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Combustion Evaluation of Single Cylinder 4 Stroke CI Engine Fueled with Jatropha Biodiesel and Diesel Blend

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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 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, the Taguchi experiment identifies that at JB50, injection pressure 150 bar, engine water flow 400 lph, and engine load 11 kg is the optimum parameter setting for higher engine mechanical efficiency. This experiment was conducted using the optimal combination of parameters has indicated that peak pressure decreased by about 1.66% and 3.06%, maximum fuel line pressure was reduced by 5.09% and 8.04%, and the net heat release was lowered by 10.70% and 21.41% for JB50 and JB100 respectively***.*

Keywords - *Jatropha biodiesel, Transesterification,Combustion Evaluation, CI engine*

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 feedstocks 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 has very similar properties to diesel, but the ignition point, flash point, kinematic viscosity is high in Jatropha oil. It can be produced by a 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 biodiesel. Biodiesel can be manufactured from Jatrophacurcas plants, which can cultivate in drained, semi-arid, and wasteland in India [8]. It requires less water and stimulant and infertile soil. The Jatropha seeds have 35-40% oil in it and can be produced in rural areas [9]. It will also provide a green cover over the wasteland as well increases the rural economy, and reduces air pollution. The Jatropha oil can directly use in the CI engine as well as it can be used after blending with diesel fuel.

II. LITERATURE SURVEY

Tiwari et al. (2007) produced biodiesel from jatropha oil (Jatrophacurcas) 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. The 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, H.C., 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 I.P. and C.R. and discovered that at the peak value of I.P. and C.R. the performance of the engine was improved. The BSFC increased by 10%, and BTE increased by 8.9% [11]. **Gumus et al. (2012)** experimented with observing the effect of injection pressure on the exhaust emission of a 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 increasing and SFC was decreasing [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 a 15% mixture, the peak of heat release was reduced. Still, it was higher in the combustion stage. The cylinder and exhaust temperature were higher. JHE15 improved the thermal brake 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 the 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 the Taguchi method of optimization to derive the highest mechanical efficiency and concluded that the 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 analyze 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 was 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 with producing 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 Jatrophacurcas, 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 the CI DI VCR engine to find out the combustion analysis of the engine by using a mixture of biodiesel blends. The method used to prepare jatropha biodiesel 25 (JB25) was the most 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 decrease, and NO_x increase for the blends compared to diesel at compression ratios 17 & 18 [18]. **Sankumgon et al. (2018)** performed an experiment to find out the properties and performance of micro-emulsion fuel (M.F.). Ethanol surfactant was used in the 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 M.F. 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 Jatrophacurcus methyl ester, and its utilization in a single-cylinder diesel engine. The fuel was prepared by the transesterification method. An optimization process was done by the Taguchi method. The parameters considered during the experiment were thermal brake 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; C.O. and H.C. 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 Jatrophacurcas contains about 55% 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.

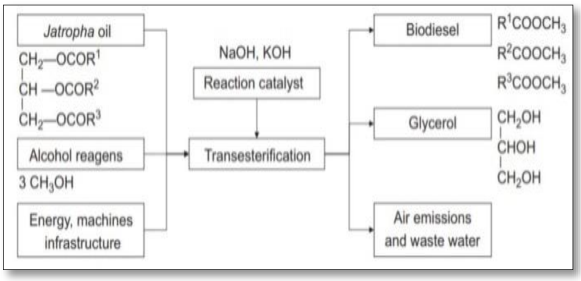

Fig 1: Inputs and outputs of the transesterification process [21]

A. 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 an oil basis), 1.0% NaOH by mass on an oil basis [22]. Maximum ester yield is achieved after 90min reaction time at 60℃ [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 I.

Table I
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
Flashpoint	°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. 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.,the 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.

