et al., [10] used biodiesel methanol blend for Optimization of VCR engine operating parameters like fuel blend, compression ratio and load on engine and response was observed on BTE, BSFC and emission parameters using approach of Derringers Desirability. From the results it is concluded that the VCR engine has the best performance results and the lowest emissions at a compression ratio of 18, fuel blend 5 % and load on the engine 9.03 kg. It is concluded from experimental data and mathematical models that methanol biodiesel blend has maximum efficiency and minimum emissions at optimised conditions.

**Table 1.** Fuel Properties

| Test Description | Unit | Test Method | Pure Diesel | B20 |
|---|---|---|---|---|
| Kinematic Viscosity at $40^0$C | cSt | ASTM D 7042 2021 | 2.305 | 2.548 |
| Density at $15^0$C | g/cc | ASTM D 4052 2018 a | 0.8259 | 0.8375 |
| Gross Calorific Value | Cal/g | IS 1448(P6)2018 | 10960 | 10695 |
| Flash Point | $^0$C | IS 1448(P21)2019 | 65 | 67 |
| Fire Point | $^0$C | ASTM D9358T | 56 | 74 |

The optimum conditions for input parameters are injection pressure 231.35 bar, injection timing $23.7^0$ bTDC, Engine load 60.49 % and biodiesel blend 14.32 %.The results of Optimization for output parameters are BSFC as 0.3135 Kg/KWh, BTE as 24.28 % and Cylinder peak pressure as 58.95 bar. Akula et al., [26] conducted research using palm oil methyl ester to study combustion, performance and emission by using exhaust gas recirculation and changing injection timing. Various blends of palm oil biodiesel like 10 %, 20 %, and 30 % with diesel are prepared on a volume basis and tested in CI engine by varying load. The outcome shows that higher BTE can be obtained for B20 at $27^0$ bTDC and 20 % EGR. High peak pressure, less HC and NOx emissions compared to diesel are obtained at $23^0$ bTDC and without recirculation of exhaust gases. Progression in injection with 20%EGR gives more dense smoke. Avinash et al., [2] used Karanja oil blends with diesel in a single cylinder diesel engine to analyse emission and performance. To reduce oil viscosity, use of a specially designed heat exchanger was done by utilizing waste heat from exhaust gases. It was observed that lower blends show significant improvement in thermal performance and emission with and without preheating. The NOx emissions for all the blends were observed to be less than mineral diesel. Up to 50 % (v/v) karanja oil blends can be used to replace diesel in CI engine, giving less emissions and better thermal performance. Md. Nurun et al., [28] used neem oil biodiesel blends with diesel in a four stroke direct injection diesel engine. It was observed that biodiesel blends give less CO and smoke emissions and more NOx emissions but when EGR is used NOx emissions are reduced compared to diesel. Based on the above survey, one could deduce that varying parameters such as compression ratio (CR), injection pressure (IP), injection timing (IT) could lead to varying objective results. Also, as NOx is a restricting outcome of biodiesel combustion, the research also focuses on varying the above parameters with variations in EGR. Later the obtained results based on DOE are channelized to achieve the goal of best performance and least emissions with 50:50 weightage.

In the present research work, biodiesel produced from non edible cocklebur seed oil is used for experimentation using alkaline based single stage transesterification [5, 35]. The botanical name of the plant is Xanthium strumarium L., which grows in barren land and arid areas almost everywhere in all parts of the world [35]. The plant has high production potential. The aim of the research is to find suitability of Xanthium strumarium seeds oil biodiesel blend (B20) in diesel engine and compare with diesel. The objectives are to find values of various operating parameters of the engine for best thermal performance and least emissions.

## 2. Materials and Methods

### *2.1. Materials*

The fruits of Xanthium strumarium L. plant were collected from barren land in Bawada village (18.73909N, 74.20779) located in Satara district (MH), India. Matured fruits were collected in the month of December 2020.The fruits, after dehulling, seeds are subjected to oil extraction by mechanical pressing. Two kilograms of oil was collected from ten kilograms of seeds. Biodiesel is produced using a single stage alkaline based transesterification process [5,35]. For biodiesel production, methanol is used as alcohol, NaOH as an alkali catalyst, reflux condenser along with a water bath heater and stirrer. The chemicals were purchased from Vijay chemicals, Pune (MH).During biodiesel production, optimised conditions are used, i.e. Methanol : oil mass molar ratio 6:1, temperature of heating $55^0$C, Catalyst concentration 0.8 % weight, heating time 45 minutes and stirring speed 600 rpm . The properties of biodiesel are measured at Chem Tech laboratory, Pune and observed to be as per ASTM standards [27,35]. The fuel sample is prepared by mixing diesel and cocklebur biodiesel on a volume basis in the required proportion. Experimentation is done in two stages using a computerized single cylinder, 4 stroke, water cooled Variable Compression Ratio Diesel Engine 1. Using a mixture of diesel 80 % and Cocklebur biodiesel 20 % on a volume basis. 2. Using only diesel fuel. The fuel properties are as in Table 1.The details of the engine are as per Table 2. and The experimental setup is as in Fig. 1.

### *2.2. Experimental Procedure*

The engine operating parameters are varied to get maximum brake thermal efficiency, minimum brake specific fuel consumption and less pollution. The operating parameters selected are Compression ratio, Injection pressure, Injection timing and Exhaust Gas Recirculation. The engine is operated at full load condition and constant speed of 1500 rpm. The compression ratio is varied between 16, 17 and 18 because most of the researchers estimated that maximum thermal efficiency can be obtained at a higher compression ratio [11, 12, 37]. The fuel injection pressure is varied between 180 bar, 210 bar and 240 bar as thermal efficiency increases with increase in injection pressure [14].

**Table 2.** Engine Specifications

| | |
|---|---|
| Engine Make | Kirloskar |
| Product | 240PE |
| Stroke Length | 110 mm |
| Bore | 87.5mm |
| Capacity | 661cc |
| Power | 3.5KW |
| RPM | 1500 |
| Loading | Eddy Current dynamometer |
| CR range | 12 to 18 |
| Injection Variation | 0 to $25^0$ bTDC |

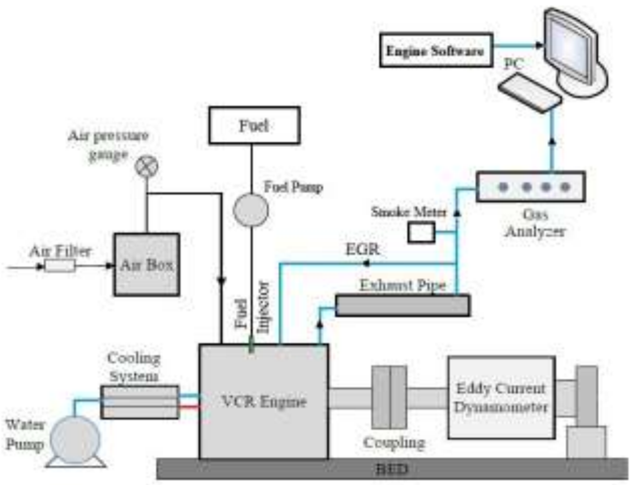



**Fig. 1.** Block diagram of experimental Setup

The fuel injection timing is between 19, 22 and 25 as compared to standard 23.5 because researchers reported that retarding injection timing reduces NOx emissions [17, 25]. Exhaust gas recirculation between 5%, 10%, and 15% to study the effect on BTE and NOx emissions. EGR can be used to increase BTE and to reduce NOx [19, 30]. A number of researchers found that the B20 blend of various biodiesels gives results closer to diesel [3, 13]. Therefore, the B20 blend was used for testing. Experiments are designed using the Taguchi method for Optimization. Nine different experiments are conducted for each fuel. Each experiment is repeated three times and the average value is used for calculation. By measuring fuel consumption brake thermal efficiency, brake specific fuel consumption can be determined. Using a five point exhaust gas analyzer (AVL make, model AVL444N), exhaust emissions like CO, $CO_2$, HC, NOx etc are measured. Smoke opacity is measured using a smoke meter (Make-AVL, Model-AVL437). Exhaust gas temperature, combustion pressure etc are measured for comparison. The Eddy Current Dynamometer used for loading purposes has following specifications. Make-Technomech, Model- TMEC10, 10BHP@1500-5000 RPM, Arm length-185mm. Loading arrangement-Make-Apex, Model-AX155, Type-constant speed, Supply-230V AC. The uncertainties in measurement of various parameters are as in Table 3.

First testing is done for B20 (Diesel 80 % + Cocklebur Biodiesel 20 %) blend prepared on a volume basis and then for diesel (B00) as fuel. During the trial, a load of 12 Kg and a speed of 1500 RPM was kept constant with maximum variation of only 2 % in speed and 0.6 % in load. By varying operating parameters, fuel consumption, CO, $CO_2$, HC, NOx, Smoke, O2, EGT, Pressure difference in water manometer etc are noted. Experiments are designed using the Taguchi method.

