# Parametric Optimization of Single Cylinder 4 Stroke Water Cooled CI Engine Fueled with Jatropha Biodiesel & Diesel Blend for Mechanical Efficiency using Taguchi Approach

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***Abstract:*** The present experimental study aims at exploring the effect of Jatropha biodiesel and diesel blends on a single cylinder four stroke water cooled diesel engine. Jatropha biodiesel has been obtained from Jatropha oil by Transesterification process. In this experimentation, the effects of parameters` i.e. injection pressure, blend ratio, inlet water-flow rate and load are taken as adaptable for optimization. The Taguchi method of optimization has been used with four parameters and three levels of experiments. In the end, Taguchi experiment identifies that at JB50, injection pressure 150 bar, engine water flow 400 lph and engine load 11 kg were found to be the optimum parameter settings for higher mechanical efficiency. Engine performance has been typically influenced by engine loading conditions and least influenced by water inlet flow. This experiment was conducted using optimal combination of parameters indicated that mechanical efficiency originate from the experiment was much nearer to the predicated value.

***Index Terms:*** **Jatropha biodiesel, Transesterification, Mechanical efficiency, CI engine, Taguchi method**

## I. INTRODUCTION

Energy plays a significant role in boosting economic growth, and the demand for fossil fuels continues to increase over the years. The depletion of world oil reserves leads to the development of biofuels since these fuels are promising alternatives to substitute fossil fuels [1]. Conversely, approximately 95% of the biodiesels produced today are derived from edible vegetable oils due to the abundance of agricultural crops [2]. This results in an ongoing debate regarding the use of agricultural lands for fuel purposes as well as growing concern over global food security [3, 4]. For these reasons, non-edible feed-stocks are being explored by the scientific community for biodiesel production. However, the sufficiency of raw materials, the type of plants and the harvest capacity per period are among the factors that need to be considered for biodiesel production, along with the sustainability of the program [5]. Jatropha is a renewable, non-edible plant. The Jatropha oil can be extracted from its seed which have very similar properties to diesel, but ignition point, flash point, kinematic viscosity is high in Jatropha oil. It can be produced by chemical process known as ‘Transesterification’ [6]. It is a process in which the vegetable oil or animal fat reacts with an alcohol such as methanol [7]. This reaction requires a catalyst, and it is a strong acid such as sodium or potassium hydroxide. After this process the new chemical compound which is made is known as methyl ester, and it is also known as a biodiesel. Biodiesel can be manufactured from Jatropha curcas plants, which can cultivate in drained, semi-arid and waste land in India [8]. It requires less water and stimulant and can infertile soil. The Jatropha seeds have 35-40% oil in it and can be produced in the rural areas [9]. It will also provide a green cover over the wasteland as well increases the rural economy and reduces the air pollution. The Jatropha oil can directly use in CI engine as well as it can be used after blending with the diesel fuel.

