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Performance and Combustion Analysis of Diesel Engine Fueled with Jatropha Biodiesel—Diesel Blends Using Taguchi's Approach

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ABSTRACT
The aim of this work is to analyze performance and combustion of the various blends of diesel fuels and jatropha biodiesel. Experiments have been carried out using a single-cylinder, four-stroke, variable compression ratio CI engine fueled with jatropha biodiesel and its blends with diesel fuel. The test has been conducted using the fuel blends of 0%, 50% and 100% by volume biodiesel with diesel fuel. The percent biodiesel (0%, 50% and 100%), compression ratio (16, 17, 18), injection pressure (200, 180, 160 bar) and load (2, 7, 12 kg) are considered as input parameters. The responses for the experiments are specific fuel consumption (SFC), brake thermal efficiency (BTHE) and peak pressure. Taguchi approach is used to reduce the number of experiments. The optimum sets of the parameters are selected on signal-to-noise ratio basis. Optimum set for BTHE is 16 compression ratio, 0% biodiesel, 200 bar injection pressure and 12 kg engine load. The predicted value of BTHE (43.17) is closer to the experimented value (41.32 %) of BTHE at these levels. Optimum set for SFC is 16 compression ratio, 0% biodiesel, 200 bar injection pressure and 12 kg engine load. The predicted value of SFC (0.33 kg/kWh) is closer to the experimented value (0.37 kg/kWh) of SFC at these levels. Optimum set for peak pressure is 18 compression ratio, 0% biodiesel, 200 bar injection pressure and 12 kg engine load. The predicted value of peak pressure (82.83 bar) is closer to the experimented value (81.25 bar) of peak pressure at these levels.

Keywords: *combustion, diesel engine, jatropha, performance, Taguchi approach*

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INTRODUCTION

Day to day population is increasing. The development of megacities and urban cities increases so that the use of automobile vehicles such as car, two-wheeler, commercial vehicle, etc. increases [1]. Air pollution is an impact health problem. Vehicle exhaust in most gases is hydrocarbons (HC), carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_x), lead, smoke or particle matters, sulfur dioxide (SO_2) etc. [2, 3]. Air pollution can harm health like irritation of eyes, nose, throat pain, coughing, chest tightness problem, etc. [4]. Air pollution can cause a variety of environmental effects. Acid rain is precipitation containing harmful amounts of nitric and sulfuric acids. These acids are formed primarily by nitrogen oxides and sulfur oxides released into the atmosphere when fossil fuel is burned [5, 6]. This affects wildlife, water, ozone depletion, crop and forest damage, greenhouse effect. Emission of carbon monoxide is produced by lack of air in combustion chamber [7]. Lack of air through incomplete combustion process takes place and CO is emitted into the atmosphere. Excess air in suction valve so complete combustion through HC and CO recused but high temperature creates and nitrogen oxide increase [8]. In Indian market transport sector, 70% diesel fuel consumption, both direct as well as retail sales, is shown at all Indian states. Low commercial vehicles (LCV), high commercial vehicles (HCV), and buses together consume about 38% fuel consumption. This is due to the largest distance transports goods as well as passengers. Car and utility vehicles (UVs) category contributed nearly about 22%, in which private vehicles consume a little less than 60% of the total in this category. Agriculture sector consumes around 13% fuel consumption [9, 10].

LITERATURE SURVEY

A study on Taguchi method is used to ascertain the ideal set of a parameter with performance, combustion analysis used to the diesel, palm seeds, and its blend. Analysis B10%, B20, B30% of palm seed oil, diesel with compression ratio 16, 17, 18), injection pressure (160, 180, 200 bar), and load (2, 6, 10 kg) predict a result of brake thermal efficiency (BTHE) 40.80% [11]. A study on Taguchi method is done using pyrolysis oil and diesel blends. Ideal factor level for optimum multi-performance diesel engine runs with different blends ratio. The four factors are low-percentage blend ratio, compression ratios, injection pressure and load which three levels. L9 orthogonal result is used to cluster data for various engine performances. S/N ratio is used to find the optimum set of parameter [12]. The experiment concluded different static injection timings of 31.5, 32, 34.5 and 35.5 earlier top dead center (TDC) at rated injection opening operation of 205 bar. Jatropha biofuel injection timing has to be advanced as compared to diesel opening in order to compensate for the higher delay. 3 crank angle advanced (33.5 bTDC) injection timing and improved increase in the BTHE from 25.7% to 27.3% [13]. Experimented on jatropha oil. Jatropha fuel viscosity is more than diesel fuel, so viscosity is reduced to 33 by increasing oil temperature using waste heat exhaust gases. Experiment on jatropha oil is done with exhaust gas recirculation (EGR) system [14]. The diesel engine runs with jatropha oil that emits higher nitrogen oxide. HOT EGR system is a low-cost technique running on jatropha oil of exhaust gas recirculation. Ganapathy et al. [15] studied dual biodiesel blends: one is palm seed oil and the other is jatropha oil. The results for the lower blend of biodiesel D90JB5PB5 with diesel showed 4.65% average increase in BTHE. There were 7.1%, 17.7% and 14.5% average reductions in CO emissions with samples D90JB5PB5, D80JB10PB10 and D70JB15PB15, respectively, when compared to diesel. Lower blends of diesel samples D90JB5PB5 and D80JB10PB10 showed 5.3% and 9.2% average increase in NO_x emissions, respectively, than diesel [16].

NON-EDIBLE JATROPHA BIODIESEL PRODUCTION AND PROPERTIES

The possibility of using vegetable oils as fuels in diesel engine is that vegetable oils have a very high viscosity, so used as fuel by lowering its viscosity. Transesterification method is used for decreasing the viscosity of jatropha oil. This method is a reaction of a fat oil (triglyceride) with alcohol to form esters and glycerol: a reaction between triglyceride and alcohol with a catalyst. A catalyst is used to ameliorate the reaction rate and yield [17, 18]. The physical and chemical properties of jatropha biodiesel are shown in Table 1. The blend density and calorific value are shown in Table 2.