**Table 3.** Uncertainties in measurement

| Parameters | Uncertainty (%) |
|---|---|
| Load | 0.2 |
| Speed | 0.1 |
| Fuel Measurement | 1 |
| CO | 0.2 |
| HC | 0.1 |
| $CO_2$ | 0.3 |
| NOx | 0.2 |
| Smoke | 1 |

Nine different experiments are performed for each fuel by considering Compression ratio, Injection Pressure, Injection Timing and Exhaust Gas Recirculation as Engine operating parameters and their response is measured on performance parameters BTE, BSFC and emission parameters CO, $CO_2$, HC, NOx and Smoke. By giving full weightage (100 %) to each response parameter, optimum conditions of operating parameters are determined. By considering 50:50 weightage to thermal performance and emissions, optimum conditions are also determined. ANOVA contribution of each factor is determined. Table 4 shows selection of Taguchi Optimization Characteristics for various parameters.

**Table 4.** Selection of Taguchi Optimization Characteristics

| Sr. No. | Response parameter | Optimization Characteristics |
|---|---|---|
| 1 | BTE | Larger the better |
| 2 | BSFC | Smaller the better |
| 3 | CO | Smaller the better |
| 4 | $CO_2$ | Larger the better |
| 5 | HC | Smaller the better |
| 6 | NOx | Smaller the better |
| 7 | Smoke | Smaller the better |

*2.3. Taguchi Design for Optimization*

The Taguchi is a statistical technique to optimize the process by method of experimentation with available resources. In the present study, the Taguchi design methodology was performed using Minitab 19 software, considering four input parameters such as Compression Ratio (CR), Injection Pressure (IP), Injection Timing (IT) and

Exhaust Gas Recirculation (EGR). The standardized Taguchi orthogonal array L9 ($3^4$) where three levels have been fitted and assigned for low level, middle level and higher level values as shown in Table 5. In multi-objective optimization, the effect of all input parameters analyzed for maximizing the brake thermal efficiency (BTE) and carbon dioxide ($CO_2$), minimizing the brake specific fuel consumption (BSFC), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and smoke considering two categories of performance characteristics i.e.

Larger is the better (maximize): $\frac{S}{N} = -10 \times \log_{10}\left(\sum {}^{1}/_{Y^2}/_{n}\right)$ (1)

Smaller is the better (minimize):

$\frac{S}{N} = -10 \times \log_{10}\left(\sum {}^{Y^2}/_{n}\right)$ (2)

Where, n is the number of test, and Y is the result of each test.

**Table 5.** Taguchi design variables and levels

| Variables | Units | Levels | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| CR | | 16 | 17 | 18 |
| IP | bar | 180 | 210 | 240 |
| IT | $^0$bTDC | 19 | 22 | 25 |
| EGR | % | 5 | 10 | 15 |

For each fuel nine experiments are performed as per the Table 6 below

**Table 6.** Taguchi Design L9 ($3^4$) Orthogonal Array

| Expt No. | CR | IP | IT | EGR |
|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 | 2 |
| 3 | 1 | 3 | 3 | 3 |
| 4 | 2 | 1 | 2 | 3 |
| 5 | 2 | 2 | 3 | 1 |
| 6 | 2 | 3 | 1 | 2 |
| 7 | 3 | 1 | 3 | 2 |
| 8 | 3 | 2 | 1 | 3 |
| 9 | 3 | 3 | 2 | 1 |

## 3. Results and Discussion

### *3.1. Diesel 80%+Cocklebur Biodiesel 20% (B20)*

First experimentation was done using B20 fuel. The experimental results are given in Table 7 and corresponding S/N ratios for response parameters are given in Table 8.

**Table 7.** Experimental results for B20 fuel

| Expt. No. | BTE (%) | BSFC (Kg/KWh) | CO (%) | $CO_2$ (%) | HC (ppm) | NOx (ppm) | Smoke (%) |
|---|---|---|---|---|---|---|---|
| 1 | 24.18 | 0.33 | 0.11 | 3.7 | 16 | 336 | 9.9 |
| 2 | 21.44 | 0.38 | 0.21 | 4 | 27 | 196 | 17.3 |
| 3 | 18.01 | 0.45 | 3.91 | 4.5 | 233 | 171 | 39.5 |
| 4 | 14.11 | 0.57 | 1.1 | 4.1 | 121 | 103 | 22.1 |
| 5 | 21.12 | 0.38 | 0.26 | 4.2 | 30 | 183 | 19.4 |
| 6 | 23.74 | 0.34 | 0.33 | 4.7 | 27 | 138 | 21.4 |
| 7 | 22.94 | 0.35 | 0.17 | 4 | 22 | 331 | 5.3 |
| 8 | 18.75 | 0.43 | 1.9 | 3.4 | 84 | 47 | 2.2 |
| 9 | 23.01 | 0.35 | 1.1 | 4 | 17 | 520 | 2.5 |

**Table 8.** S/N Ratio for response parameters of B20 fuel

| S/N 1 | S/N 2 | S/N 3 | S/N 4 | S/N 5 | S/N 6 | S/N 7 | COF 50:50 |
|---|---|---|---|---|---|---|---|
| 27.7 | 9.56 | 19.2 | 11.36 | -24.08 | -50.53 | -19.91 | 2.91 |
| 26.6 | 8.51 | 13.6 | 12.04 | -28.63 | -45.85 | -24.76 | 1.42 |
| 25.1 | 7.00 | -11.8 | 13.06 | -47.35 | -44.66 | -31.93 | -4.24 |
| 22.9 | 4.88 | -0.8 | 12.26 | -41.66 | -40.26 | -26.89 | -2.77 |
| 26.5 | 8.38 | 11.7 | 12.46 | -29.54 | -45.25 | -25.76 | 1.08 |
| 27.5 | 9.40 | 9.6 | 13.44 | -28.63 | -42.80 | -26.61 | 1.73 |
| 27.2 | 9.11 | 15.4 | 12.04 | -26.85 | -50.40 | -14.49 | 2.65 |
| 25.5 | 7.35 | -5.6 | 10.63 | -38.49 | -33.44 | -6.85 | 0.83 |
| 27.2 | 9.13 | -0.8 | 12.04 | -24.61 | -54.32 | -7.96 | 1.52 |

**Table 9.** Optimum conditions for responses of B20 fuel

| Responses | CR | IP | IT | EGR | % R-sq | Insignificant Factor |
|---|---|---|---|---|---|---|
| BTE | 18 | 240 | 19 | 5 | 96.88 | IP |
| BSFC | 18 | 240 | 19 | 5 | 94.89 | IP |
| CO | 16 | 180 | 19 | 10 | 93.07 | IT |
| $CO_2$ | 17 | 240 | 25 | 10 | 89.44 | EGR |
| HC | 18 | 180 | 19 | 5 | 91.42 | IP |
| Nox | 17 | 210 | 19 | 15 | 91.28 | IT |
| Smoke | 18 | 210 | 19 | 5 | 85.46 | IT |
| 50:50 | 18 | 210 | 19 | 10 | 92.22 | IP |

S/N ratios as in Table 8 and ANOVA as in Table 11 is used to determine the significant contributing parameters of BTE, $CO_2$, BSFC, CO, HC, NOx and smoke. The peak point of each response graph used for selecting the optimum combinations of parameters as tabulated in Table 9. The contribution of each factor on responses is shown in Table 10.

**Table 10.** Contribution in percentage of each factor on responses

| Responses | CR | IP | IT | EGR |
|---|---|---|---|---|
| BTE | 07.13 | 03.12 | 12.70 | 77.04 |
| BSFC | 10.80 | 05.10 | 13.87 | 70.21 |
| CO | 08.75 | 22.83 | 06.92 | 61.48 |
| $CO_2$ | 35.55 | 42.22 | 11.66 | 10.55 |
| HC | 09.44 | 08.58 | 10.69 | 71.26 |
| Nox | 22.22 | 18.55 | 08.72 | 50.49 |
| Smoke | 58.02 | 12.36 | 14.53 | 15.06 |
| 50:50 | 11.43 | 07.78 | 15.07 | 65.70 |