## II. LITERATURE SURVEY

**Tiwari et al. (2007)** produced biodiesel from jatropha oil (Jatropha curcas) with high free fatty acids and the transesterification process gave a yield of jatropha biodiesel above 99% having properties satisfying the standards for biodiesel. RSM method of optimization has been used during this experiment and Quadratic polynomial models were obtained to predict acid value and % conversion [7]. **Ganapathy et al. (2009)** observed the Influence of injection timing on performance, combustion and emission characteristics of Jatropha biodiesel engine. Spill method was used to set the static injection timing of the test. After the study, they have concluded that the best injection timing for Jatropha biodiesel operation with minimum BSFC, CO, HC and smoke and with maximum BTE, peak pressure and at any given injection timing, load, torque and speed, BSFC, peak pressure and NO are higher with Jatropha biodiesel than that of diesel [10].**Jindal et al. (2010)** observed the effect of injection pressure and compression ratio in a direct injection diesel engine with Jatropha methyl ester at three values of IP and CR and discovered that at peak value of IP and CR the performance of the engine was improved. The BSFC increased by 10% and BTE increased by 8.9% [11]. **Gumus et al. (2012)** experimented to observe the effect of injection pressure on the exhaust emission of diesel engine fuelled with biodiesel and diesel blends and discovered that as the load on the engine increases, the exhaust temperature and emission of gases were also increase and SFC was decrease [12]. **Kim Bao et al. (2014)** studied the scope of combustion performance and emission characteristics by adding hydrogen peroxide in Jatropha emulsion and found that with 15% mixture the peak of heat release was reduced, but it was higher in the combustion stage. The cylinder and exhaust temperature were higher. JHE15 improved the brake thermal efficiency of the engine. The PM and soot emission were also reduced [13]. **Patel et al. (2015)** conducted experiments on a single cylinder 4-stroke CI engine fueled with jatropha biodiesel and diesel blend using taguchi approach optimization to find lowest brake specific fuel consumption and concluded that engine performance was mostly influenced by the engine load and was least influenced by compression ratio [14]. **Patel et al. (2015)** performed experiments on a water cooled CI engine for jatropha biodiesel-diesel blends using taguchi method of optimization to derive highest mechanical efficiency and concluded that highest performance was found at 50% blend ratio, 10kg of engine load and compression ratio 16 and commented that the engine performance was mostly influenced by the engine load and was least influenced by blend ratio [15].**Chaudhari et al. (2016)** experimented on a small capacity diesel engine fueled with jatropha biodiesel blends to analyse the performance characteristics of the engine and concluded that, at the higher loads brake thermal efficiency of all the biodiesel blends were more than the diesel and improved combustion process and less exergy destruction; fuel consumption of biodiesel blends were found comparatively higher than the diesel fuel at all loading condition except B20 blend which shows almost similar values as that of diesel [16].**Sun et al. (2017)** experimented to produce Jatropha biodiesel with a fast forward process and by the end of that experiment they got a novel bio-char based catalyst successfully developed by the sulfonation of partially carbonized Jatropha curcas, exhibited excellent heterogeneous acid catalytic activity and stability in the synthesis of lubrication blend components from simultaneous esterification and transesterification [17]. **Hosamani et al. (2018)** experimented on CI DI VCR engine in order to find out combustion analysis of the engine by using mixture of biodiesel blends. The method used to prepare jatropha biodiesel 25 (JB25) was the mostly used transesterification method. After the experiment it has been concluded that combustion duration has been increased with an increased volume percentage of biodiesel in blends. Carbon monoxide, hydrocarbon emissions decreases, and $NO_x$ increases for the blends compared to diesel at compression ratios 17 & 18 [18]. **Sankumgon et al. (2018)** performed an experiment to find out properties and performance of micro-emulsion fuel (MF). Ethanol surfactant was used in blending of jatropha and diesel oil. The parameters considered in this experiment were B.P., BSFC, exhaust gas temperature, engine speed and emission parameters. It's been concluded that the MF from crude JCO-ethanol-diesel can be used as a biofuel in current diesel engines without major modification. The emission rate of $CO_2$ & CO has been improved [19]. **Yadav et al. (2018)** performed an experiment regarding the process optimization, kinetics of production Jatropha curcus methyl ester and its utilization in single cylinder diesel engine. The fuel was prepared by transesterification method and optimization process was done by taguchi method. The parameters considered during the experiment were brake thermal efficiency (BTE), brake power (B.P.), exhaust gas temperature (EGT), loading condition and emission parameters. After the practical it's been observed that BTE, BSFC, EGT were improved significantly; CO and HC emissions considerably decreased as well ,$NO_X$ and $CO_2$ emissions increased simultaneously at lower load to higher load [20].

## III. JATROPHA BIODIESEL

Jatropha biodiesel can be acquired from jatropha oil. It is conveyed that a gasping seed of Jatropha curcas contains about 55% of oil. JCL oil is primarily transesterified to methyl ester and glycerol. Considering JCL biodiesel as the final-product, transesterification should be considered the next step in the production process (Figure 1). Glycerol is an essential derivative.