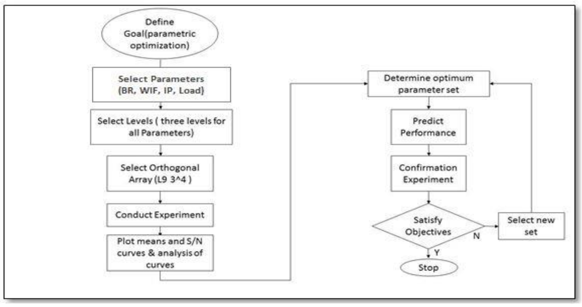

Fig 2: Flow Chart of Taguchi Design of Experiment

V. EXPERIMENTAL SETUP

The setup was a single cylinder 4- stroke water-cooled research engine coupled with an 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 the combustion chamber by specially designed tilting cylinder block arrangement. Different other instruments are 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 a computer for pressure crank-angle diagrams. Instruments are provided to interface airflow, fuel flow, temperatures, and load measurements. The setup has a stand-alone panel box consisting of an airbox, two fuel flow measurements, a process indicator, and a hardware interface. Rotameters are provided for cooling water and calorimeter water flows measurement. A battery, starter, and battery charger are provided for an 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 online performance evaluation. Engine setup specifications are shown in Table II. The technical specifications of Eddy Current Dynamometer are shown in Table III.

Table II
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 & Speed	3.5 kW @ 1500 rpm
Compression Ratio	12:1 to 18:1
Cylinder diameter (D)	87.5 mm
Stroke length (L)	110 mm
Connecting rod length	234 mm
Dynamometer	Eddy current water-cooled with loading unit

Table III
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

A. *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 the 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.

VI. OBSERVATIONS AND RESULT DATA

The observed data from the experiment on a single-cylinder 4-stroke water-cooled diesel engine is shown in the table. The result data obtained from the observed data for performance and combustion parameters are shown in Table V& Table VI, respectively.

Table IV
Observation Table

Exp. No.	B.D. (%)	IP (bar)	WIF (ph)	Load (kg)	Speed (rpm)	F.C. (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 V
Result Table for the experiments

Exp. No.	ρ (kg/m^3)	CV (kJ/kg)	SFC (kg/kWh)	B.P. (kW)	BTE (%)	$\eta_{Mech.}$ (%)	$\eta_{Vol.}$ (%)
1	896	44000	1.30	0.31	6.47	9.06	75.8
2	896	44000	0.36	1.74	23.73	37.55	75.69
3	896	44000	0.29	3.22	29.29	50.85	75.56
4	864	40496	0.32	3.26	27.92	52.39	74.84
5	864	40496	0.91	0.4	9.69	11.48	75.25
6	864	40496	0.37	1.83	24.10	38.25	75.28
7	832	39100	0.35	1.76	25.12	36.90	75.95
8	832	39100	0.29	3.26	31.04	53.72	74.89
9	832	39100	1.68	0.24	5.24	7.68	76.23

Table VI
Result Table for the Combustion Parameters

Exp. No.	Peak Pressure (bar)	Fuel Line Pressure (bar)	Net Heat Release Rate (J/°CA)	Pressure Rise Rate (bar/°CA)
1	49.54	107.216	23.2	2.66
2	57.04	144.084	32.88	3.89
3	68.70	186.747	51.85	5.93
4	67.56	177.2325	46.3	5.39
5	48.85	129.319	21.145	2.45
6	56.59	91.0465	31.855	3.7
7	56.13	106.427	31.32	3.6
8	66.60	171.734	40.75	4.85
9	48.16	176.432	19.72	2.42

VII. COMBUSTION ANALYSIS

The result and discussion regarding the combustion parameters are briefly explained in this section.

A. *Pressure–Crank Angle Diagram*

Figure 4 shows the pressure crank angle (p-Θ) chart for base diesel, diesel - jatropha oil blend (JB50), and jatropha biodiesel (JB100) of the base engine at peak load. The peak pressure depends on the volume of fuel involved in the unrestrained combustion phase, which is directed by the delay period and the spray envelope of the injected fuel [23]. Thus, the higher viscosity and poor volatility of the jatropha oil results in a lower peak pressure as compared to that of diesel. The peak pressure for the diesel, JB50, and JB100 is 68.7 bar, 67.56 bar, and 66.6 bar, at 7°CA, 8°CA, and 9°CA, respectively, after TDC with the base engine at full load. It is observed that the peak pressure decreased by 1.66% & 3.06% for JB50 and JB100, respectively, as compared to that of diesel fuel at peak loading conditions. This can be possible due to the high viscosity and density of the jatropha oil. The rise in pressure of cylinder for JB100 may be due to the improved air fuel-air mixture formation rates as a result of lower fuel viscosity.