**Table 11.** ANOVA Model for B20 Fuel

| Source | Adj SS | F-value | P-value |
|---|---|---|---|
| | BTE (%) | | |
| CR | 6.188 | 2.29 | 0.304 |
| IT | 11.028 | 4.07 | 0.197 |
| EGR | 66.861 | 24.69 | 0.039 |
| Error | 2.708 | | |
| Total | 86.785 | | |

| Source | Adj SS | F-value | P-value |
|---|---|---|---|
| | BSFC (Kg/KWh) | | |
| CR | 0.004979 | 2.11 | 0.321 |
| IT | 0.006396 | 2.72 | 0.269 |
| EGR | 0.032360 | 13.74 | 0.068 |
| Error | 0.002354 | | |
| Total | 0.046090 | | |

| Source | Adj SS | F-value | P-value |
|---|---|---|---|
| | CO (%) | | |
| CR | 1.0851 | 1.26 | 0.442 |
| IP | 2.8314 | 3.30 | 0.233 |
| EGR | 7.6235 | 8.88 | 0.101 |
| Error | 0.8589 | | |
| Total | 12.3988 | | |

| Source | Adj SS | F-value | P-value |
|---|---|---|---|
| | $CO_2$ (%) | | |
| CR | 0.4267 | 3.37 | 0.229 |
| IP | 0.5067 | 4.00 | 0.200 |
| IT | 0.1400 | 1.11 | 0.475 |
| Error | 0.1267 | | |
| Total | 1.2000 | | |

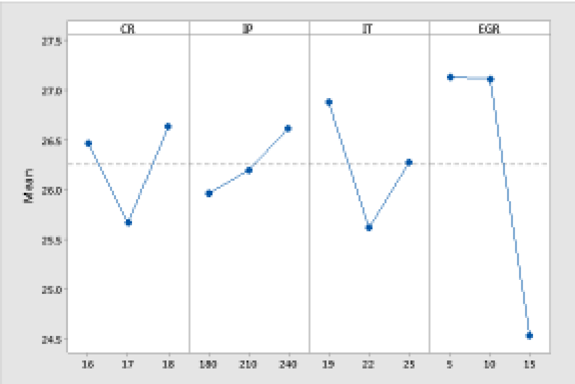
| Source | Adj SS | F-value | P-value |
|---|---|---|---|
| | HC (ppm) | | |
| CR | 4004 | 1.10 | 0.476 |
| IT | 4534 | 1.25 | 0.445 |
| EGR | 30204 | 8.30 | 0.108 |
| Error | 3638 | | |
| Total | 42381 | | |

| Source | Adj SS | F-value | P-value |
|---|---|---|---|
| | Nox (ppm) | | |
| CR | 37838 | 2.55 | 0.282 |
| IP | 31581 | 2.13 | 0.320 |
| EGR | 85971 | 5.79 | 0.147 |
| Error | 14851 | | |
| Total | 170240 | | |

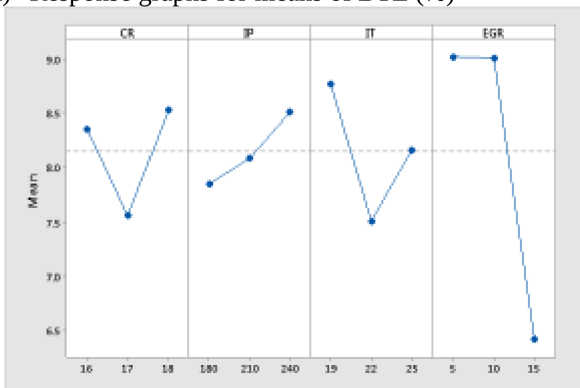
| Source | Adj SS | F-value | P-value |
|---|---|---|---|
| | Smoke (%) | | |
| CR | 669.7 | 3.99 | 0.200 |
| IP | 142.7 | 0.85 | 0.540 |
| EGR | 173.9 | 1.04 | 0.491 |
| Error | 167.8 | | |
| Total | 1154.1 | | |

| Source | Adj SS | F-value | P-value |
|---|---|---|---|
| | 50:50 Weightage | | |
| CR | 5.424 | 1.47 | 0.405 |
| IA | 7.149 | 1.94 | 0.340 |
| EGR | 31.166 | 8.44 | 0.106 |
| Error | 3.691 | | |
| Total | 47.431 | | |

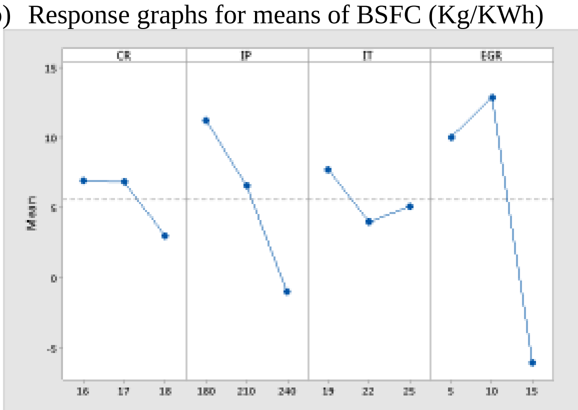
The values of response parameters can be determined by using regression equations as below Table 12.



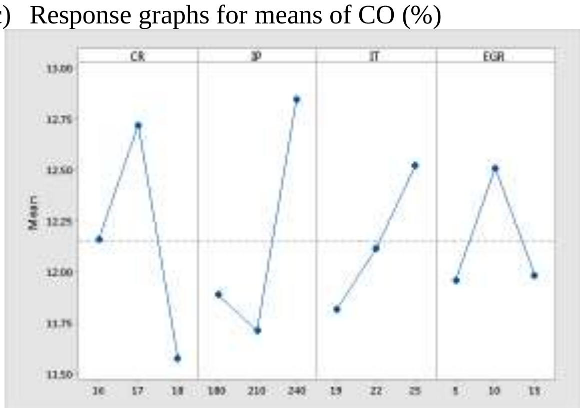

(a) Response graphs for means of BTE (%)



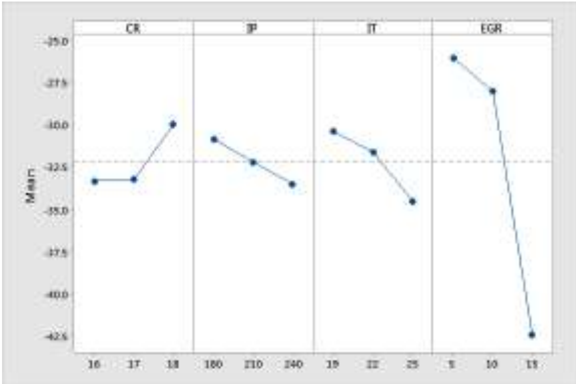

(b) Response graphs for means of BSFC (Kg/KWh)



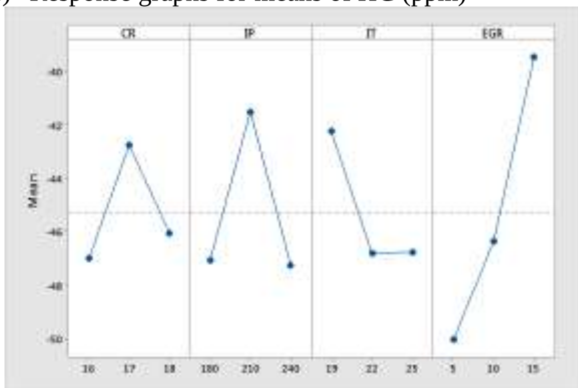

(c) Response graphs for means of CO (%)



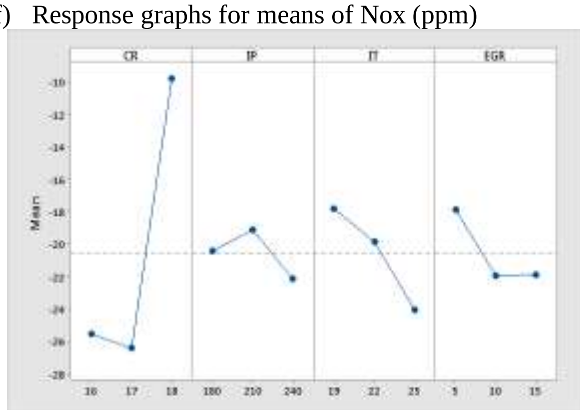

(d) Response graphs for means of $CO_2$ (%)



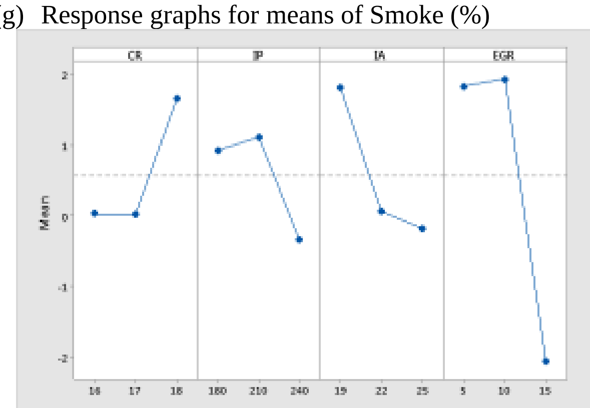

(e) Response graphs for means of HC (ppm)




(f) Response graphs for means of Nox (ppm)




(g) Response graphs for means of Smoke (%)




(h) Response graphs for means of 50:50 Weightage

**Fig. 2.** Response graphs for means of B20 fuel (a) BTE (b) BSFC (c) CO (d) $CO_2$ (e) HC (f) NOx (g) Smoke (h) 50:50 Weightage