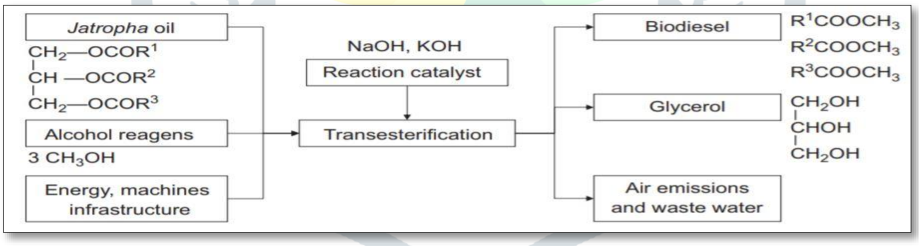

**Fig.1** Inputs and outputs of the transesterification process [21]

### *3.1 Transesterification Process*

Although the transesterification process is quite straightforward, the genetic and environmental background of the produced oil might require modification of the input ratios of the alcohol reagent and reaction catalyst as well as alterations to reaction temperature and time, in order to reach optimal bio-diesel production results. The optimal inputs for the transesterification of JCL oil (3.1% free fatty acids and acid number 6.2mg KOH g$^{-1}$ ) are identified to be 20% methanol (by mass on oil basis), 1.0% NaOH by mass on oil basis [22]. Maximum ester yield is achieved after 90min reaction time at 60°C [22]. Optimal conversion of JCL oil with high free fatty acids (14%) and high acid number (28mg KOH g$^{-1}$) needs pretreatment reaction with methanol using $H_2SO_4$ as catalyst (1.43%) during 88min at 60°C. After pretreatment a maximal conversion rate of more than 99% was achieved by transesterification with methanol and 0.6% KOH by weight during 24min [7]. The properties of jatropha biodiesel used in the experiment are listed below in Table 1.

Table 1 Properties of Jatropha biodiesel

| Parameter | Unit | Value |
|---|---|---|
| Density @ 15°C | kg/m$^3$ | 896 |
| Calorific value | kJ/kg | 39100 |
| Kinematic viscosity @ 40°C | cp | 14.69 |
| Kinematic viscosity @ 100°C | cp | 9.82 |

| | | |
|---|---|---|
| Flash point | °C | 135 |
| Sulfur content | mg/kg | 14 |
| Carbon residue | % by mass | 0.015 |
| Sulfated ash | ppm | 26 |
| Water content | mg/kg | 1054 |
| Total contamination | mg/kg | 11 |
| Acid value | mg KOH/gm | 24 |
| Methanol content | % by mass | 0.14 |
| Ethanol content | % by mass | 0.18 |
| Ester content | % by mass | 98.11 |
| Free Glycerol content | mg/kg | 152 |
| Total Glycerol content | % by mass | 0.14 |

## IV. FACTORS AND LEVELS

The experiments were designed according to the taguchi L9 orthogonal array for blend percentage, injection pressure, water inlet flow and load. It has 9 rows corresponding to the number of testes with 4 columns at 3 levels and 4 parameters. This orthogonal array was chosen due to its ability to check the interaction among factors. Selected factors and their levels shown in Table 2. The experimental results were transferred into S/N ratio. There are three categories of quality characteristics in analysis S/N ratio:

(i) The lower the better
(ii) The higher the better
(iii) The nominal the better

The category higher the better was applied to calculated the S/N ratio for mechanical efficiency. Taguchi method was applied to select the control factors levels (blend ratio. Injection pressure, water inlet flow and load) in order to find out optimal response value of mechanical efficiency.

Table 2 Factors and their Levels

| **Factors** | **Levels** | | |
|---|---|---|---|
| | **Level 1** | **Level 2** | **Level 3** |
| **%BD** | 0 | 50 | 100 |
| **IP (bar)** | 100 | 150 | 200 |
| **WIF (lph)** | 200 | 300 | 400 |
| **Load (kg)** | 1 | 6 | 11 |

## V. METHODOLOGY

The rising problems of increasing demand for highly efficient engines with lower specific fuel consumption can be solved by applying various optimization techniques i.e. Taguchi approach, RSM method, non-linear regression method, ANOVA, genetic algorithm etc. The Taguchi approach of optimization has been applied in this experimentation. This method consists of mathematical and statistical techniques, which are useful in the parametric optimization and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response. The flow chart for the experiment design is shown in Figure 2. The steps for the experiment have been listed below:

1) Identify the performance characteristics to be evaluated
2) Design and conduct the experiments.
3) Analyze the outcomes to decide the perfect situations.
4) Run a confirmatory test using the finest situations.