Jatropha Biodiesel Properties

Table 1. *Physical and chemical properties for various biodiesels [19–24].*

Parameter	Unit	Diesel	Jatropha	Palm	Soybean	Sunflower	Peanut	Catton
Density at 15°C	kg/m^3	833	896	870	874	860	889	856
Kinematic viscosity at 100°C	Centipoise	3.0	9.82	4.8	5.19	4.9	5.3	4.5
Flash point	^{0}C	74	135	130	160	150	166	146
Fire point	^{0}C	120	148	171	150	122	153	120
Cetane		49	61.2	62	56	60	53	66
Calorific value	kJ/kg	42850	39100	38600	38100	37250	36000	35500

Table 2. *Blends density and calorific value.*

Parameter	Density (kg/m^3)	Calorific value (kJ/kg)	Quantity of fuel used
100D0B (100% diesel and 0% jatropha biodiesel by volume)	832	42,000	2 l (D)
50D50B (100% diesel and 0% jatropha biodiesel by volume)	864	40,496	1 l (D) + 1 l (B)
0D100B (100% diesel and 0% jatropha biodiesel by volume)	896	39,100	1 l (B)

EXPERIMENT SETUP

Figure 1 shows the schematic diagram and engine setup of the experiment. The setup consists of single-cylinder, four-stroke, variable compression ratio multi-fuel engine coupled with eddy current dynamometer for loading. The detailed specification of the engine is shown in Table 3. The tests have been conducted at the rated speed of 1500 rpm at different parameter changes. Diesel fuel is used to start the engine and is allowed to warm up. The engine setup in air flow and fuel flow, temperature, load, injection pressure, and engine speed sensor used are shown in Table 4. A computerized data acquisition system is used to collect, store and analyze data acquisition data during the experiment by various sensors. The engine performance and combustion analysis were done by software Sense and encoding by "Engisoft".

Table 3. *Setup specification [25].*

Engine Manufacturer	**Kirloskar/MINI-185SM**
Product	Research engine setup single cylinder, 4-stroke, multifuel, VCR, product code 240 computerized
Engine cylinder size	Stroke 110mm, Bore 87.5mm, capacity 661cc
Diesel mode	Power 5.2 kW, speed-1500 rpm, C-R range 12:1-18:1, injection pressure range 160 bar-200 bar
Dynamometer	Eddy current with water cooled loading unit
Temperature sensor	RTD type, PT-100, thermocouple
Load indicator	Digital, range 0-50 kg
Load sensor	Strain gauge, 0- 50 kg
Software	Enginesoft, engine performance analysis

Table 4. *List of sensor in VCR engine experiment model [25].*

Symbol	Sensor Name
F1	Fuel flow sensor
F2	Air flow sensor
W	Load sensor
N	Engine speed sensor
PT	Cylinder injection pressure sensor
T1-T6	Temperature sensor

Compression Ratio Adjustment

The following steps were used to change the compression ratio:

- Slightly loosen 6 Allen bolts provided for clamping the tilting block.

- Loosen the lock nut on the adjuster and rotate the adjuster so that the compression ratio is set to "maximum". Refer the marking on the CR indicator.
- Lock the adjuster by the lock nut.
- Tighten all the 6 Allen bolts gently.
- You may measure and note the center distance between two pivot pins of the CR indicator. After changing the compression ratio, the difference can be used to know the new CR.

Injection Pressure Adjustment

The following steps are used to adjust the injection pressure:

- It is presumed that engine is running in diesel mode and online diesel injection plot is being displayed on the monitor using software.
- The injection point is displayed on the software,
- Turn the injection point adjusting the nut gradually, and note its effect on diesel injection plot. The diesel injection plot shifts horizontally to advance or till retarded injection point is obtained.

Load Adjustment

Eddy current dynamometer is used to vary load on engine. To adjust the load, the following steps are used:

- When knob is rotated in clockwise direction, the electric magnetic force increases.
- Electric magnetic force is produced in the opposite direction of the engine speed.
- When the knob rotates in clockwise direction, at that time the load increases, and when the knob rotates in anticlockwise, the load decreases.
- Load variation shows the load indicator.