**Table 12.** Regression model of B20 fuel

| Responses | Regression Equation | $R^2$ |
|---|---|---|
| BTE (%) | 20.811 + 0.399 CR_16 - 1.154 CR_17 + 0.756 CR_18 + 1.412 IT_19 - 1.291 IT_22- 0.121 IT_25 + 1.959 EGR_5 + 1.896 EGR_10 - 3.854 EGR_15 | 0.975 |
| BSFC (Kg/KWh) | 0.3970 - 0.0122 CR_16 + 0.0329 CR_17 - 0.0207 CR_18 - 0.0303 IT_19 + 0.0346 IT_22 - 0.0043 IT_25 - 0.0426 EGR_5 - 0.0422 EGR_10 + 0.0848 EGR_15 | 0.948 |
| CO (%) | 1.010 + 0.400 CR_16 - 0.447 CR_17 + 0.047 CR_18 - 0.550 IP_180 - 0.220 IP_210 + 0.770 IP_240 - 0.520 EGR_5 - 0.773 EGR_10 + 1.293 EGR_15 | 0.903 |
| $CO_2$ (%) | 4.0667 + 0.000 CR_16 + 0.267 CR_17 - 0.267 CR_18 - 0.133 IP_180 - 0.200 IP_210 + 0.333 IP_240 - 0.133 IT_19 - 0.033 IT_22 + 0.167 IT_25 | 0.879 |
| HC (ppm) | 64.1 + 27.9 CR_16 - 4.8 CR_17 - 23.1 CR_18 - 21.8 IT_19 - 9.1 IT_22 + 30.9 IT_25 - 43.1 EGR_5 - 38.8 EGR_10 + 81.9 EGR_15 | 0.914 |
| Nox (ppm) | 225.0 + 9.3 CR_16 - 83.7 CR_17 + 74.3 CR_18 + 31.7 IP_180 - 83.0 IP_210 + 51.3 IP_240 + 121.3 EGR_5 - 3.3 EGR_10 - 118.0 EGR_15 | 0.912 |
| Smoke (%) | 15.51 + 6.72 CR_16 + 5.46 CR_17 - 12.18 CR_18 - 3.08 IP_180 - 2.54 IP_210 + 5.62 IP_240 - 4.91 EGR_5 - 0.84 EGR_10 + 5.76 EGR_15 | 0.854 |
| 50:50 Weightage | 0.571 - 0.542 CR_16 - 0.556 CR_17 + 1.098 CR_18 + 1.253 IA_19 - 0.512 IA_22 - 0.742 IA_25 + 1.268 EGR_5 + 1.364 EGR_10 - 2.631 EGR_15 | 0.921 |

*3.2. Diesel Fuel (B00)*

After testing B20 fuel, experimentation was done using diesel fuel. Table 13 shows various recorded readings for nine different experiments and S/N ratios for response parameters are shown in Table 14.

**Table 13.** Experimental results

| Expt. No. | BTE (%) | BSFC (Kg/KWh) | CO (%) | $CO_2$ (%) | HC (ppm) | NOx (ppm) | Smoke (%) |
|---|---|---|---|---|---|---|---|
| 1 | 22.72 | 0.345 | 0.14 | 5 | 25 | 608 | 4.4 |
| 2 | 23.62 | 0.332 | 0.12 | 3.7 | 19 | 268 | 13.5 |
| 3 | 18.94 | 0.414 | 1.09 | 4.5 | 58 | 58 | 6.3 |
| 4 | 19.35 | 0.405 | 1.57 | 4.8 | 94 | 75 | 4.2 |
| 5 | 22.46 | 0.349 | 0.14 | 3.9 | 19 | 517 | 2.2 |
| 6 | 22.34 | 0.351 | 0.29 | 4 | 24 | 143 | 9.6 |
| 7 | 23.64 | 0.332 | 0.2 | 4.7 | 23 | 365 | 1.4 |
| 8 | 16.25 | 0.483 | 2.9 | 3.7 | 143 | 58 | 6.4 |
| 9 | 22.74 | 0.345 | 0.13 | 3.9 | 18 | 456 | 1.4 |

S/N ratios as in Table 14 and ANOVA similar to B20 is used to determine the significant contributing parameters of BTE, $CO_2$, BSFC, CO, HC, NOx and smoke. The peak point of each response graph used for selecting the optimum combinations of parameters is tabulated in Table 15.The contribution of each factor on responses is shown in Table 16.

**Table 14.** S/N Ratio for response parameters of Diesel fuel

| S/N 1 | S/N 2 | S/N 3 | S/N 4 | S/N 5 | S/N 6 | S/N 7 | COF (50:50) |
|---|---|---|---|---|---|---|---|
| 27.1 | 9.23 | 17.1 | 13.9 | -27.9 | -55.7 | -12.9 | 2.55 |
| 27.5 | 9.57 | 18.4 | 11.4 | -25.6 | -48.6 | -22.6 | 2.56 |
| 25.6 | 7.65 | -0.75 | 13.1 | -35.3 | -35.3 | -15.9 | 0.88 |
| 25.7 | 7.84 | -3.9 | 13.6 | -39.5 | -37.5 | -12.5 | 0.42 |
| 27.0 | 9.13 | 17.1 | 11.8 | -25.6 | -54.3 | -6.85 | 3.26 |
| 26.9 | 9.09 | 10.8 | 12.0 | -27.6 | -43.1 | -19.7 | 2.26 |
| 27.5 | 9.58 | 13.9 | 13.4 | -27.2 | -51.3 | -2.92 | 3.86 |
| 24.2 | 6.32 | -9.3 | 11.4 | -43.1 | -35.3 | -16.1 | -1.60 |
| 27.1 | 9.24 | 17.7 | 11.8 | -25.1 | -53.2 | -2.92 | 3.93 |

**Table 15.** Optimum conditions for responses of Diesel fuel

| Responses | CR | IP | IT | EGR | % R-sq | Insignificant Factor |
|---|---|---|---|---|---|---|
| BTE | 16 | 180 | 22 | 10 | 97.74 | CR |
| BSFC | 16 | 180 | 22 | 10 | 95.87 | CR |
| CO | 16 | 240 | 22 | 5 | 93.37 | IP |
| $CO_2$ | 16 | 180 | 25 | 15 | 96.95 | EGR |
| HC | 16 | 240 | 25 | 5 | 92.96 | IP |
| Nox | 17 | 240 | 19 | 15 | 98.86 | IT |
| Smoke | 18 | 180 | 25 | 5 | 83.16 | IT |
| 50:50 | 18 | 240 | 25 | 5 | 99.96 | CR |

**Table 16.** Contribution in percentage of each factor on responses

| Responses | CR | IP | IT | EGR |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| BTE | 02.25 | 03.64 | 07.17 | 86.92 |
| BSFC | 04.13 | 05.52 | 08.82 | 81.50 |
| CO | 08.16 | 06.63 | 09.01 | 76.19 |
| $CO_2$ | 06.63 | 86.28 | 04.02 | 03.04 |
| HC | 07.26 | 07.03 | 09.39 | 76.30 |
| Nox | 01.94 | 07.05 | 01.14 | 89.85 |
| Smoke | 29.00 | 19.08 | 16.84 | 35.06 |
| 50:50 | 0.043 | 6.35 | 16.11 | 77.49 |

The values of response parameters can be determined by using regression equations as below Table 17.

**Table 17.** Regression model of Diesel fuel

| Responses | Regression Equation | $R^2$ |
|---|---|---|
| BTE (%) | 21.340 + 0.563 IP_180 - 0.563 IP_210 - 0.000 IP_240 - 0.903 IT_19 + 0.563 IT_22 + 0.340 IT_25 + 1.300 EGR_5 + 1.860 EGR_10 - 3.160 EGR_15 | 0.945 |
| BSFC (Kg/KWh) | 0.37319 - 0.01219 IP_180 + 0.01504 IP_210 - 0.00286 IP_240 + 0.02004 IT_19 - 0.01216 IT_22 - 0.00789 IT_25 - 0.02652 EGR_5 - 0.03466 EGR_10 + 0.06118 EGR_15 | 0.938 |
| CO (%) | 0.731 - 0.281 CR_16 - 0.064 CR_17 + 0.346 CR_18 + 0.379 IT_19 - 0.124 IT_22 - 0.254 IT_25 - 0.594 EGR_5 - 0.528 EGR_10 + 1.122 EGR_15 | 0.933 |
| $CO_2$ (%) | 4.2444 + 0.1556 CR_16 - 0.0111 CR_17 - 0.1444 CR_18 + 0.5889 IP_180 - 0.4778 IP_210 - 0.1111 IP_240 - 0.0111 IT_19 - 0.1111 IT_22 + 0.1222 IT_25 | 0.969 |
| HC (ppm) | 47.00 - 13.0 CR_16 - 1.3 CR_17 + 14.3 CR_18 + 17.0 IT_19 - 3.3 IT_22 - 13.7 IT_25 - 26.3 EGR_5 - 25.0 EGR_10 + 51.3 EGR_15 | 0.929 |
| Nox (ppm) | 283.1 + 28.2 CR_16 - 38.1 CR_17 + 9.9 CR_18 + 66.2 IP_180 - 2.1 IP_210 - 64.1 IP_240 + 243.9 EGR_5 - 24.4 EGR_10 - 219.4 EGR_15 | 0.988 |
| Smoke (%) | 5.49 + 2.58 CR_16 - 0.16 CR_17 - 2.42 CR_18 - 2.16 IP_180 + 1.88 IP_210 + 0.28 IP_240 - 2.82 EGR_5 + 2.68 EGR_10 + 0.14 EGR_15 | 0.831 |
| 50:50 Weightage | 2.0129 + 0.2639 IP_180 - 0.6064 IP_210 + 0.3425 IP_240 - 0.9454 IA_19 + 0.2905 IA_22 + 0.6550 IA_25 + 1.2316 EGR_5 + 0.8829 EGR_10 - 2.1145 EGR_15 | 0.9985 |

