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Application of Taguchi Method to Reduce Particulate Matter and Smoke Opacity of CIDI Engine Fueled with Jatropha Biodiesel

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Abstract: *The objective of the present research work is to determine the optimum engine condition that reduces the exhaust emissions of the diesel engine when fueled with jatropha biodiesel and its diesel blends. Fuel injection pressure, engine load and percentage of biodiesel content in the blend were chosen as three influencing control factors on the response parameters: particulate matter (PM), and smoke opacity emissions. Taguchi method was employed to investigate the each control parameter influence and to identify the right optimum combination of parameters on each response parameter. L16 orthogonal array was designed using Design of Experiments (DoE) methodology and experimentation was conducted using jatropha biodiesel and its diesel blends. Taguchi's signal-to-noise (S/N) ratio values revealed that PM and smoke opacity were primarily influenced by the engine load followed by percentage of biodiesel content in blend and least influenced by fuel injection pressure of the diesel engine. The advance in injection pressure from factory settings caused reduction in emission levels. Furthermore, the optimized emissions were found at 220 bar of injection pressure of diesel engine running at 25% of load condition when fueled with B40 jatropha biodiesel blend.*

Keywords: *Biodiesel, Optimization, Taguchi Method, Exhaust Emissions, Design of Experiments*

I. Introduction

Nowadays, the rate of energy utilization has become a measurement of industrial growth and the quality of human life. The major challenge faced globally is production of energy with none or minimum hazardous emissions released into atmosphere. The majority of air pollution originates from diesel engines due to incomplete burning of fuel, chemical process at high temperature and pressure in the combustion chamber, combustion of lubricating oil and its additives [1]. The importance of the biodiesel has risen in the energy sector not only due to its eco-friendliness, but also due to dwindling fossil fuel reserves and ever increasing fuel prices. Moreover, fossil fuel resources are densely located in few geographic locations and are non-renewable, toxic, and polluting. However, alternative renewable energy sources such as bio-fuels are indigenously produced from biodegradable feedstocks, less polluting, less toxic, clean-burning, and essentially free of sulfur and aromatics. The feedstock for biodiesel is from plant based oils and is domestically produced, so it supports the rural economic growth and increases the job opportunities [2]. It can be considered as an acceptable alternative to petro-diesel fuel as plant based biodiesel and their diesel blends have physical-chemical characteristics similar to those of diesel fuel [3].

The past research results revealed that neat vegetable oil can be used as it is or in the form of biodiesel in place of diesel, with noticeable decreased brake power, thermal efficiency, increase in BSFC, BSEC with lower emissions [4-7]. This is due to higher density and lower calorific value of biodiesel. Hence to improve the engine performance, it is essential to study the effects of engine design and parameters when the engine is fueled with biodiesel in the place of diesel fuel. Recently, a few research studies have revealed that modifications in the engine design and operating parameters such as fuel injection pressure, compression ratio, fuel injection timings, use of multiple injections, oil preheating improves the engine performance and reduces the emissions [8–10, 21]. However, the engine alteration cost should be the bare minimum; hence it is prudent to have very few design modifications and essential to run the engine with optimum engine operating parameters. The conventional optimization technique application may be cumbersome and so it is highly desirable to employ some statistical optimization method to identify the right combination of engine operating parameters that increases the engine performance and reduces the emissions [11]. Generally genetic algorithm, response surface method, grey relational analysis, non linear regression, artificial neural network (ANN) and Taguchi method were most widely used to find the optimized engine parameters that influence engine characteristics [12,13]. In this work, Taguchi optimization technique was employed to investigate the effect and to determine the combined optimum engine parameters to reduce the particulate matter (PM) and smoke opacity emissions of a single cylinder diesel engine when fueled with jatropha curcas oil methyl ester. Fuel injection pressure, percentage of biodiesel content in the blend and engine load were chosen as influencing control parameters of the engine. The particulate matter (PM) and smoke opacity emissions were chosen as response parameters for the present study.