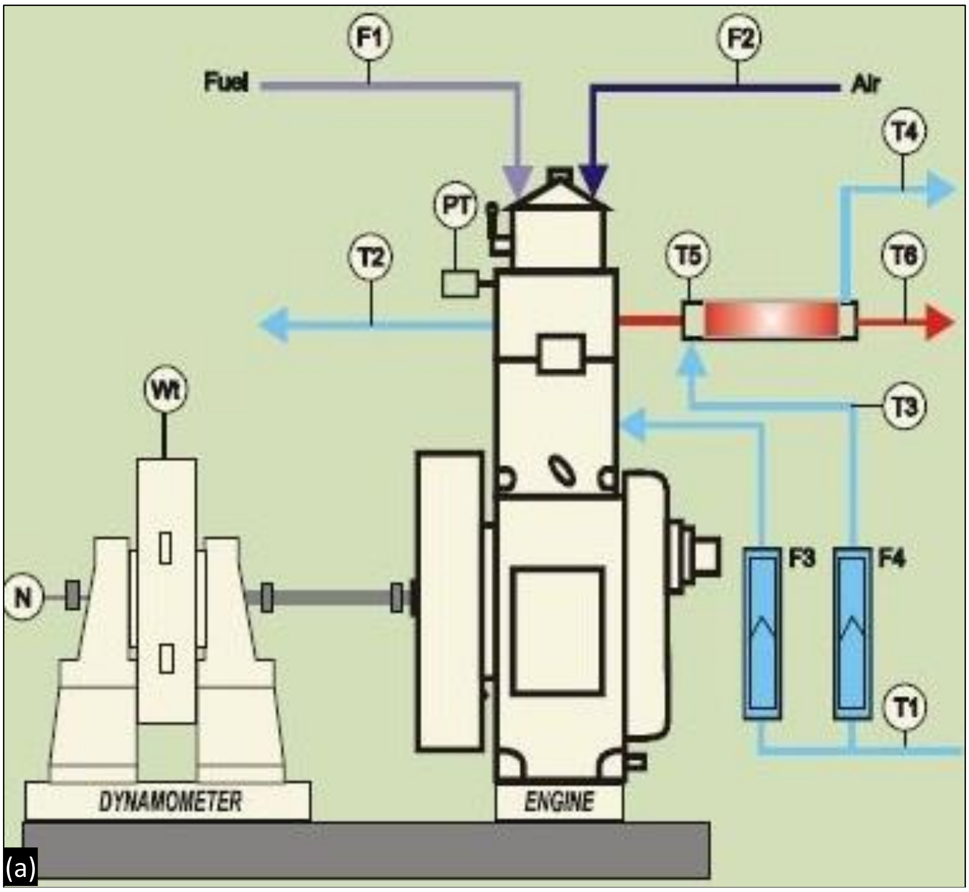

Fig. 1. *Schematic diagram and engine setup of VCR engine [25].*

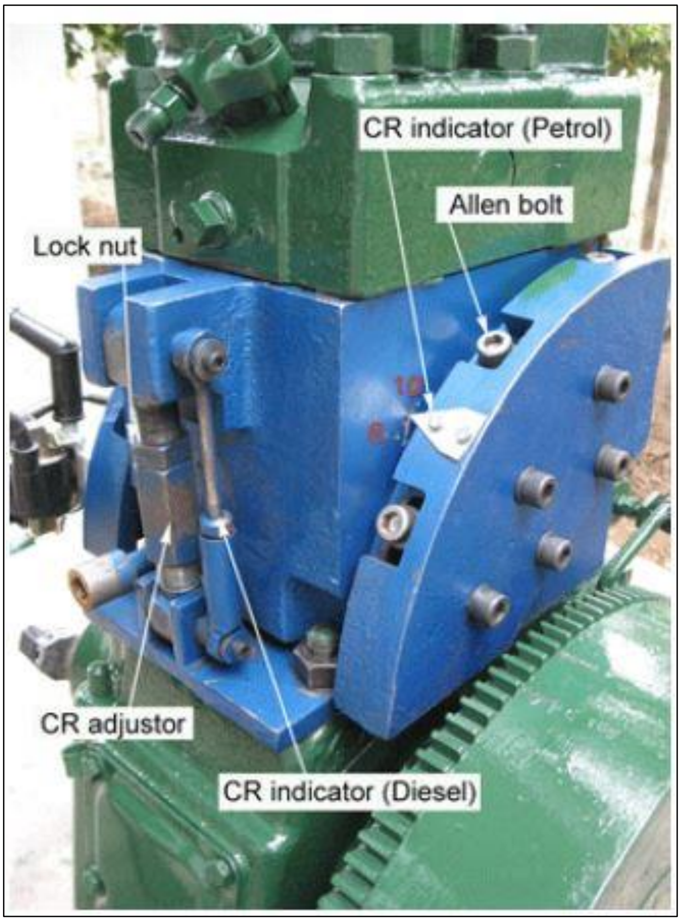

Fig. 2. *Compression ratio adjustment [25].*

Fig. 3. *Injection pressure adjustment [25].*

Fig. 4. *Eddy current dynamometer and load switch [25].*

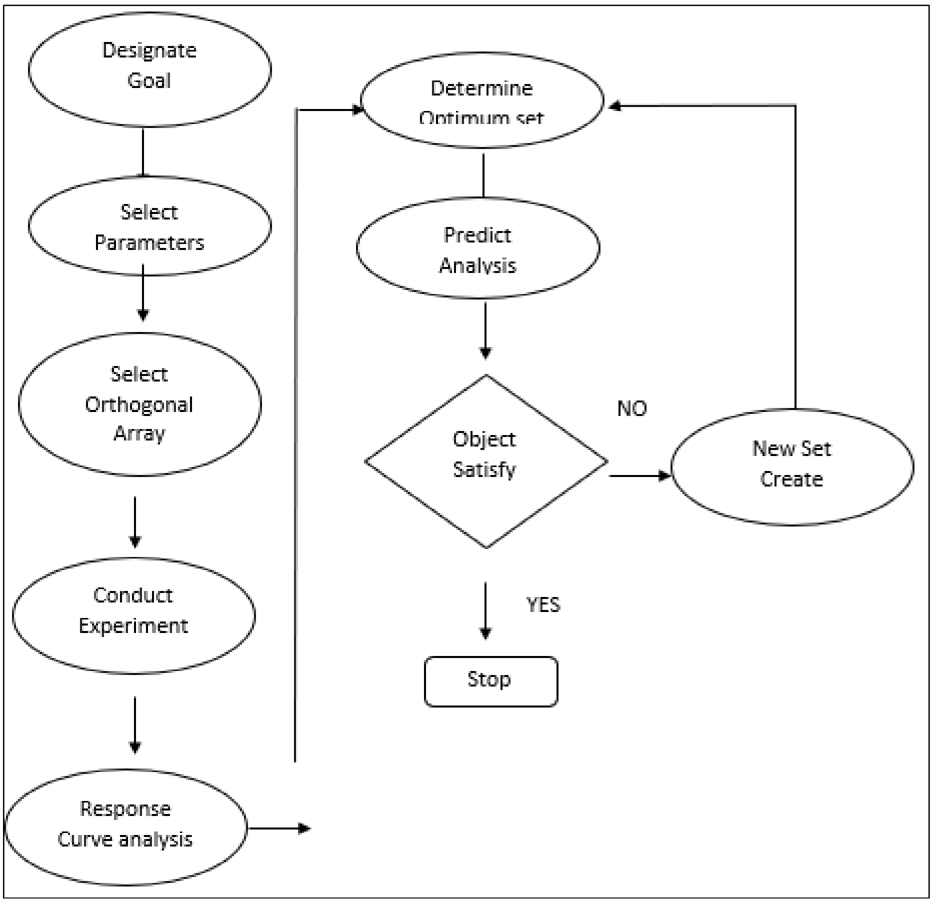

Fig. 5. *Flow chart of Taguchi method.*

METHODOLOGY

The Taguchi method is used for simple and effective solutions to study the performance parameters as well as experiment planning. Taguchi experiment in used in two-step optimization process: S/N ratio identification and no-affect noise factor. In Taguchi analysis, the mean of means and S/N ratio are considered. S/N ratios measure how the response varies relative to the nominal. S/N ratio is chosen by goal of experiment. Minitab software offers four types of S/N ratio: larger is better, smaller is better, nominal best, nominal is best (default), smaller is better [26]. Taguchi approach in L9 array experiment table is shown in Figure 5 [27].

In the experiment performed before, Taguchi analysis table is generated by Minitab software, which shows the control factor compression ratio, blend ratios, injection pressure and engine load (Table 5).

DOE technique is used to identify the key factors of experiment. DOE advice orthogonal array is selected on the basis of control factor and level of experiment. Experiment in four number of factor with 3 level so L9 design of array generated shown in Table 6 [28].

Table 5. *Setting level of design factor.*

Control factors	**Level 1**	**Level 2**	**Level 3**
Compression **ratio**	16	17	18
% **biodiesel by volume**	0	50	100
Injection **pressure** (bar)	200	180	160
Load (kg)	2	7	12

OBSERVATION AND RESULT TABLE

Experiments are conducted on jatropha biodiesel, diesel and its blend which change the injection pressure, compression ratio, engine load and BTHE, specific fuel consumption, and fuel consumption. Tables 7 and 8 show the observation data sheet directly generated by Enginesoft software.