### *3.3. Comparison for Contribution of Different Operating Parameters*

When diesel is used as fuel, it is seen that EGR is the major contributing factor as the p value is smallest and close to zero. It affects BTE, BSFC, CO, HC, NOx and smoke, but not $CO_2$ emissions. Injection pressure is more important for complete combustion. Selection of the Compression ratio is important for reducing smoke.

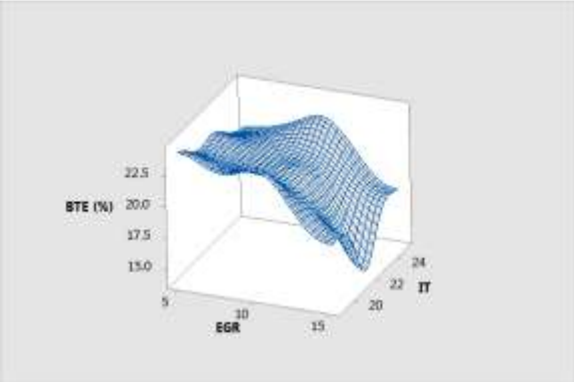
When a mixture of Diesel 80 % and Cocklebur biodiesel 20 % is used as fuel, then also EGR seems to be a significant factor for all performance parameters except $CO_2$ and smoke. For complete combustion, injection pressure and compression ratio are more important.

### *3.4. Selection of operating parameters for optimum performance and emission*

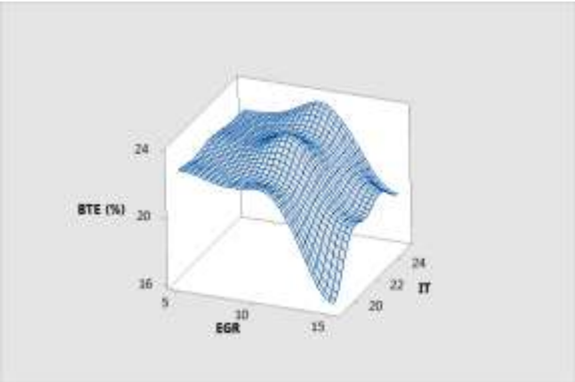
#### *3.4.1. Brake Thermal Efficiency (BTE)*

It is an indication of effective utilization of heat energy supplied for producing power output. For maximum BTE, when diesel is used as fuel, compression ratio of 16, injection pressure of 180 bar, injection timing of $22^0$ bTDC and EGR of 10 % can be used so that the amount of fuel required to be supplied in the combustion chamber decreases. EGR is the main factor affecting BTE. EGR of 10 % and 5 % should be used when diesel and B20 are used as the fuels respectively. If we increase EGR for B20, BTE will decrease. It is observed that brake thermal efficiency increases with an increase in compression ratio for biodiesel. For biodiesel, as shown in Fig. 2(a), the compression ratio should be high (18) compared to diesel. As the compression ratio increases, air pressure and temperature increase, which results in better combustion. Injection pressure also should be high (240 bar) which results in a supply of more dense charge. Injection Timing should be retarded ($19^0$ bTDC). Exhaust gas recirculation should be less (5 %). Lower BTE is obtained when biodiesel is used as fuel due to the less calorific value of biodiesel than diesel, which requires more fuel consumption for the same power output [19].

The surface plot as in Fig 3. shows that BTE for diesel fuel is maximum at 10% EGR and $22^0$bTDC while that for B20 is maximum at 5%EGR and $19^0$bTDC.EGR is the main affecting factor (86.92%) for BTE. As diesel contains less oxygen than biodiesel, there may be more CO in exhaust compared with biodiesel which can be recirculated for complete combustion to produce $CO_2$, so 10% EGR is recommended for diesel and 5% for biodiesel.




(a) BTE (%) Vs IT, EGR for B20 fuel



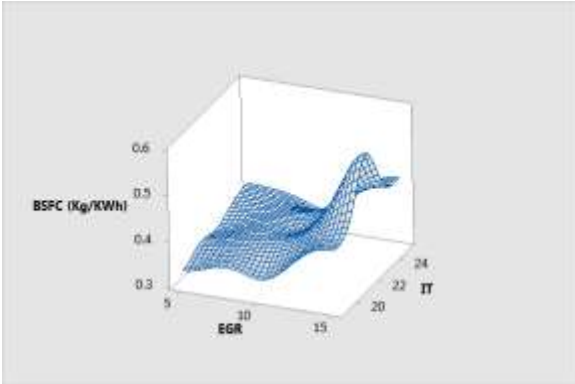

(b) BTE (%) Vs IT, EGR for Diesel fuel

**Fig. 3.** Surface plot for BTE (%) Vs Main Contributing factors

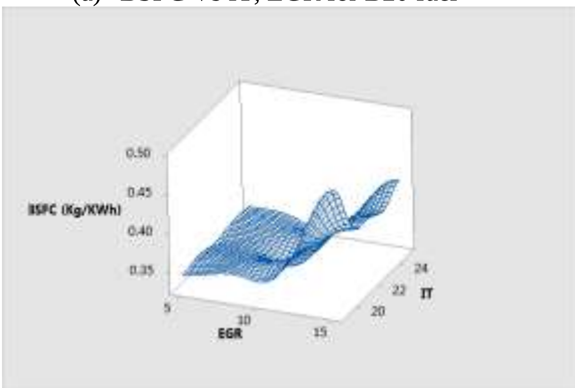
### 3.4.2. *Brake Specific Fuel Consumption (BSFC)*

It is the indication of fuel energy and its utilization. The smaller the better is the condition used. To get the minimum BSFC, the engine is to be operated under the same conditions as to get the maximum BTE for the diesel and biodiesel blend. For diesel fuel, a compression ratio (16), less injection pressure (180 bar), injection time ($22^0$ bTDC) and less exhaust gas recirculation (10 %) is preferable. For biodiesel fuel, as shown in Fig. 2(b), a larger compression ratio (18), more injection pressure (240 bar), retarded injection time ($19^0$ bTDC) and less exhaust gas recirculation (5 %) is preferable. As BSFC is calculated on a mass basis, the density of biodiesel is more than diesel, it causes more mass to be injected for the same volume at the same pressure of injection. Also, since the calorific value of biodiesel is less than diesel, it requires more fuel to be supplied for producing the same power. For these reasons, BSFC for biodiesel is more than diesel [21].

The surface plot as in Fig. 4 shows that BSFC for diesel fuel is minimum at 10% EGR and $22^0$bTDC while that for B20 is at 5% EGR and $19^0$bTDC.Circulation of exhaust gases in large amount will reduce the amount of fuel supplied in combustion chamber thereby reducing BSFC, hence BSFC for diesel is less than biodiesel.