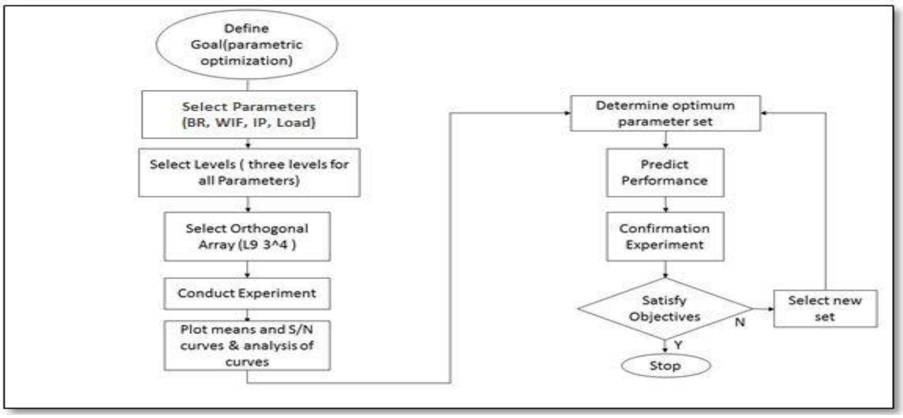

**Fig.2** Flow Chart of Taguchi Design of Experiment

## VI. EXPERIMENTAL SET UP

The setup was a single cylinder 4- stroke water cooled research engine coupled with eddy current dynamometer for various loading conditions. The mode of operation in this engine can be changed from diesel to Petrol or from Petrol to Diesel with some slight changes. In both operation modes the compression ratio can be changed without stopping the engine and no other changes needed for the geometry of combustion chamber by specially designed tilting cylinder block arrangement. Different other instruments provided to vary airflow, fuel flow, temperatures and load measurement. Rota-meter was provided to measure cooling water flow and calorimeter water flow. A battery, starter and battery charger were provided to start the engine. Analysis software Engine-soft was synced in with engine setup to find performance evaluation and lab view based Engine Performance. The test engine used in the experiment is shown in Figure 3.

**Fig.3** Overview of Experimental Setup

The injection point and spark point can be changed for research tests. Setup is provided with necessary instruments for combustion pressure, Diesel line pressure and crank-angle measurements. These signals are interfaced with computer for pressure crank-angle diagrams. Instruments are provided to interface airflow, fuel flow, temperatures and load measurements. The setup has stand-alone panel box consisting of air box, two fuel flow measurements, process indicator and hardware interface. Rota-meters are provided for cooling water and calorimeter water flow measurement. A battery, starter and battery charger is provided for engine electric start arrangement. The Experimental setup is utilized to observe VCR engine performance for Brake Power, Indicated Power, Frictional Power, Brake Mean Effective Pressure, Indicated Mean Effective Pressure, Brake Thermal Efficiency, Indicated Thermal Efficiency, Mechanical Efficiency, Volumetric Efficiency, Specific Fuel Consumption, A/F Ratio and Combustion Analysis. Lab view based engine Performance Analysis software package "Engine soft" is provided for on line performance evaluation. Engine setup specifications are shown in Table 3. The technical specifications of Eddy Current Dynamometer are shown in Table 4.

Table 3 Engine Setup Specifications

| | |
|---|---|
| Engine manufacturer | Apex Innovations (Research Engine test set up) |
| Software | Engine soft Engine performance analysis software |
| Engine | Single cylinder water cooled CI engine |
| Engine Type | Variable Compression Ratio |
| Capacity | 553 cc |
| Power Rating & Engine Speed | 3.5 kW @ 1500 rpm |
| Compression Ratio | 12:1 to 18:1 |
| Cylinder diameter (B) | 87.5 mm |
| Stroke length (L) | 110 mm |
| Connecting rod length | 234 mm |
| Dynamometer | Eddy current water cooled with loading unit |

Table 4 Technical Specification of Eddy Current Dynamometer

| | |
|---|---|
| Model | AG10 |
| Manufacturer | Saj Test Plant Pvt. Ltd. |
| End Flanges (on both sides) | Cardon Shaft Model 1260 Type A |
| Water Inlet (bar) | 1.6 |
| Minimum (kPa) | 160 |
| Pressure (lbf/in$^2$) | 23 |
| Torque (N-m) | 11.5 |

| | |
|---|---|
| Hot Coil Voltage max.(volts) | 60 |
| Continuous Current (amps) | 5.0 |
| Cold Resistance (ohms) | 9.8 |
| Speed max.(rpm) | 10000 |
| Load (kg) | 3.5 |
| Bolt Size | M12 × 1.75 |
| Weight (kg) | 130 |

### 6.1 *Experimental Procedure*

All the tests were directed at the rated speed of 1600 rpm. All readings were taken only after the engine attained stable operation. All the instruments were intermittently calibrated. The compression ratio and injection timing were kept constant at the rated value throughout the experiments. The injection pressure and water inlet flow of engine were varied in steps of 100 bars, 150 bars and 200 bars and 200 lph, 300 lph and 400 lph respectively. The water flow in the calorimeter was kept constant (100 lph) in all the experiments. The engine output was varied from 1ow load to full load in steps of 1 kg, 6 kg and 11 kg in the normal operation of the engine and the varied percentage of biodiesel in order of 0%, 50% and 100%. At each load various readings related to performance parameters were documented. The pressure-crank angle data of 10 cycles were also noted by using the "Engine-Soft" in the personal computer.