RESULT AND DISCUSSION

Experiments have been carried out by used compression ratio (18, 17, 16), % biodiesel (0%, 50%, 100%), injection pressure (200 bar, 180 bar, 160 bar), and engine load (2 kg, 7 kg, 12 kg). Minitab 18 software is used for Taguchi analysis. Minitab 18 software generated graphs and table for means of means and S/N ratio. Optimum set of parameter is found out by the value of S/N ratio.

Analysis Brake Thermal Efficiency

For the analysis of engine performance parameter BTHE, responsible variable was S/N ratio which is higher is better. Figure 6 shows the mean of means for BTHE. Figure 7 shows the S/N ratio for BTHE. The value of S/N ratio is higher with 16 compression ratio, 0% bio diesel, 200 bar injection pressure and 12 kg load, which are the values of optimum set parameter. This set gives to higher BTHE than the other set of parameters.

Refer Table 9 for S/N ratio in delta value maximum 20.65 for injection pressure and minimum value 2.15 for compression ratio. It is concluded that injection pressure is the most affected parameter of BTHE and compression ratio is the least affected parameter.

From the above analysis, the optimum set of parameters having the maximum BTHE is found out and given in Table 10.

Analysis of Specific Fuel Consumption

For the analysis of engine performance for specific fuel consumption, the responsible variable was S/N ratio which is lower is the better. Figure 8 shows the mean of means for specific fuel consumption. Figure 9 shows the S/N ratio for specific fuel consumption. The higher value of S/N ratio is 18 compression ratio, 50% biodiesel, 180 bar injection pressure and 7 kg load, which are the values of optimum set parameter. This set gives the lower specific fuel consumption than the other set of parameter.

Refer Table 11 for the S/N ratio in delta value maximum 4.57 for blend ratio and minimum value 1.83 for compression ratio. It is concluded that % biodiesel is the most affected parameter for specific fuel consumption and compression ratio is the least affected parameter.

Table 7. *Observation table.*

Experiment	Compression ratio	% Biodiesel by volume	Injection pressure (bar)	Load (kg)	Fuel (cc/min)
1	18	0	160	12	10
2	18	50	200	2	5
3	18	100	180	7	7
4	17	0	180	12	10
5	17	50	160	2	4
6	17	100	200	7	7
7	16	0	160	7	7
8	16	50	200	12	9
9	16	100	180	2	4

Table 8. *Result table.*

Experiment	Compression ratio	% Biodiesel by volume	Injection pressure (bar)	Load (kg)	BTHE %	SFC (kg/kWh)
1	18	0	160	12	54.01	0.15
2	18	50	200	2	20.36	0.39
3	18	100	180	7	45.66	0.17
4	17	0	180	12	52.56	0.15
5	17	50	160	2	22.21	0.36
6	17	100	200	7	45.37	0.18
7	16	0	160	7	44.9	0.18
8	16	50	200	12	58.54	0.14
9	16	100	180	2	23.05	0.21

***Table 9.** Response table for S/N ratios of brake thermal efficiency.*

Level	Compression ratio	% Biodiesel by volume	Injection pressure (bar)	Load (kg)
1	42.16	50.49	52.64	33.09
2	40.05	33.70	31.99	36.88
3	40.01	38.03	37.59	52.25
Delta	2.15	16.79	20.65	19.16
Rank	4	3	1	2

***Table 10.** Optimum set parameter of brake thermal efficiency.*

Compression ratio	% Biodiesel by volume	Injection pressure (bar)	Load (kg)	Predicted value of BTHE %	S/N ratio
16	0	200	12	133	39.3558

From the above analysis, the optimum set of parameters having the minimum specific fuel consumption is found out and given in Table 12.

***Table 11.** Response table for S/N ratio of specific fuel consumption.*

Level	Compression ratio	% Biodiesel by volume	Injection pressure (bar)	Load (kg)
1	15.18	15.95	16.15	12.97
2	13.42	11.38	12.74	12.66
3	13.35	14.61	13.05	16.32
Delta	1.83	4.57	3.41	3.66
Rank	4	1	3	2

***Table 12.** Optimum set parameters of specific fuel consumption.*

Compression ratio	% Biodiesel by volume	Injection pressure (bar)	Load (kg)	Predicted value of SFC (kg/kWh)	S/N ratio
0	0	200	12	0.33	10.0053

Combustion Analysis

Three phases of CI engine combustion analysis: ignition delay period, uncontrolled combustion, and period control combustion [29-30]