(a) BSFC Vs IT, EGR for B20 fuel



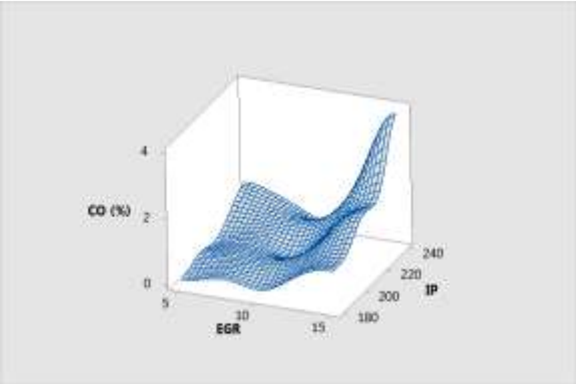

(b) BSFC Vs IT, EGR for Diesel fuel

**Fig. 4.** Surface plot for BSFC (Kg/KWh) Vs Main Contributing factors

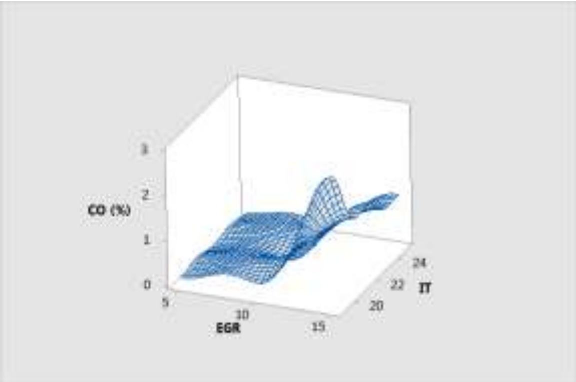
### 3.4.3. *Carbon Monoxide (CO) Emissions*

The production of CO during combustion is an indication of incomplete combustion. It is expected that any engine should produce less CO. The smaller the better is the condition used. When diesel is used as fuel, EGR is a major influencing factor in CO emissions. It is suggested to use only 5 % EGR, then the second contributing factor is injection timing, which should be $22^0$ bTDC followed by compression ratio of 16 and injection pressure of 240bar.As shown in Fig. 2(c), when biodiesel blend (B20) is used as fuel, then also EGR is the main affecting factor, which is suggested to be 10% followed by injection pressure of 180 bar then compression ratio16 and injection timing $19^0$ bTDC.

The surface plot as in Fig. 5 shows that CO emissions are minimum for diesel fuel at 5% EGR and $22^0$bTDC while that for B20 are at 10% EGR and 180 bar IP this may be due to the reason that if we increase EGR amount, it results into dilution of incoming charge as the quantity of oxygen in the combustion chamber decreases that may result into production of more CO emissions. As biodiesel contains more oxygen than diesel, 10% EGR can be used in biodiesel while only 5% EGR is suggested for diesel.




(a) CO (%) Vs IP, EGR for B20 fuel



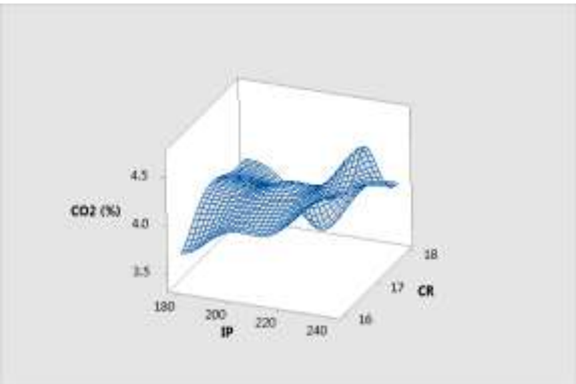

(b) CO (%) Vs IT, EGR for Diesel fuel

**Fig. 5.** Surface plot for CO (%) Vs Main Contributing factors

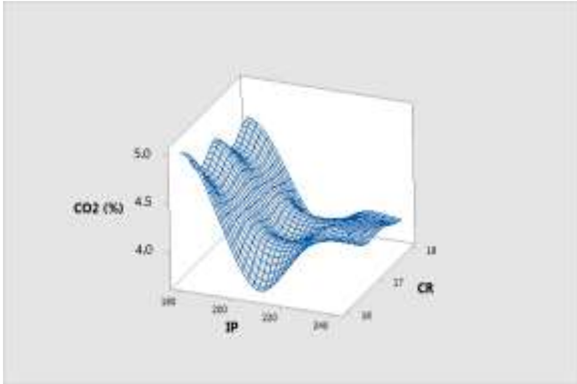
*3.4.4. Carbon Dioxide ($CO_2$) Emissions*

Combustion is said to be complete if carbon present in the fuel is converted into $CO_2$. Presence of $CO_2$ on the product side is a positive indication. The larger the better is the condition used. When diesel is used as fuel for more $CO_2$ emissions, i. e. for complete combustion, injection pressure is an important, affecting factor, which is recommended to be 180 bar, followed by a compression ratio of 16, then the injection timing, $25^0$ bTDC and 15 % EGR.

As shown in Fig. 2(d), when B20 is used, as fuel, then also injection pressure is main contributing factor, which should be 240 bar followed by compression ratio 17 then injection timing $25^0$ bTDC and EGR of 10 % is recommended.




(a) $CO_2$ (%) Vs CR, IP for B20 fuel



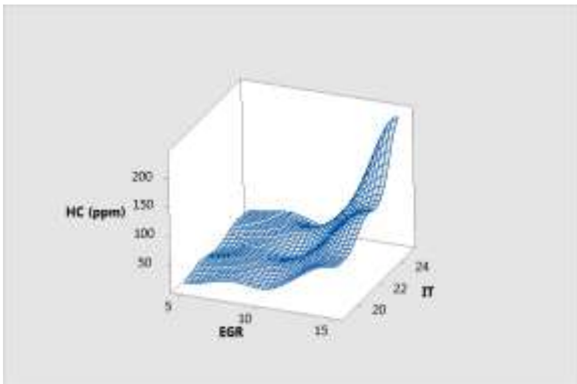

(b) $CO_2$ (%) Vs CR, IP for Diesel fuel

**Fig. 6.** Surface plot for $CO_2$ (%) Vs Main Contributing factors

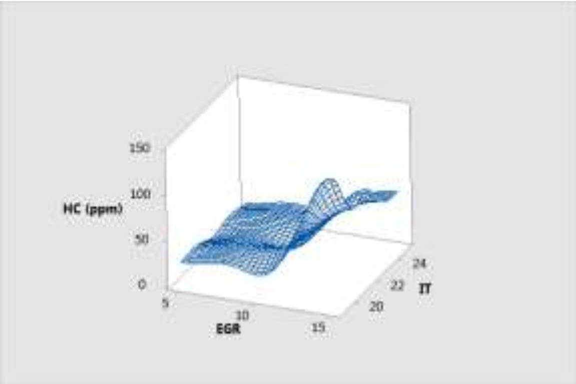
The surface plot as in Fig. 6 shows that for diesel fuel, $CO_2$ emissions are maximum at 180 bar IP and 16 CR while that for B20 are 240 bar IP and 17 CR. For complete combustion fuel injection pressure (IP) is more important than any other operating parameters. As size of biodiesel particles is larger than diesel, efficiency of combustion and combustion temperatures are smaller so larger injection pressure 240 bar is required for biodiesel.

*3.4.5. Hydrocarbon Emissions (HC)*

The presence of HC in exhaust emission is an indication of less combustion efficiency. The smaller the better is the condition to be used. The operating conditions for reducing HC emissions are almost the same as reducing CO emissions. When diesel is used as fuel, again EGR is the main affecting factor, which is suggested to be 5 % followed by injection timing $25^0$ bTDC then compression ratio 16 and injection pressure 240 bar. As shown in Fig. 2(e), when B20 is used as fuel, it is suggested to use EGR of 5 % followed by injection timing $19^0$ bTDC, compression ratio 18 and injection pressure 180 bar.




(a) HC (ppm) Vs IT, EGR for B20 fuel



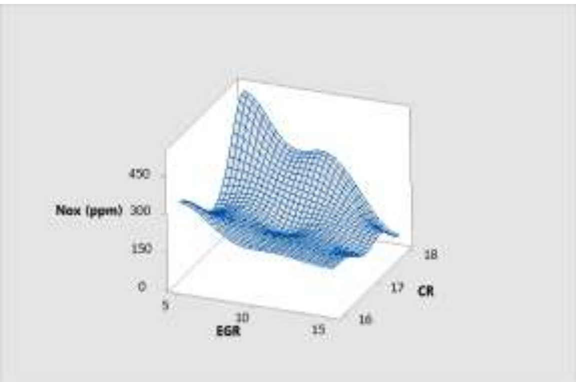

(b) HC (ppm) Vs IT, EGR for Diesel fuel

**Fig. 7.** Surface plot for HC (ppm) Vs Main Contributing factors

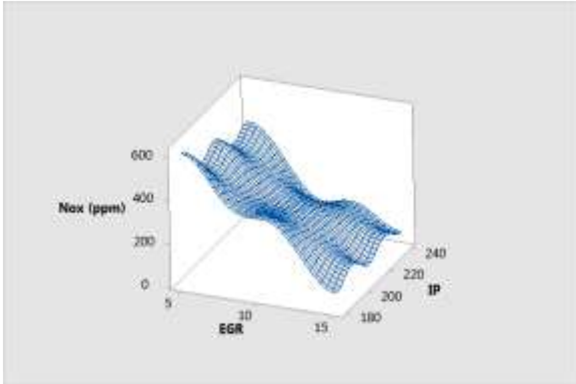
The surface plot as in Fig. 7 shows that for diesel fuel HC emissions are minimum at 5%EGR and $25^{0}$bTDC while that for B20 are at 5%EGR and $19^{0}$ bTDC. EGR is the main affecting factor for controlling HC emissions. If we increase amount of EGR, it dilutes the incoming charge since quantity of oxygen in the combustion chamber decreases and that results in more HC emissions. Hence EGR of 5% is recommended for both the fuels.