II. Experimental Section

2.1 Preparation of Biodiesel

Crude jatropha curcas oil was collected from the local vendor to prepare the biodiesel. The jatropha curcas oil can be used directly in unmodified diesel engine in its pure form, but it is not preferable [14]. This is because the higher viscosity, density, and lower cetane number of the jatropha oils creates engine problems such as severe carbon deposits, injector choking and piston ring sticking in the diesel engine [15]. As shown in Figure 1, in transesterification process triglycerides (vegetable oil/fat) react with ethyl/methyl alcohol in the presence of a catalyst (potassium hydroxide/sodium hydroxide) and produce ethyl/methyl ester of oil/fat, which is called biodiesel and glycerol as by-product. In this work, biodiesel in the form of jatropha curcas oil methyl ester (JCOME) was prepared using methyl alcohol in the presence of sodium hydroxide as catalyst through transesterification process. The prepared jatropha biodiesel was blended with diesel fuel at ratios of 20:80, 40:60, 60:40 and 100:0 by volume to prepare B20J, B40J, B60J and B100J of jatropha biodiesel blends for experimental investigation respectively.

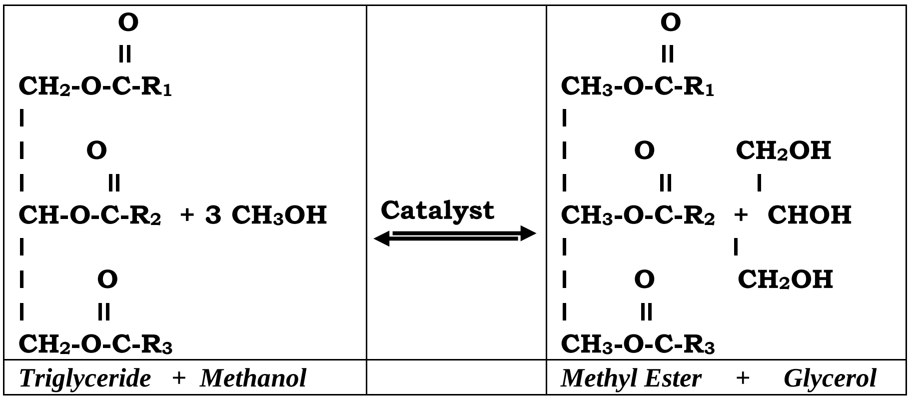

Fig.1 Transesterification Reaction

The properties of jatropha curcas oil methyl ester adheres to the ASTM standards and its properties along with mineral diesel are reported in Table 1.

Table 1: Properties of Diesel and Biodiesel

Fuel Property	Unit	ASTM Standards	Diesel	Jatropha Biodiesel
Kinematic Viscosity @ 40^{0}C	CST	D445	3.52	5.4
Flash Point	^{0}C	D93	49	169
Density @ 15^{0}C	kg/m^3	D1298	830	872
Calorific Value	kJ/kg	D4868	42850	38500
Cetane Number	--	D613	50	53
Total Sulfur	% by mass	D5453	0.01	Nil
Carbon Residue	% w/w	D4530	0.1	0.36
Ash Content	% by mass	D1119	0.01	0.03

2.2 Application of Taguchi Method

Taguchi method is one of the widely used methods to study the impact of interaction between the variables which have largely been ignored [16].Generally, the performance of the product or desired value of the output may be influenced by many engine factors. The selection of controllable influencing factors is a major factor in Taguchi optimization process in order to obtain the best results. In this work, the process parameters chosen affecting the engine characteristics were fuel injection pressure, engine load and percentage of biodiesel content in the blend. The three control parameters that are selected for the investigation with four levels are presented in Table 2.

Table 2: Control Parameters and Levels

Control Parameters	Level 1	Level 2	Level 3	Level 4
A. Engine Load	25	50	75	100
B. Biodiesel Percentage in Blend	20	40	60	100
C. Injection Pressure	210	220	230	240

In order to employ the Taguchi method, design of experiments (DoE) was used to define the orthogonal arrays that provides layout for experimentation trials with the various possible combinations of different levels of engine parameters. In this work, L16 orthogonal array was designed with 16 experimental trials for different combinations of engine parameters to carry out the investigation and presented in Table 3.