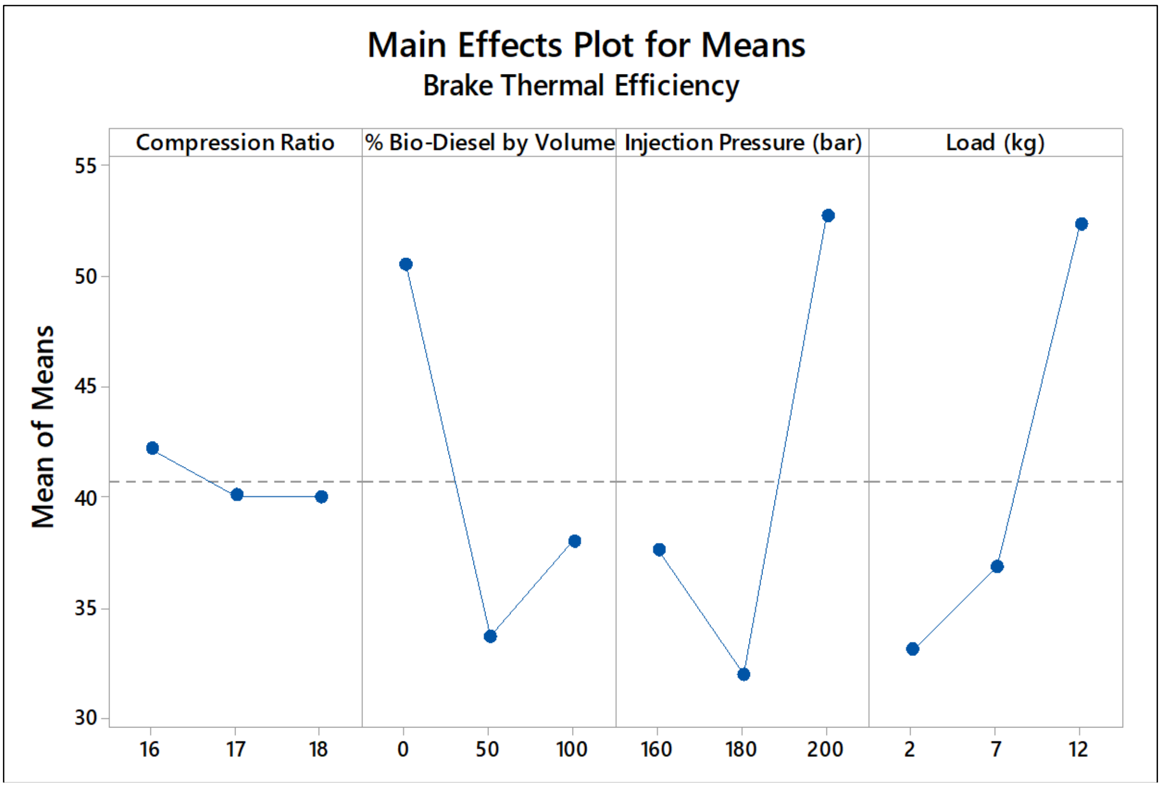

***Fig. 6.** Main effects plot for the mean for means of brake thermal efficiency.*

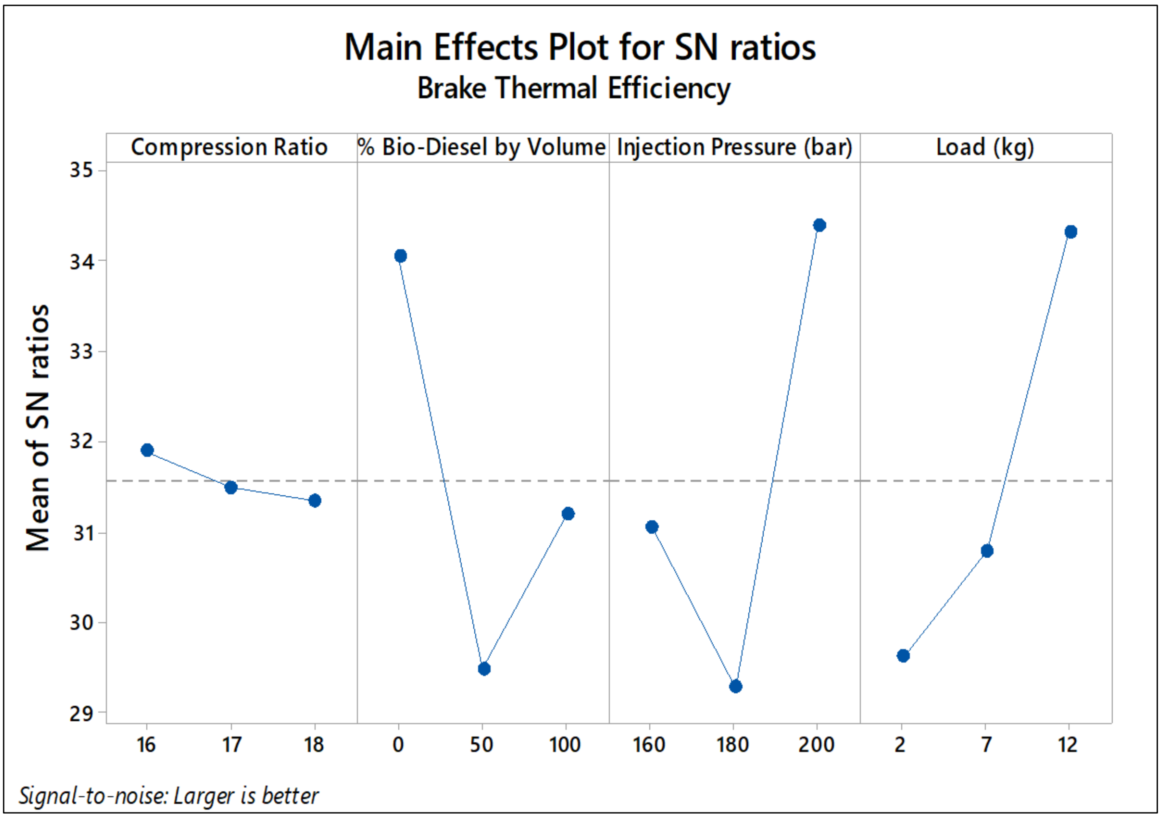

Fig. 7. *Main effect plot of S/N ratio for brake thermal efficiency.*

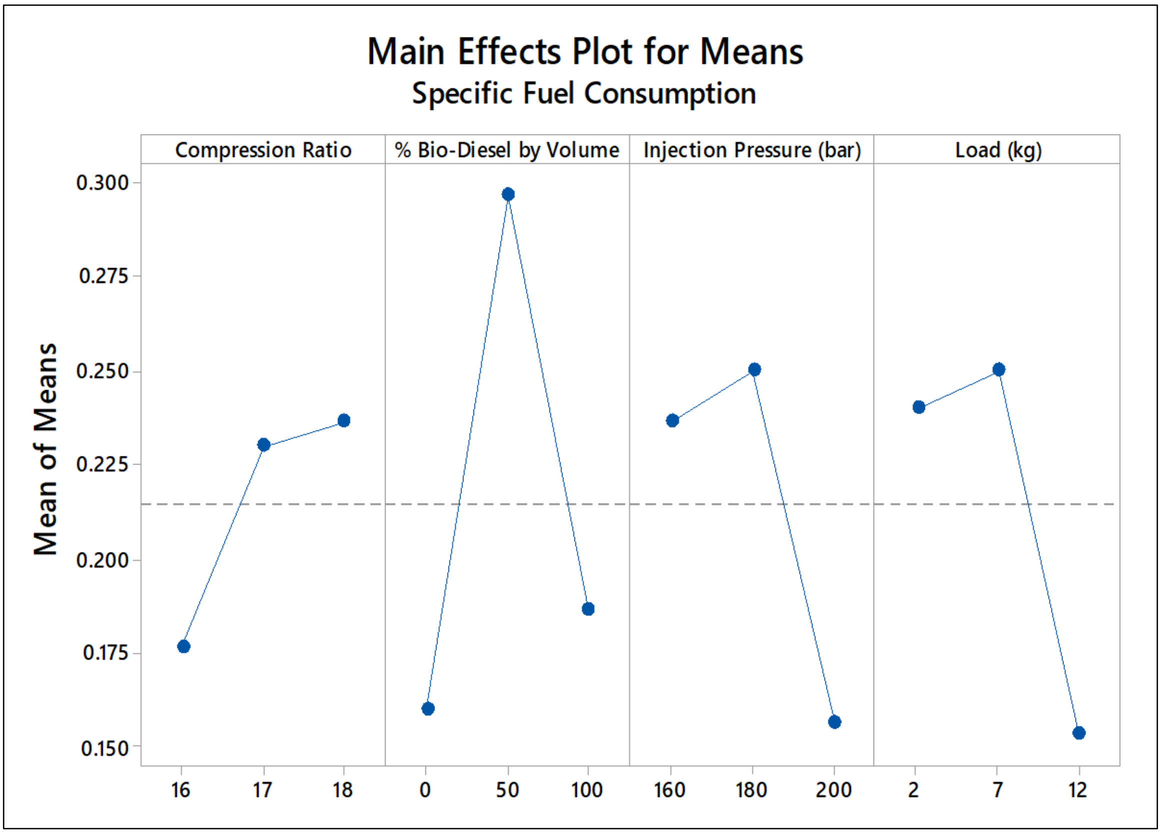

Fig. 8. *Main effects plot for the means of specific fuel consumption.*

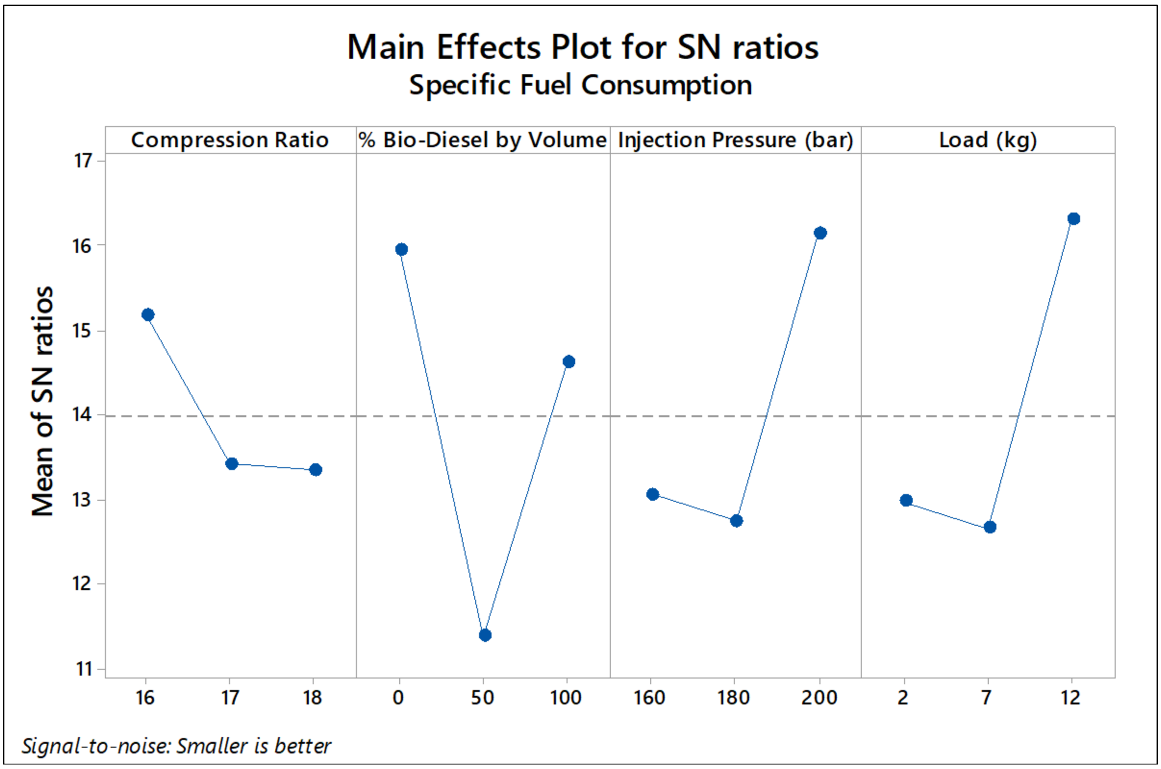

Fig. 9. *Main effects plot for the S/N ratio of specific fuel consumption.*

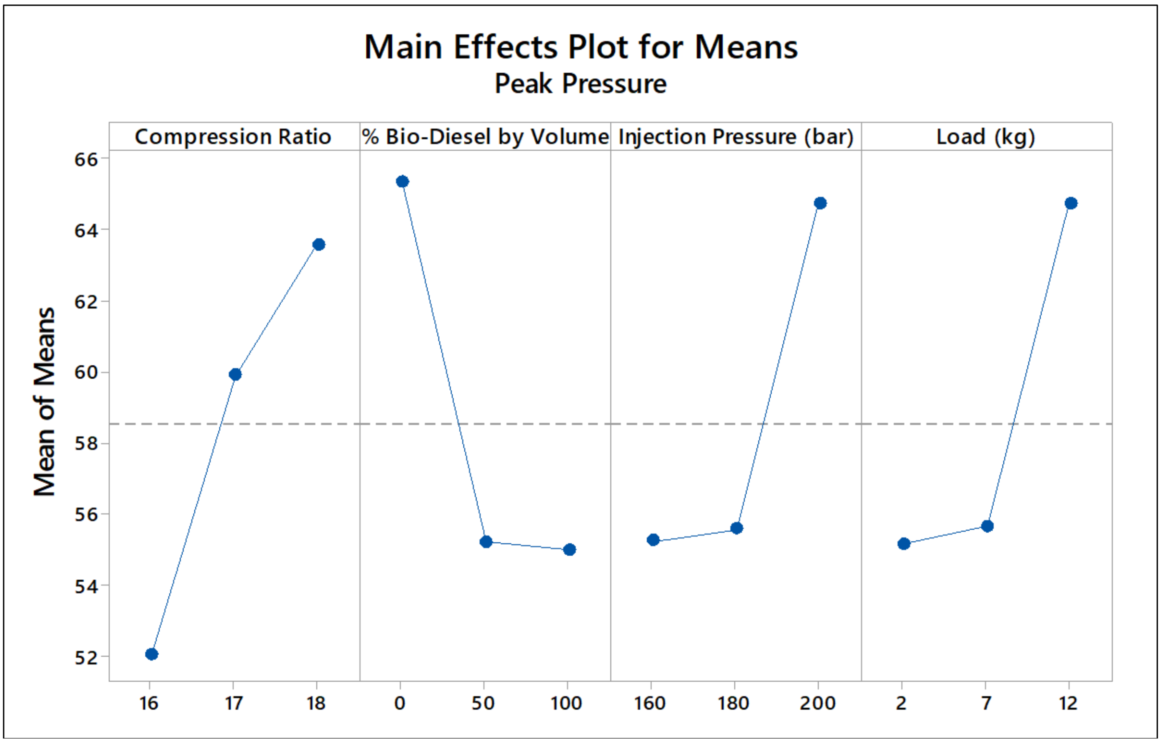

Fig. 10. *Main effects plot for means of peak pressure.*

Analysis of Peak Pressure

For the analysis of engine combustion for peak pressure, the responsible variable was S/N ratio which is higher is the better. Figure 10 shows the mean of means for peak pressure. Figure 11 shows the S/N ratio for peak pressure. The higher value of S/N ratio is 18 compression ratio, 0% bio diesel, high injection pressure and 12 kg load, which are the values of optimum set parameter. This set gives the higher peak pressure than the other set of parameters shown in Table 13.