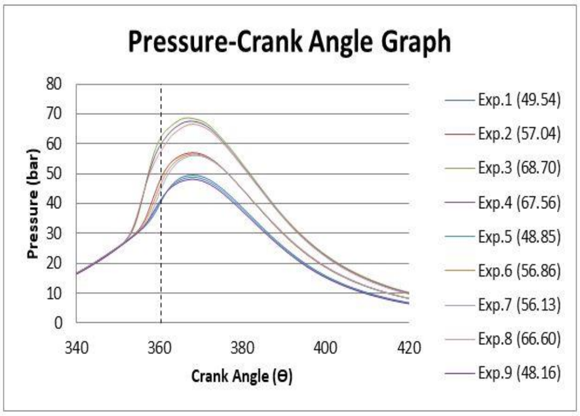

Fig 4: Cylinder pressure variation with C.A.

B. Net Heat Release Rate

In a CI engine, during the combustion process, the burning proceeds in three distinguishable stages. In the first stage, the rate of burning is generally very high and lasts for only a few crank angle degrees. It corresponds to the period of rapid cylinder pressure. The second stage corresponds to a period of a gradual decrease in the cylinder pressure. In the third stage of combustion, about 20 percent of the total fuel energy is released.

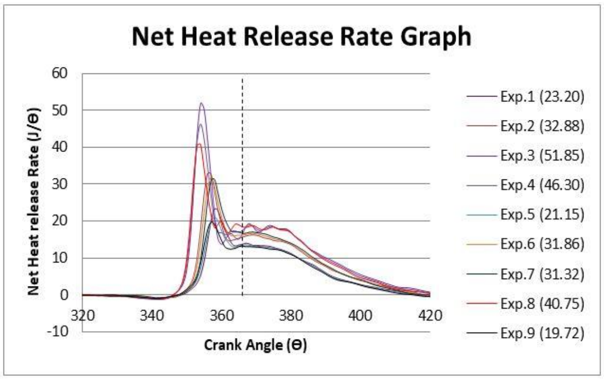

Fig 5: Variation of Net Heat release rate with C.A.

The comparison of the heat release rate with the crank angle at full load for diesel, JB50, and JB100 are shown in Figure 5. The maximum heat release rate for diesel, JB50, and JB100 is 51.85 J/°CA, 46.30 J/°CA, and 40.75 J/°CA, respectively, with the base engine. The observation indicates that the heat release is lowered by 10.70% and 21.41% for JB50 and JB100, respectively, at peak loading conditions.

C. Maximum Pressure Rise Rate

Figure 6 shows the maximum pressure rise rate with respect to the crank angle with the base engine at the peak loading condition. In a diesel engine, the pressure rise rate depends upon the combustion rate at the initial phases, which is inclined by the quantity of fuel taking part in the unrestrained combustion. The unrestrained or uncontrolled combustion stage is directed by the delay period causing an advanced or high value of the maximum pressure rise rate. The outcomes indicate that the maximum pressure rise rate is much more significant for diesel by 15.61% with the base engine operation at all loads.

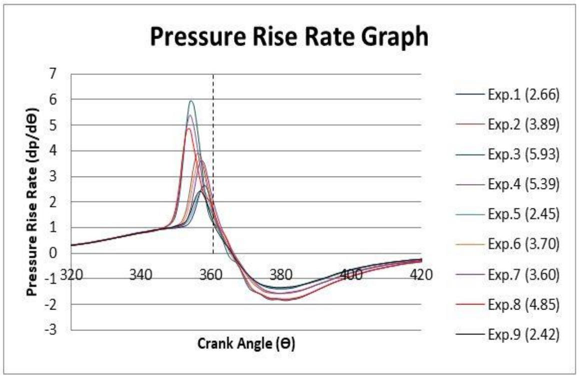

Fig 6: Variation of the maximum rate of pressure rise with C.A.

The maximum pressure rise rate for diesel, JB50, and JB100 is 5.93bar/°CA, 5.39bar/°CA, and 4.85bar/°CA at 6ºBTDC, 5ºBTDC, and 4ºBTDC, respectively, at peak loading conditions. In a diesel fuel engine, the lower ignition delay leads to a high-pressure rise rate. A lower pressure rate has been observed for the JB50 and JB100 at all loads with the base engine. This may happen because of the high viscosity and poor volatility, leading to the accretion of fuel, which upsurges the ignition delay period and lowers pressure rise rate.