## VII. OBSERVATIONS AND RESULT DATASHEET

The observed data from the experiment on single cylinder 4-stroke water cooled diesel engine is shown in Table 5. The result data obtained from the observed data is shown in Table 6.

Table 5 Observation Table

| Experiment No. | BD (%) | IP (bar) | WIF (lph) | Load (kg) | Speed (rpm) | FC (cc/min) | Air (mmWc) |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 100 | 200 | 1.03 | 1614 | 8 | 75.81 |
| 2 | 0 | 150 | 300 | 5.79 | 1580 | 12 | 72.46 |
| 3 | 0 | 200 | 400 | 10.99 | 1541 | 18 | 68.68 |
| 4 | 50 | 100 | 300 | 11.04 | 1553 | 20 | 68.63 |
| 5 | 50 | 150 | 400 | 1.29 | 1614 | 7 | 74.72 |
| 6 | 50 | 200 | 200 | 6.1 | 1577 | 13 | 71.4 |
| 7 | 100 | 100 | 400 | 5.88 | 1576 | 12 | 72.58 |
| 8 | 100 | 150 | 200 | 10.98 | 1564 | 18 | 69.5 |
| 9 | 100 | 200 | 300 | 0.82 | 1571 | 8 | 72.66 |

Table 6 Result Table for the experiments

| Experiment No. | ρ (kg/m$^3$) | CV (kJ/kg) | FC (kg/h) | SFC (kg/kWh) | B.P. (kW) | I.P. (kW) | ITE (%) | BTE (%) | $\eta_{mech.}$ (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 896 | 44000 | 0.41 | 1.30 | 0.31 | 3.49 | 74.75 | 6.47 | 9.06 |
| 2 | 896 | 44000 | 0.62 | 0.36 | 1.74 | 4.63 | 66.2 | 23.73 | 37.55 |
| 3 | 896 | 44000 | 0.93 | 0.29 | 3.22 | 6.33 | 60.26 | 29.29 | 50.85 |
| 4 | 864 | 40496 | 1.04 | 0.32 | 3.26 | 6.22 | 23.1 | 27.92 | 52.39 |
| 5 | 864 | 40496 | 0.36 | 0.91 | 0.4 | 3.45 | 6.47 | 9.69 | 11.48 |
| 6 | 864 | 40496 | 0.67 | 0.37 | 1.83 | 4.78 | 20.46 | 24.10 | 38.25 |
| 7 | 832 | 39100 | 0.62 | 0.35 | 1.76 | 4.77 | 68.15 | 25.12 | 36.90 |
| 8 | 832 | 39100 | 0.93 | 0.29 | 3.26 | 6.07 | 57.83 | 31.04 | 53.72 |
| 9 | 832 | 39100 | 0.41 | 1.68 | 0.24 | 3.18 | 68.06 | 5.24 | 7.68 |

## VIII. TAGUCHI ANALYSIS

The results of mechanical efficiency were analyzed using Minitab 18. Minitab software can be helpful for DOEs like factorial, response surface, mixture, and Taguchi (robust). Minitab can be utilized to create, define and analyze the DOE to generate graphs of an experimental design which are similar for all design types. After conducting the analysis and entering the results, Minitab provides several analytical and graphing tools to help understand the results. The result and discussion regarding the response curve analysis for means and SN ratio for mechanical efficiency has briefly explained in this section.

### 8.1 *Response Curve Analysis*

Response curve analysis is designed to determine effective parameters and their optimum levels. It is the graphical representations of change in performance characteristics with the variation in process parameter. The curve gives a graphical view of variation of each factor and its effect on the engine performance when a parameter moves from one level to another. Figure 4 shows significant effects plot for means for each factor for 3 levels. The S/N ratio for optimal mechanical efficiency is coming under "Larger-is-better" characteristic, which can be calculated as logarithmic transformation of the loss function. The greater difference between levels indicates the highest S/N ratio and has the highest effect on the engine performance.