Table 3: L16 Orthogonal Array of Taguchi

Trial	Biodiesel Percentage in Blend (%)	Engine Load (%)	Injection Pressure (bar)
1	1	1	1
2	2	1	2
3	3	1	3
4	4	1	4
5	1	2	2
6	2	2	1
7	3	2	4
8	4	2	3
9	1	3	3
10	2	3	4
11	3	3	1
12	4	3	2
13	1	4	4
14	2	4	3
15	3	4	2
16	4	4	1

2.3 Experimental Setup

In this work, the experimental investigation was carried out using a single cylinder, four-stroke, water cooled, 3.7 kW compression ignition direct injection engine. This was connected to an eddy current dynamometer using flexible coupling for applying load. As shown in Figure 2, the major components of the experimental setup are the test diesel engine with fuel tank, dynamometer, exhaust gas line, data acquisition system, computer, exhaust gas temperature measurement system, smoke meter and multi-gas analyzer. The technical specifications of the test engine are listed in Table 4.

Table 4: Test Engine Specifications

Engine Type:	Kirloskar AV1, India,
Engine Details:	Single Cylinder, Four Stroke, Water Cooled, Direct Injection Engine
Bore & Stroke:	80 × 110 mm
Rated Power :	3.7 KW (5 HP) at 1500 rpm
Rated Speed:	1500 rpm
Injection Pressure:	200 bar
Compression Ratio:	16.5:1
Dynamometer:	Eddy Current

The experimental runs were carried out as stated in L16 orthogonal array for the four different injection pressures from quarter load to full load conditions using the diesel and jatropha biodiesel blends. The smoke meter and gas analyzer readings of emissions were recorded for 16 test conditions.

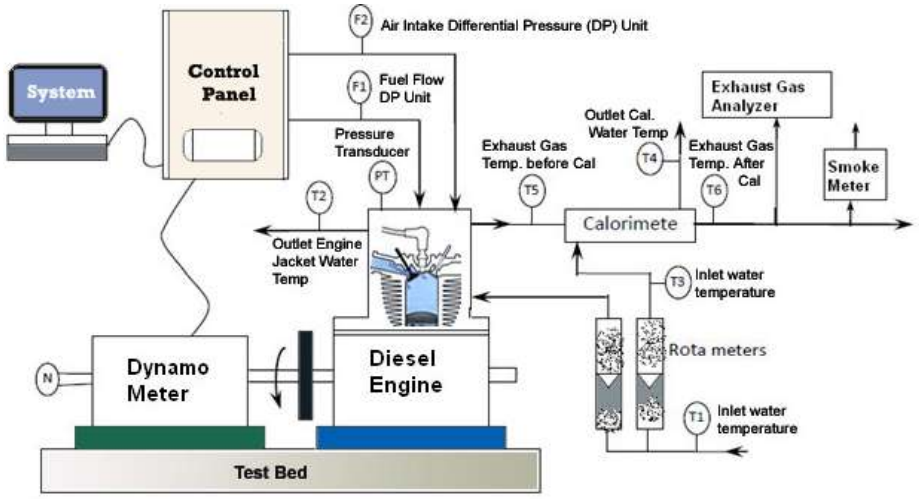

Fig. 2 Schematic Diagram of Test Engine

III. Results and Analysis

Taguchi methodology uses signal-to-noise ratio to determine the effect of input control parameters on each response variable. The S/N ratios of response parameters were computed using Minitab software (v17.1) and are listed in Table 5.