*3.4.6. NOx Emission*

It indicates the presence of oxides of nitrogen in emission. The use of biodiesel is restricted due to the large amount of NOx coming through engine exhaust. More NOx emission is due to large combustion temperature that causes oxidation of nitrogen molecules [17]. The smaller the better is the condition used. To minimize NOx emissions, when diesel is used as fuel, the engine is to be operated at medium compression ratio (17), large injection pressure (240bar), retarded injection timing ($19^{0}$ bTDC) and large EGR (15 %).As shown in Fig. 2(f), when biodiesel blend is used as fuel engine is to be operated with medium compression ratio (17), medium injection pressure (210 bar), retarded injection timing ($19^{0}$ bTDC) and large EGR (15 %).




(a) NOx (ppm) Vs CR, EGR for B20 fuel



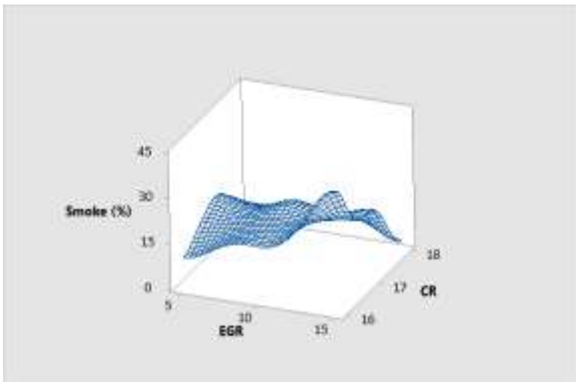

(b) NOx (ppm) Vs IP, EGR for Diesel fuel

**Fig. 8.** Surface plot for NOx (ppm) Vs Main Contributing factors

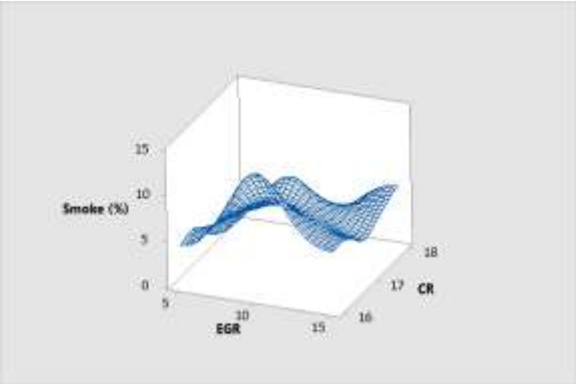
The surface plot as in Fig. 8 shows that NOx emissions for diesel fuel are minimum at EGR-15% and IP- 240 bar while that for B20 are at EGR-15% and CR-17.Circulation of exhaust gases in large amount reduces combustion temperatures thereby reducing NOx, hence EGR of 15% is recommended for both the fuels.

*3.4.7. Smoke Emissions*

Smoke opacity indicates the fraction of incident light that is adsorbed or scattered by smoke. More smoke opacity is an indication of more heavy particles in smoke. The smaller the better is the condition to be used. At higher loads, generally smoke opacity is greater. When diesel is used as fuel, to get minimum smoke emissions, the engine is to be operated with a large compression ratio (18), injection pressure (180 bar), advanced injection timing ($25^{0}$ bTDC) and less EGR (5 %). As shown in Fig. 2(g), when biodiesel blend (B20) is used as fuel, it is observed that emissions decrease by operating an engine with high compression ratio (18), medium injection pressure (210 bar), retarded injection timing ($19^{0}$ bTDC) and 5 % EGR.




(a) Smoke (%) Vs CR, EGR for B20 fuel




(b) Smoke (%) Vs CR, EGR for Diesel fuel

**Fig. 9.** Surface plot for Smoke (%) Vs Main Contributing factors

The surface plot as in Fig. 9 shows that smoke opacity is minimum for diesel as well as for B20 fuel at 5% EGR and 18 CR. Larger compression ratio, results into complete combustion giving more $CO_2$ and less CO, HC, smoke, hence larger compression ratio is recommended for both the fuels. If there is complete combustion then large EGR is not required, so 5% EGR is sufficient for both the fuels.

### *3.5.* A *Effect of Operating Parameters on Performance and Emission*

#### *3.5.1. Effect of Exhaust Gas Recirculation*

From Table 9 and 15, the following observations can be noted: when diesel is used as fuel, for better thermal performance, EGR of 10 %, to reduce CO, HC and smoke emissions, EGR 5 % and 15 % EGR to reduce NOx can be preferred. When a biodiesel blend is used as fuel, for better thermal performance EGR 5 %, to reduce CO emission EGR 10 %, to reduce HC emission EGR 5 % and 15 % EGR, to reduce NOx can be preferred. As diesel fuel after combustion may contain more CO as a result of incomplete combustion due to presence of less oxygen in diesel fuel compared to biodiesel, so more exhaust gases can be recirculated to carry out complete combustion to produce $CO_2$ for maximum BTE, so 10 % EGR can be used in diesel but 5 % is sufficient when biodiesel blend is used to get maximum BTE. As biodiesel contains more oxygen, there may be complete combustion giving more $CO_2$, which can be recirculated in the combustion chamber, so an EGR of 5 % can be used when biodiesel blend is used. If we increase EGR, then BTE will decrease while using biodiesel blend. To reduce NOx by reducing combustion temperatures, EGR of 15 % can be used in both cases.

Use of exhaust gas recirculation results in reduction of peak combustion temperatures, NOx level and oxygen concentration but increases smoke emission. A large reduction in NOx emission with a small increase in smoke was observed with 15 % EGR in B20, so to reduce NOx the most effective method is to use EGR [19]. EGR can be used for reducing NOx in diesel engines fueled with biodiesel. A considerable reduction in NOx was observed and it is concluded that 15 % is the optimum level giving better BTE, minimum smoke, CO and HC emissions with adequate reduction in NOx [24]. Due to the use of EGR in diesel engines, it results in an increase in the ignition delay, shifts beginning and end of combustion to later stages in compression and expansion stroke. The main reasons for higher NOx reduction are increased $CO_2$ dilution as more $CO_2$ enters combustion, air: fuel ratio decreases compared to diesel and causes retardation of combustion. As the EGR rate increases, dilution of incoming charge increases due which to the quantity of oxygen in the combustion chamber decreases and that results in more HC emissions [24].

#### *3.5.2. Effect of Compression Ratio*

From Table 9 and 15, the following observations can be noted. When diesel is used as fuel, it is recommended to use a compression ratio of 16 for better thermal performance and to reduce CO, $CO_2$ and HC emissions, while 17 for less NOx and 18 to reduce smoke. When B20 is used as fuel, it is recommended to use a compression ratio of 18 for better thermal performance, 16 to reduce CO, 18 to reduce HC and smoke while 17 for $CO_2$ and NOx reduction. Compression ratio plays an important role during the combustion process in diesel engines. As the compression ratio increases, the temperature of air in the cylinder increases, thereby reducing ignition lag, resulting in better and more complete combustion. Compression ratio 16 is sufficient for diesel fuel, but compression ratio 18 is required for biodiesel fuel to have complete combustion to get maximum BTE. By using a large compression ratio (18), it ensures complete combustion, giving more $CO_2$ in exhaust. Hence, a compression ratio of 16 can be suggested for diesel but 18 for biodiesel. Again, if we use a large compression ratio, it increases combustion temperatures giving more NOx hence compression ratio 17 can be preferred for both fuels. Use of biodiesel increases NOx compared to diesel, which may be due to increased exhaust temperatures and since biodiesel has excess oxygen which combines with nitrogen to form NOx.

At a higher compression ratio, due to increase in pressure and temperature, better combustion of fuel takes place which increases BTE, reduces BSFC and HC emissions. Increased compression ratio increases NOx emissions due to higher combustion temperatures. At low compression ratio, due to insufficient heat in compression, results in ignition delay, so HC and CO emissions increase. The less CO emission in biodiesel fuel may be due to complete combustion compared with diesel. Some of the CO produced during combustion of biodiesel may have been converted into $CO_2$ by using extra oxygen from the biodiesel chain [13].