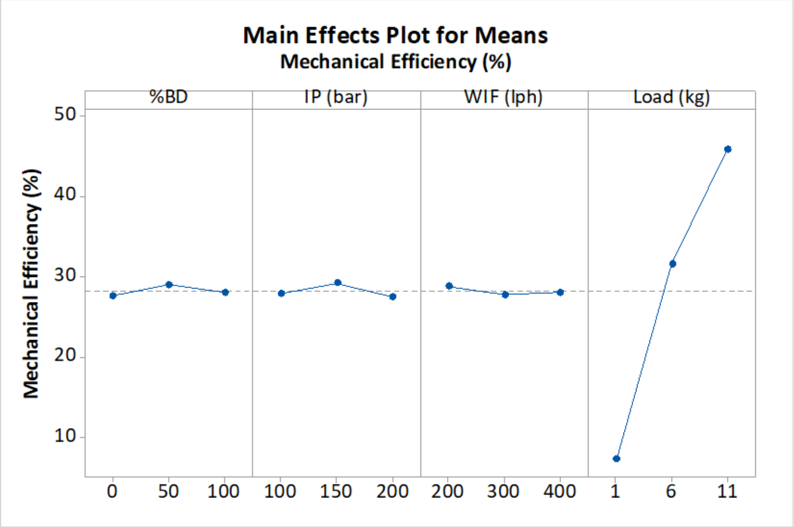

**Fig.4** Main Effects Plot for Means for Mechanical Efficiency

From the graph, mean is average value for reading has been taken for the particular parameter. Table 7 shows that for blend, mean value is maximum (34.038) for 50% blend and minimum (32.485) for 0% blend. For IP, mean value is maximum (34.250) at 150 bar and minimum (32.260) at 200 bar. For WIF, mean value is maximum (33.677) at 200 lph and minimum (32.540) at 300 lph. For load, mean value is maximum (52.318) at 11 kg engine load and minimum (9.407) for 1 kg engine load.

Table 7 Response Table for Means

| Level | %BD | IP (bar) | WIF (lph) | Load (kg) |
|---|---|---|---|---|
| 1 | 32.485 | 32.782 | 33.677 | 9.407 |
| 2 | 34.038 | 34.250 | 32.540 | 37.567 |
| 3 | 32.769 | 32.260 | 33.075 | 52.318 |
| **Delta** | 1.553 | 1.991 | 1.137 | 42.911 |
| **Rank** | 3 | 2 | 4 | 1 |

Delta is difference of maximum and minimum value of levels. Value of delta is maximum for load (42.911) and minimum (1.137) for water inlet flow. Delta value for IP (1.991) and blend (1.553) are between the other two parameters. Hence, the load has maximum and water inlet flow has the minimum effect on mechanical efficiency of the engine.

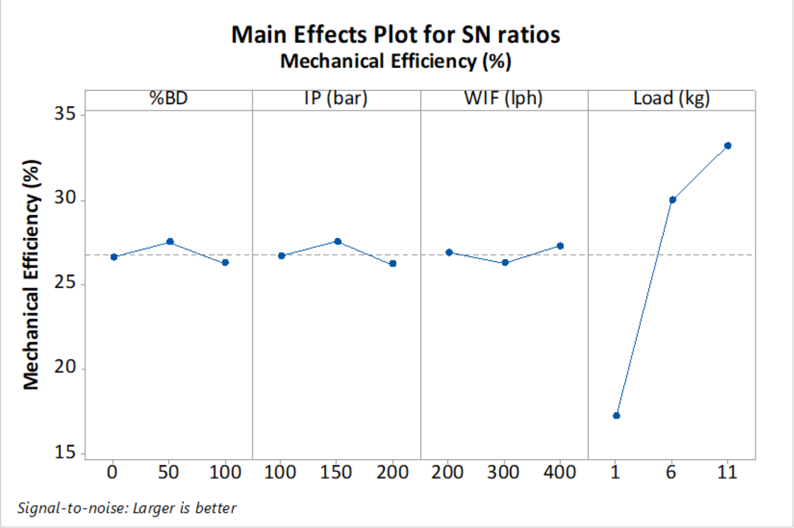

**Fig.5** Main Effects Plot for SN Ratios for Mechanical Efficiency

Figure 5 shows the response curve for S/N ratio, the highest S/N ratio was observed at 50% blend, 150 bar IP, 400 lph WIF and 11 kg of engine load, which is the optimum parameter setting for highest mechanical efficiency. Table 8 displays the delta value is maximum (15.02) for engine load and minimum (1.03) for water inlet flow. Engine load has major effect while, water inlet flow has the minor effect on mechanical efficiency of the engine.