D. Fuel Line Pressure

The comparison of the fuel line pressure with the crank angle at full load for diesel, JB50, and JB100 is shown in Figure 7. The maximum fuel line pressure for diesel, JB50, and JB100 is 186.747 bars, 177.232 bars, and 171.734, respectively, at the peak loading condition.

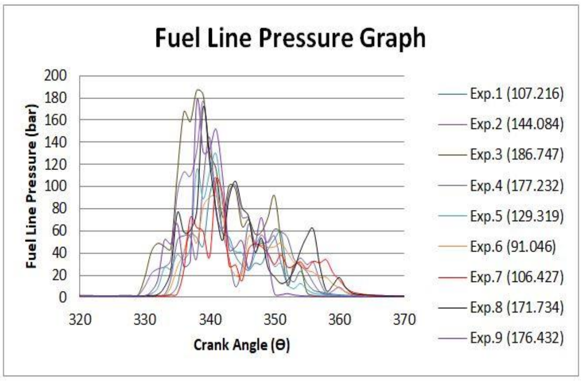

Fig 7: Variation of Fuel Line Pressure with CA

E. Pressure-Volume Diagram

The pressure Vs.The volume diagram at all loads for diesel, JB50, and JB100 is shown in Figure

7.5. The maximum work obtained by diesel at IP 200 bar, WIF 400 lph& load 11 kg (Exp.3); by JB50 at IP 100 bar, WIF 300 lph& load 11 kg (Exp.4); and by JB100 at IP 150 bar, WIF 200 lph& load 11 kg (Exp.8) respectively.

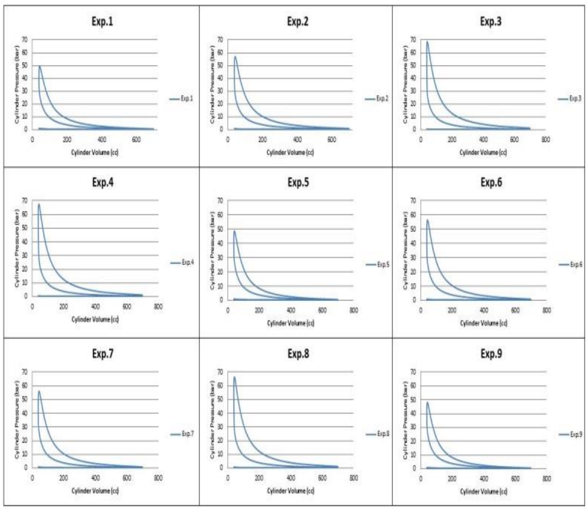

Fig 8: Pressure Vs. Volume Diagram for All the Experiments

VIII. CONCLUSIONS

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, the Injection pressure of 150 bars, and Water inlet flow of 400 is the optimum parameter setting for least specific fuel consumption, higher brake thermal efficiency, and mechanical efficiency.
2) The peak pressure decreased by about 1.66% and 3.06% for JB50 and JB100, respectively, at peak loading conditions.
3) The maximum pressure rise rate is much higher for diesel by 15.61% with the base engine operation at all loads.
4) The pressure rate has been observed for the JB50 and JB100 decreased by 9.11% and 18.21%, respectively, at all loads with the base engine.
5) The maximum fuel line pressure for JB50 and JB100 was reduced by 5.09% and 8.04%, respectively, at peak loading conditions.
6) The heat release has been lowered by 10.70% and 21.41% for JB50 and JB100, respectively, at peak loading conditions.

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APPENDIX

VCR	variable compression raio	B.P.	brake power, kW
I.P.	injection pressure, bar	I.P.	indicated power, kW
WIF	water inlet flow, lph	F.P.	friction power, kW
lph	liter per hour	BTE	brake thermal efficiency,%
F.C.	fuel consumption, kg/h	JB50	jatropha biodiesel (50% diesel+50% jatropha)
BSFC	brake specific fuel consumption, kg/kWh	JB100	jatropha biodiesel (100% jatropha)
EGT	exhaust gas temperature, ℃	JCL	jatrophacurcus L.
M.F.	micro-emulsion fuel	C.O.	carbon monoxide, ppm
H.C.	hydrocarbon, ppm	NO_X	nitrogen oxides, ppm