#### *3.5.3. Effect of Injection* Timing

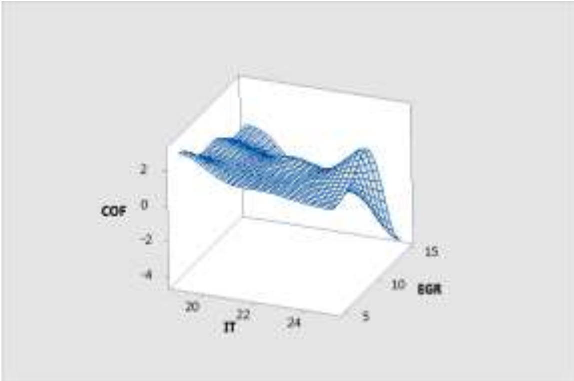
From Table 9 and 15, the following observations can be noted. When diesel is used as fuel for better thermal performance, injection timing of $22^0$ bTDC, $25^0$ bTDC for less emissions and $19^0$ bTDC to reduce NOx emissions is recommended. When the biodiesel blend is used, injection timing of $19^0$ bTDC is recommended in all respects except for complete combustion to increase $CO_2$.Advancement in injection timing increases the oxidation process between carbon and oxygen molecules due to high cylinder temperature which reduces BSFC, EGT, HC, CO, smoke and increases NOx, BTE, BMEP, combustion pressure with rate of heat release. Any change in injection timing from standard decreases BTE for diesel and increases BSFC. Retardation in injection timing means fuel injection starts later, which reduces combustion time resulting in, a decrease of peak cylinder pressure which reduces peak cylinder temperatures, thus reducing NOx emissions. If we keep advanced injection timing, while using B20, it will reduce BTE and increase emissions because that may increase temperatures with more NOx emissions, so injection timing of $19^0$bTDC is recommended for B20.If we are using diesel fuel, standard injection timing is recommended for maximum BTE. Advancement in injection timing reduces CO, HC and smoke with increase in $CO_2$ with increase in temperature that causes better combustion, but to reduce NOx, retarded injection timing of $19^0$bTDC should be preferred to reduce combustion temperatures.

Advancement in injection timing affects positively on volumetric efficiency. Retardation in fuel injection largely affects engine performance, combustion and emissions. Due to retardation of fuel injection, incomplete combustion occurs which decreases BTE and increases BSFC [15]. In diesel engines, to reduce NOx emissions, retarded injection timing is an effective method but it leads to reduction in engine power, more fuel consumption, more HC emissions and heavy smoke [19].

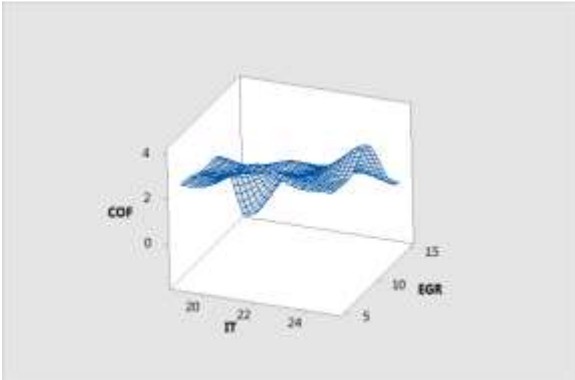
### *3.5.4. Effect of Injection Pressure*

From Table 9 and 15, the following observations can be drawn. When diesel is used as fuel, injection pressure of 180 bar is recommended for better thermal performance while injection pressure of 240 bar for less CO,HC and NOx emissions. When a biodiesel blend is used as fuel injection pressure of 240 bar for better thermal performance and 180 bar for less CO and HC emissions, while 210 bar to reduce NOx and smoke can be preferred. As the calorific value of biodiesel is less than diesel, in order to have more BTE, there should be complete combustion, i.e. more $CO_2$ should be produced which requires, large injection pressure, ultimately large combustion temperature, but for diesel with less injection pressure, complete combustion can occur, producing more $CO_2$.If we keep large injection pressure for B20, it will increase combustion temperature hence increasing NOx therefore to reduce HC, CO and to increase $CO_2$ it should be 210 bar. In diesel with 240 bar injection pressure, more $CO_2$ will be produced instead of CO, HC and NOx because of less oxygen molecules present. In case of a biodiesel blend, due to the presence of more oxygen that may combine with nitrogen to form NOx, a pressure of 210 bar can be preferred.

It was observed that BTE increases with increase in injection pressure. This may be due to a high degree of atomization at more injection pressure resulting in complete combustion. BSFC reduces with increase in IP. This is due to proper atomization at large IP which exposes more surface area of fuel droplet to large temperature air resulting, in complete combustion. BSFC for biodiesel is more than diesel due to more viscosity and lower calorific value. The EGT increases with IP due to complete combustion of fuel generating more heat in the exhaust.EGT for biodiesel is less than diesel and may be due to less calorific value. The CO and HC emission reduces, while $CO_2$ increases with increase in IP due to the cause that fuel is atomized into fine droplets and a large surface area is available for combustion which forms a good quality fuel mixture, leading to complete combustion.CO emission for biodiesel is less than diesel due to more oxygen in biodiesel fuel. When fuel burns, carbon combines with oxygen forming $CO_2$, hence less CO and more $CO_2$ emissions. The NOx emission increases with increase in IP due to more fuel burning resulting in higher temperatures. For biodiesel due to the presence of oxygen, higher temperatures are produced in the engine cylinder, giving more NOx. The smoke decreases with increase in IP. Smoke intensity for biodiesel is more than diesel [14].




(a) COF Vs IT, EGR for B20 fuel




(b) COF Vs IT, EGR for Diesel fuel

**Fig. 10.** Surface plot for COF (50:50) Vs Main Contributing factors

The surface plot as in Fig. 10 and Fig. 2(h) shows that COF ( 50:50 weightage) for diesel fuel is optimum at 5%EGR and $25^0$bTDC while that for B20 is at 10%EGR and $19^0$bTDC.The EGR is the main affecting factor for combine objective function. As 50:50 weightage is given to both thermal performance and emissions by taking into consideration all the parameters 5% EGR is recommended for diesel and 10 % for biodiesel fuel. Exhaust Gas Temperature during combustion of diesel may be more than biodiesel due to higher calorific value so to achieve better BTE and to reduce NOx, CO, HC, smoke only 5%EGR is suggested for diesel fuel while 10% for biodiesel due to more oxygen.

Above results as in Table 18, shows that BTE and BSFC for both the fuels are comparable. $CO_2$ emissions are almost equal. There is reduction in NOx due to use of EGR but simultaneous increase in CO, HC and smoke.

The summary of various optimum operating parameters for different biodiesel fuel blends is given in Table 19.

**Table 18.** Validation test results

| Fuel | CR | IP | IT | EGR | BTE (%) | BSFC (Kg/KWh) | CO (%) | $CO_2$ (%) | HC (ppm) | NOx (ppm) | Smoke (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Diesel 80% + Cocklebur Biodiesel 20% | 18 | 210 | 19 | 10 | 21.37 | 0.3712 | 1.4 | 3.9 | 63 | 74 | 2.7 |
| Diesel 100% | 18 | 240 | 25 | 5 | 23.04 | 0.3418 | 0.11 | 4.1 | 16 | 325 | 1.3 |

**Table 19.** Summary of optimum operating parameters for different biodiesel fuel blends

| Sr. No. | Name of Researcher | Biodiesel Fuel Blend used | Compression Ratio | Injection Pressure (bar) | Injection Timing ($^0$bTDC) | Exhaust Gas Recirculation (%) | Optimization Method | References |
|---|---|---|---|---|---|---|---|---|
| 1 | S. Pawar et al. | Xanthium strumarium L. (B20) | 18 | 210 | 19 | 10 | Taguchi | This work |
| 2 | C. Srinidhi et al. | Azadirachta indica (B25) | 17.25 | 227.86 | 27 | - | RSM | [31] |
| 3 | S. V. Channapattana et al. | Callophyllum Inophyllum (B60) | 18 | 227 | 22 | - | GA and ANN | [9] |
| 4 | A. Singh et al. | Jatropha Curcas (B30) | 18 | 180 | - | - | RSM | [1] |
| 5 | A. N. Kumar et al. | Elaeis guineensis (B20) | - | - | 27 | 20 | - | [26] |

## 4. Conclusion

The values estimated using regression equations for each response shows close agreement with measured values as Correlation coefficient ($R^2$) is closer to 0.9. Exhaust gas recirculation is the major contributing factor in all respect considering thermal performance, emissions and NOx also. Considering equal weightage to both thermal performance and emission as optimum condition, it is recommended to use 10 % EGR when biodiesel blend B20 is used as fuel compared with 5 % for diesel. Injection angle is a second contributing factor. For all conditions it is recommended to use retarded injection angle of $19^0$ bTDC when B20 is used as fuel as compared to $25^0$ bTDC for diesel. Injection pressure is a third contributing factor which should be 240 bar while using diesel compared with 210 bar when B20 is used. Fourth contributing factor is compression ratio which should be 18 for both fuels. Average relative reduction in the value of BTE is 2.48 % and average relative increase in BSFC is 6.37 % when B20 is used as fuel compared with diesel, also there is average relative increase in CO (22.93%), HC (36.40%), smoke (1.83%) but reduction in NOx (20.52%) and $CO_2$ (4.2%) when B20 is used as fuel compared with diesel. Experiments performed for validation using optimum conditions of operating parameters gives better results with thermal efficiency comparatively less than diesel and the emissions are within limits as per BS6 and EURO6 norms. Hence B20 can be effectively used as fuel without any engine modifications.

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