Refer Table 12 for the S/N ratio in delta value maximum 1.80 for compression ratio and minimum value 1.47 for injection pressure. It is concluded that compression ratio is the most affected parameter and peak pressure as well as injection pressure is the least affected parameter.

Table 13. *Response table for S/N ratios for peak pressure.*

Level	Compression ratio	% Biodiesel by volume	Injection pressure (bar)	Load (kg)
1	34.20	36.19	36.19	34.59
2	35.47	34.81	34.71	34.87
3	36.00	34.67	34.78	36.21
Delta	1.80	1.51	1.47	1.61
Rank	1	3	4	2

Table 14. *Optimum set parameters of peak pressure.*

Compression ratio	% Biodiesel by volume	Injection pressure (bar)	Load (kg)	Predicted value of peak pressure	S/N ratio
18	0	200	12 kg	82.83	38.9102

From the above analysis, the optimum set of parameters having the maximum peak pressure is found out and given in Table 14.

Figure 12 shows the rise of cylinder pressure at the time of fuel injected on the combustion chamber. Figure 13 shows the higher cylinder pressure up to 73.25 bar and lower cylinder pressure 42.29 bar. Compression ratio 18, injection pressure 160 bar, 12 kg engine load with neat diesel are the parameters that give higher cylinder pressure up to 73.25 bar. Injection starts at 340° crank angle rotation and combustion starts at 350° crank rotation. The time between which the injection and combustion start is called ignition delay period. The second stage starts at 350° crank rotation, and up to 380° crank rotation, it is a stage in which the pressure rapidly increases and combustion is uncontrolled. After 380° crank rotation, combustion is under control. Injection pressure 180 bar, 2 kg engine load with pure jatropha biodiesel, lower cylinder pressure prior to 42.29 bar. Injection starts at 340°crank angle rotation and combustion starts at 350° crank rotation. The second stage starts at 350° crank rotation, and up to 380° crank rotation, it is a stage in which the pressure rapidly increases and combustion is uncontrolled. After 380° crank rotation, the combustion is under control.

Table 15. *List of set parameters for experiment.*

Experiment	Compression ratio	% Biodiesel by volume	Injection pressure (bar)	Load (kg)	Peak pressure (bar)
EX 1	18	0	160	12	73.25
EX 2	18	50	200	2	54.5
EX 3	18	100	180	7	63
EX 4	17	0	180	12	70
EX 5	17	50	160	2	50
EX 6	17	100	200	7	59.75
EX 7	16	0	160	7	52.75
EX 8	16	50	200	12	61.2
EX 9	16	100	180	2	42.29

Table 16. *Predicted value and experimented value.*

Response	Predicted value	Experimented value	Difference
Brake thermal efficiency (%)	43.1733	41.32	1.8533
Specific fuel consumption (kg/kWh)	0.33	0.37	0.04
Peak pressure (bar)	82.83	81.25	3.10

The rate of pressure increase depends on the amount of fuel present at the end-delay period. Diesel fuel density is lower than jatropha biodiesel, so more atomization of diesel is required. Cylinder pressure rise rate also depends on compression ratio and injection pressure. In diesel experiment, compression ratio is 18, and in jatropha biodiesel, compression ratio is 16. So diesel experiment has higher combustion pressure. Refer Table 15 for peak pressure as per the experiment data.

Refer Table 16 for BTHE 43.1733%, specific fuel consumption 0.33 kg/kWh, peak pressure 75.83 bar, which are the predicted values of optimum set. When this optimum set performs, it gives value of BTHE 41.32%, specific fuel consumption 0.37 kg/kWh, peak pressure 81.25 bar near about the predicted value.