Table 5: S/N Ratios of Output Response Parameters

Trial	Biodiesel Percentage in Blend	Engine Load (%)	Injection Pressure (bar)	S/N Ratio for PM	S/N Ratio for Smoke Density
1	20	25	210	4.58296	-19.0849
2	20	50	220	2.97483	-22.3454
3	20	75	230	2.15811	-25.6207
4	20	100	240	1.41162	-27.8187
5	40	25	220	5.51448	-17.2665
6	40	50	210	2.73354	-22.9226
7	40	75	240	1.93820	-25.2014
8	40	100	230	1.83030	-27.1205
9	60	25	230	5.35212	-17.3846
10	60	50	240	2.97483	-21.2892
11	60	75	210	2.61537	-24.1903
12	60	100	220	2.61537	-25.9333
13	100	25	240	5.19275	-17.3846
14	100	50	230	3.74173	-20.3407
15	100	75	220	3.34982	-23.6938
16	100	100	210	2.73354	-25.5751

3.1 Particulate Matter (PM)

Particulate matter (PM) is one of the hazardous emissions from diesel engine which causes severe impact on environment such as radiation, environmental imbalance, change in cloud formation and global warming [17,18]. It is always a prerogative to control and reduce the PM content in air pollution, so the *Smaller-is-Better* criterion of S/N ratio is the best suitable option for the optimization of PM. The main effects plot for S/N Ratio plots as shown in Figure 3 and delta values of Table 6 confirm that the engine load is the prime factor that influences the PM emission followed by the biodiesel content percentage in blend and injection pressure has the lowest effect. The cyclical or repeating pattern of Figure 4 shows that residuals may not be independent and instead dependent on other engine parameters. It is also noticed, based on the PM related S/N rations of Table 5, that the PM emission can be reduced when the test engine runs at quarter load condition with 220 bar of injection pressure when it is fueled with B40J jatropha biodiesel.