Table 8 Response Table for Signal to Noise Ratios (Larger is better)

| Level | %BD | IP (bar) | WIF (lph) | Load (kg) |
|---|---|---|---|---|
| 1 | 28.25 | 28.29 | 28.47 | 19.35 |
| 2 | 29.08 | 29.10 | 27.86 | 31.50 |
| 3 | 27.89 | 27.83 | 28.89 | 34.37 |
| **Delta** | 1.19 | 1.27 | 1.03 | 15.02 |
| **Rank** | 3 | 2 | 4 | 1 |

### *8.2 Optimum Parameter Setting*

The term optimum set of parameters is reflects optimum arrangement of the parameters defined by this experiment for peak mechanical efficiency. The optimal parameter setting is determined by choosing the level with the highest S/N ratio. From the Figure and Table 8, the optimum parameter setting for highest mechanical efficiency is 50% blend, 150 bar IP, 400 lph WIF and 11 kg load.

### *8.3 Predicted Performance at Optimum Setting*

Using optimum set of parameters, which was achieved by response curve analysis was used for prediction by Minitab software is displayed in Table 9.

Table 9 Predicted Value for Mechanical Efficiency

| Mechanical efficiency | S/N ratio |
|---|---|
| 54.39 | 36.2183 |

### *8.4 Experiment Validation*

In this step of the optimal set of parameter obtained by the taguchi approach has been taken into account to perform the confirmation experiment to verify the obtained predicted value of the mechanical efficiency. Table 10 shows that, the predicated value of mechanical efficiency was found nearer to the experimental value of mechanical efficiency.

Table 10 Validation of Experiment

| Mechanical Efficiency (%) | |
|---|---|
| **Predicted value** | **Experimental value** |
| 54.39 | 54.12 |

## IX. CONCLUSIONS

The Taguchi method was found to be an efficient technique for quantifying the effect of control parameters. From the results of the experiment it's been concluded that;

1) For better performance of the engine, JB50 fuel at 11 kg of engine load, Injection pressure of 150 bars and Water inlet flow of 400 lph are the optimum parameter setting for highest mechanical efficiency.
2) Engine performance is majorly influenced by engine load and mannerly influenced by water inlet flow for mechanical efficiency.
3) Performance results obtained from the validation of the experiment using optimal parameter setting revealed excellent agreement with the predicated result. The experimental value of mechanical efficiency 54.12% was nearer to the predicted value 54.39%.

## REFERENCES

[1] Dharma S, Masjuki HH, Ong HC, Sebayang AH, Silitonga AS, Kusumo F, Mahlia TM. 2016. Optimization of biodiesel production process for mixed Jatropha curcas–Ceiba pentandra biodiesel using response surface methodology. Energy Conversion and Management, 115:178-90.

[2] Ashraful AM, Masjuki HH, Kalam MA, Fattah IR, Imtenan S, Shahir SA, Mobarak HM. 2014. Production and comparison of fuel properties, engine performance, and emission characteristics of biodiesel from various non-edible vegetable oils: a review. Energy Conversion and Management, 80:202-28.

[3] Atabani AE, da Silva César A. Calophyllum inophyllum L. 2014. A prospective non-edible biodiesel feedstock. Study of biodiesel production, properties, fatty acid composition, blending and engine performance. Renewable and Sustainable Energy Reviews, 37:644-55.

[4] Dharma S, Hassan MH, Ong HC, Sebayang AH, Silitonga AS, Kusumo F, Milano J. 2017. Experimental study and prediction of the performance and exhaust emissions of mixed Jatropha curcas-Ceiba pentandra biodiesel blends in diesel engine using artificial neural networks. Journal of cleaner production, 164:618-33.

[5] Bora DK, Baruah DC, Das LM, Babu MK. 2012. Performance of diesel engine using biodiesel obtained from mixed feedstocks. Renewable and Sustainable Energy Reviews, 16(8):5479-84.

[6] Momin GG. 2013. Experimental investigation on Jatropha oil as a biodiesel fuel with analysis of its emission characteristics. International Journal of Research in Advent Technology, 1(4):102-10.

[7] Tiwari AK, Kumar A, Raheman H. 2007. Biodiesel production from jatropha oil (Jatropha curcas) with high free fatty acids: an optimized process. Biomass and bioenergy, 31(8):569-75.

[8] Pramanik K. 2003. Properties and use of Jatropha curcas oil and diesel fuel blends in compression ignition engine. Renewable energy, 28(2):239-48.

[9] Berchmans HJ, Hirata S. 2008. Biodiesel production from crude Jatropha curcas L. seed oil with a high content of free fatty acids. Bioresource technology, 99(6):1716-21.