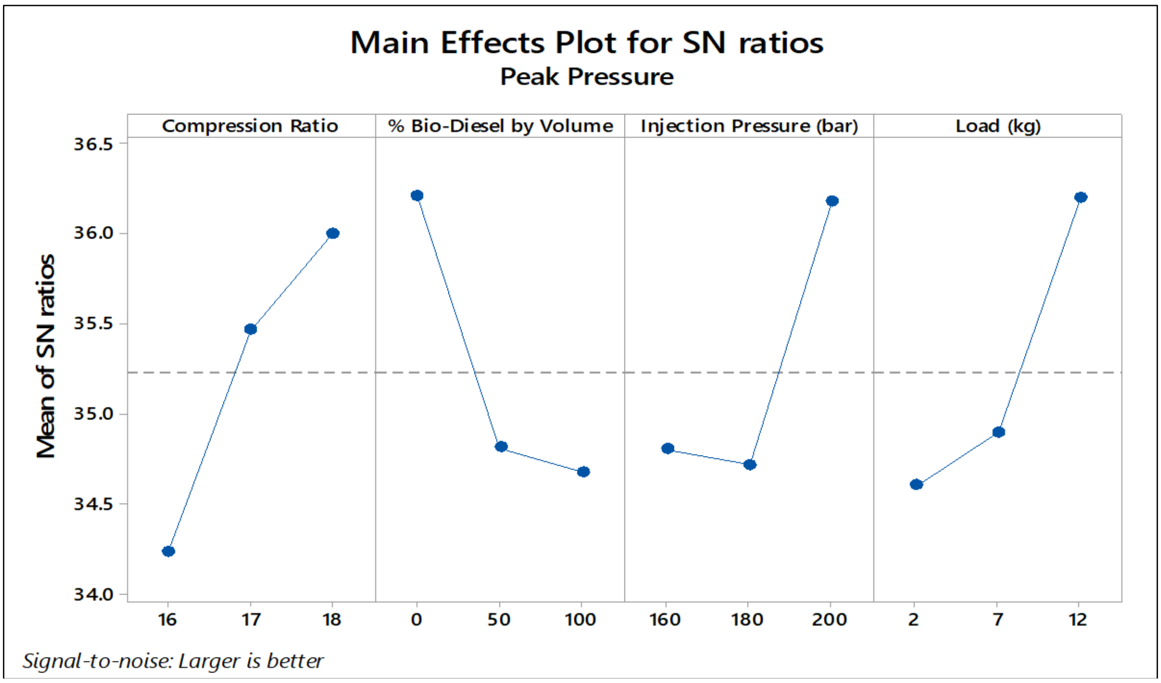

Fig. 11. *Main effect plot for SN ratios of peak pressure.*

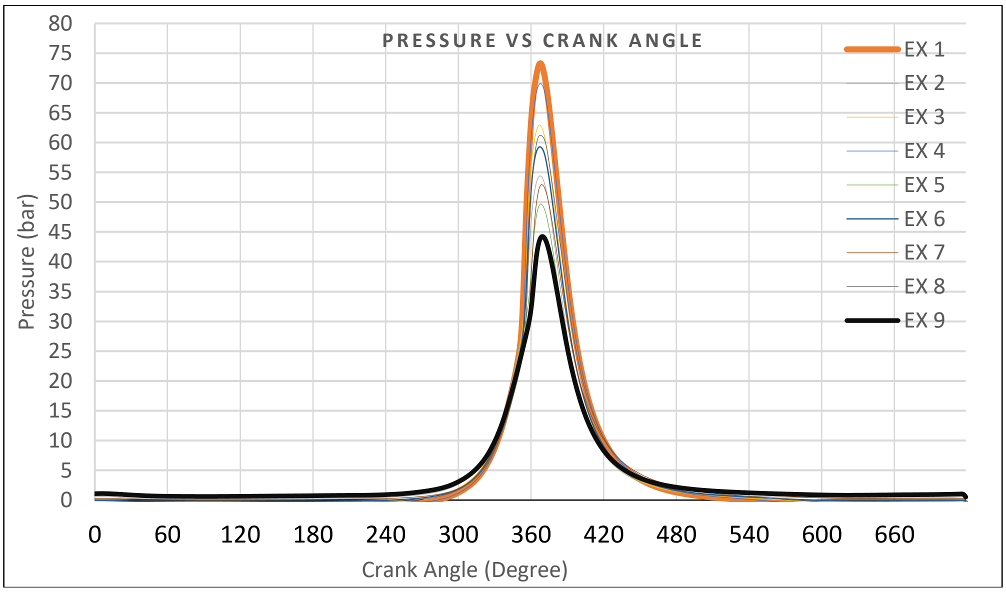

Fig. 12. *Full view of pressure versus rank angle.*

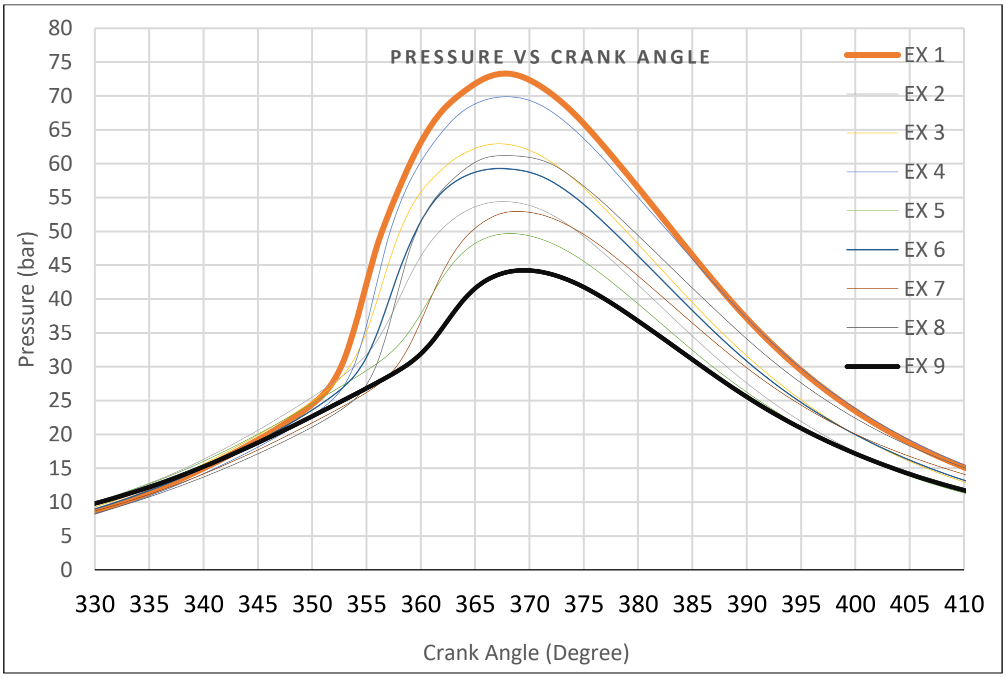

Fig. 13. *Pressure versus crank angle.*

CONCLUSIONS

The Taguchi analysis used to find the optimum set parameter for control factor and level of experiment.

- Optimum set for BTHE is 16 compression ratio, 0% biodiesel, 200 bar injection pressure and 12 kg engine load. The predicted value of BTHE (43.17) is closer to the experimented value (41.32 %) of BTHE at these levels.
- Optimum set for SFC is 16 compression ratio, 0 % biodiesel, 200 bar injection pressure and 12 kg engine load. The predicted value of SFC (0.33 kg/kWh) is closer to the experimented value (0.37 kg/kWh) of SFC at these levels.
- Optimum set for peak pressure is 18 compression ratio, 0 % biodiesel, 200 bar injection pressure and 12 kg engine load. The predicted value of peak pressure (82.83 bar) is closer to the experimented value (81.25 bar) of peak pressure at these levels.

Combustion analysis of experiment for a P–V diagram and P–ϴ diagram concluded that 18 compression ratio, 0% biodiesel, and 160 bar injection pressure with 12 kg engine load experiment set give 73.25 bar peak pressure after 7○ TDC. This set of parameters gives 7.61 kW indicated power, 3.61 kW brake power, 47.51 % mechanical efficiency, 92.26 % volumetric efficiency, 54.1 % BTHE and 0.15 kg/kWh specific fuel consumption. Experiment set of parameters of 16 compression ratio, 0 % biodiesel, and 180 bar injection pressure with 12 kg engine load set give 42.19 bar peak pressure after 7○ TDC. This set of parameters gives 4.27 kW indicated power, 0.62 kW brake power, 14.46 % mechanical efficiency, 90.13 % volumetric efficiency, 23.05 % BTHE and 0.21 kg/kWh specific fuel consumption.

Nomenclature

CR: Compression ratio
IP: Injection pressure
S/N: Signal-to-noise
VCR: Variable compression ratio
100D0B: 100% diesel and 0% jatropha biodiesel
50D50B: 50% diesel and 50% jatropha biodiesel

0D100B: 0% diesel and 100% jatropha biodiesel
TDC: Top dead center

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