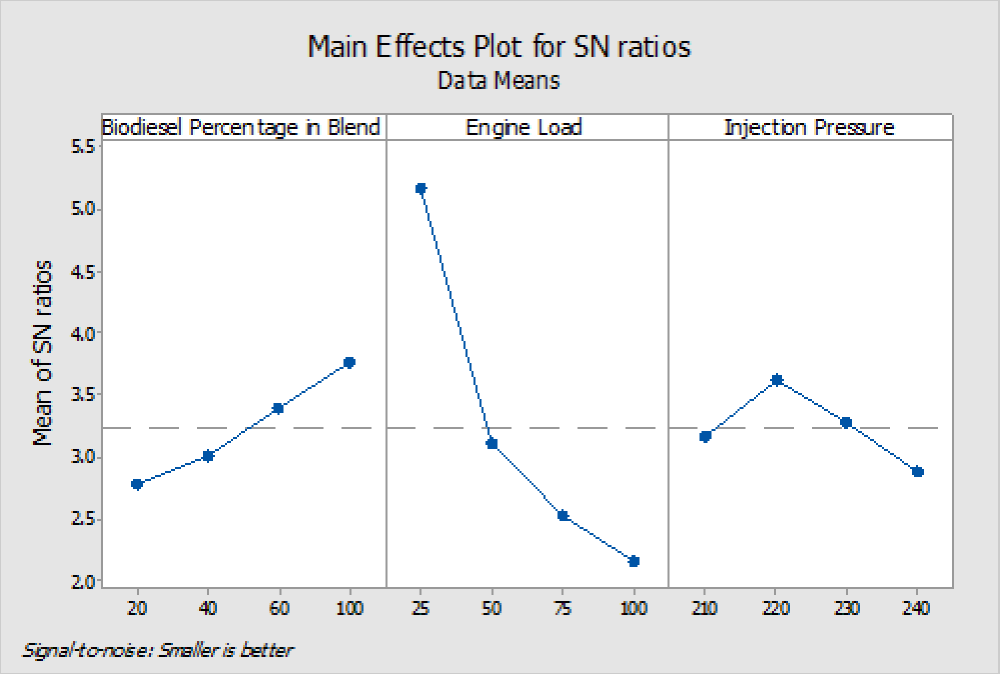

Fig. 3 Main Effects Plot for S/N Ratio – PM

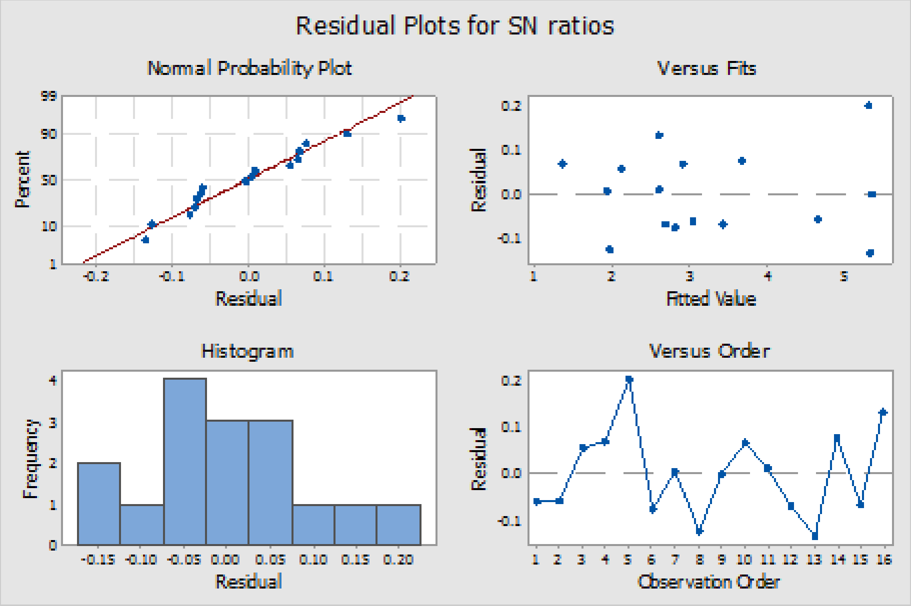

Fig. 4 Residual Plots for S/N Ratio – PM

Table 6: Response Table for Signal to Noise (S/N) Ratios – PM

Level	Biodiesel Percentage in Blend	Engine Load	Injection Pressure
1	2.782	5.161	3.166
2	3.004	3.106	3.614
3	3.389	2.515	3.271
4	3.754	2.148	2.879
Delta	0.973	3.013	0.734
Rank	2	1	3

3.3. Smoke Opacity

The smoke opacity from diesel engines causes respiratory problems such as asthma, chronic obstructive pulmonary disease (COPD), airway constriction and lung cancer in humans [19,20]. Reduction of smoke density is an important priority in order to control the air pollution and hence the *Smaller-is-Better* option of S/N ratio was selected to optimize the engine parameters. The S/N ratio output is depicted in the form of graph in Figure 5 and the data is presented in Table 7. It was observed that the engine load is most influencing parameter followed by the biodiesel content percentage in blend percentage and the influence of fuel injection pressure is minimal.