[10] Ganapathy T, Murugesan KA, Gakkhar RP. 2009. Performance optimization of Jatropha biodiesel engine model using Taguchi approach. Applied Energy, 86(11):2476-86.

[11] Jindal S, Nandwana BP, Rathore NS, Vashistha V. 2010. Experimental investigation of the effect of compression ratio and injection pressure in a direct injection diesel engine running on Jatropha methyl ester. Applied Thermal Engineering, 30(5):442-48.

[12] Sayin C, Gumus M, Canakci M. 2012. Effect of fuel injection pressure on the injection, combustion and performance characteristics of a DI diesel engine fueled with canola oil methyl esters-diesel fuel blends. Biomass and Bioenergy, 46:435-46.

[13] Nguyen KB, Dan T, Asano I. 2014. Combustion, performance and emission characteristics of direct injection diesel engine fueled by Jatropha hydrogen peroxide emulsion. Energy, 74:301-8.

[14] Patel DV, Patel TM, Rathod GP. 2015. Parametric Optimization of Single Cylinder Diesel Engine for Jatropha Biodiesel and Diesel Blend for Brake Specific Fuel Consumption Using Taguchi Method. IOSR Journal of Mechanical and Civil Engineering,12:66-72.

[15] Patel DV, Patel TM, Rathod GP. 2015. Parametric Optimization of Single Cylinder Diesel Engine for Jatropha Biodiesel and Diesel Blend for Mechanical Efficiency Using Taguchi Method. IOSR Journal of Mechanical and Civil Engineering, 12:59-65.

[16] Chaudhari SG, Modi MA, Patel TM, Rathod GP. 2016. Performance of small capacity compression ignition engine using jatropha biodiesel blends. Int J Res Eng Technol, 5:129-33.

[17] Ma Y, Wang Q, Sun X, Wu C, Gao Z. 2017. Kinetics studies of biodiesel production from waste cooking oil using $FeCl_3$-modified resin as heterogeneous catalyst. Renewable Energy, 107:522-30.

[18] Hosamani BR, Katti VV. 2018. Experimental analysis of combustion characteristics of CI DI VCR engine using mixture of two biodiesel blend with diesel. Engineering Science and Technology, an International Journal, 21:769-77.

[19] Sankumgon A, Assawadithalerd M, Phasukarratchai N, Chollacoop N, Tongcumpou C. 2018. Properties and performance of microemulsion fuel: blending of jatropha oil, diesel, and ethanol-surfactant. Renewable Energy Focus, 24:28-32.

[20] Yadav M, Upadhyay S, Sharma YC. 2018. Process optimization, kinetics of production Jatropha curcus methyl ester, and its utilization in single cylinder diesel engine. Energy Conversion and Management, 160:364-74.

[21] Prueksakorn K, Gheewala SH. 2006. Energy and greenhouse gas implications of biodiesel production from Jatropha curcas L. In: Proceedings of the second joint international conference on Sustainable energy and environments, Bangkok, Thailand.

[22] Chitra P, Venkatachalam P, Sampathrajan A. 2005. Optmisation of experimental conditions for biodiesel production from alkali-catalysed transesterification of Jatropha curcas oil. Energy for Sustainable Development, 9:13–18.

## APPENDIX

Table 11 Nomenclatures

| | | | |
|---|---|---|---|
| L | engine stroke, mm | $\eta_{Vol.}$ | volumetric efficiency,% |
| B | bore diameter, mm | EGT | exhaust gas temperature, °C |
| IP | injection pressure, bar | JB50 | jatropha biodiesel (50% diesel+50% jatropha) |
| WIF | water inlet flow, lph | JB100 | jatropha biodiesel (100% jatropha) |
| lph | litre per hour | JCL | jatropha curcus L. |
| SFC | specific fuel consumption, kg/kWh | MF | micro-emulsion fuel |
| BSFC | brake specific fuel consumption, kg/kWh | CI | compression ignition |
| B.P. | brake power, kW | VCR | variable compression ratio |
| I.P. | indicated power, kW | HC | hydrocarbon, ppm |
| F.P. | friction power, kW | $CO_2$ | carbon dioxide, ppm |
| BTE | brake thermal efficiency,% | CO | carbon monoxide, ppm |
| ITE | induced thermal efficiency,% | $NO_X$ | nitrogen oxides, ppm |
| $\eta_{mech}$ | mechanical efficiency, % | RSM | response surface method |