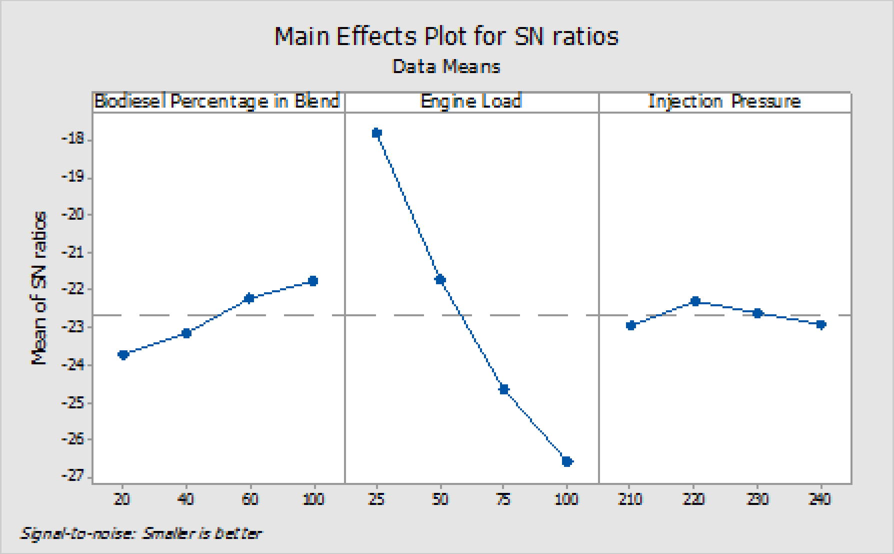

Fig. 5 Main Effects Plot for S/N Ratio – Smoke Opacity

Table 7: Response Table for Signal to Noise Ratios – Smoke Opacity

Level	Biodiesel Percentage in Blend	Engine Load	Injection Pressure
1	-23.72	-17.78	-22.94
2	-23.13	-21.72	-22.31
3	-22.20	-24.68	-22.62
4	-21.75	-26.61	-22.92
Delta	1.97	8.83	0.63
Rank	2	1	3

The residual plots of Figure 6 confirm the same as the Taguchi observations. The Taguchi experimental S/N ratio values of smoke opacity confirm that a single cylinder CIDI engine releases the lowest smoke opacity at 220 bar of injection pressure when it is fueled with B40J biodiesel blend and running at quarter load condition.

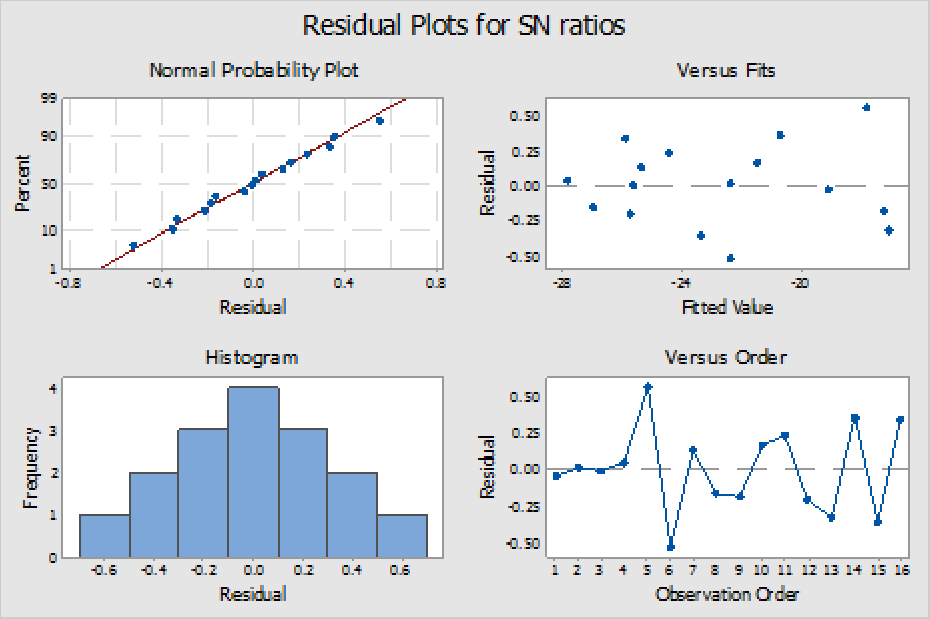

Fig. 6 Residual Plots for S/N Ratio – Smoke Opacity

IV. Conclusion

The experimental analysis was carried out using single cylinder CIDI engine as outlined in L16 orthogonal array to optimize the engine parameters. In this study, engine load, biodiesel content percentage in blend and fuel injection pressure were considered as input control engine parameters of the model to reduce the PM and smoke opacity emissions of the engine when fueled with jatropha biodiesel and its diesel blends. The signal-to-noise (S/N) ratios of Taguchi were employed to determine effect of each control parameter and optimal response conditions that reduced the PM and smoke opacity emissions. The analysis identified that the selected response parameters were mainly influenced by the engine load, followed by the biodiesel content percentage in blend and is least influenced by injection pressure. The lowest value of response parameters were found at to be at 220 bar of injection pressure of the engine when it is fueled with B40J blend of jatropha biodiesel, at 25% of engine load condition.

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