RESPONSE SURFACE METHOD TO OPTIMISE INJECTION TIMING, PERCENTAGE BLEND AND POWER OUTPUT OF A SEMI ADIABATIC ENGINE RUNNING ON BIODIESEL BLENDS

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ABSTRACT

Experiments are conducted on Kirloskar Air cooled diesel engine using 10, 20 and 30% biodiesel blends of Simarouba and Rubber seed oils to study the performance of the engine. Conventional engine is converted into the semi adiabatic engine by coating piston crown with 300 microns of partially stabilized zirconia without altering compression ratio. Exhaustive experiments are conducted on the semi adiabatic diesel engine at rated and varying injection timings (20° - Retarded, 23° - Rated and 26° - Advanced timing, before top dead centre). Performance parameters such as Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC) are computed, emissions like CO, NO_x, un-burnt hydrocarbons etc., were recorded for both engines and are analysed. Response Surface Method is used to obtain models of the responses such as Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), CO and NO_x. The results showed that BTE and BSFC of engine were improved for all blends tested at advanced injection timing. For all blends tested CO emission was decreasing and NO_x emission was increasing at advanced timing. Optimisation of Injection Timing (IT), power output and percentage biodiesel blend was performed using desirability approach of Response Surface Method (RSM) for better performance and lower emissions. Amongst two biodiesels tested Simarouba biodiesel shown better performance. An injection timing of 25.5°btdc, power output of 3.608 kW and 19.5% of fuel blend could be considered as the optimum parameters for the test engine.

KEYWORDS: Biodiesel, Injection Timing, RSM, Response & Optimisation

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1. INTRODUCTION

Industrialisation and exponential growth of the population resulted in faster rate of fossil fuel depletion and environmental pollution. The demand of fossil fuels has made to search for an alternative fuel. Vegetable oils (edible or non-edible) seem to have remarkable properties which make them promising alternative to petroleum fuels. However, the high viscosity of vegetable oil leads to incomplete combustion and loss of power due to poor atomization [1, 2]. Hence it is necessary to reduce viscosity of oil by converting it into biodiesel by the transesterification process [3]. Biodiesel is renewable, biodegradable, environmental friendly and non-toxic. It is an oxygenated fuel as it contains approximately 10-12% of oxygen by weight [4]. Tree borne non-edible oils are better choices for production of biodiesel as there may be a scarcity of edible oils for human consumption.

Simarouba Glauca DC tree is an exotic species and tree belongs to the family of Simaroubaceae, originating from South or Central America. Simarouba tree yields approximately 5-6 tonnes of seeds which are about a tonne of oil under normal conditions of growing [16]. Seeds of Simarouba contain 50-65% oil and yield of

oil is anywhere between 1-2 tonnes of oil/hectare/year [5].

The rubber tree belongs to the family of Euphrobiaceae and its seeds are of great resource for biofuel production due to their non-edible property. Its origin is from Africa and in 19th century this tree was introduced to Asian countries. Our country stands fourth in rubber tree cultivation and has nearly 7-8 lakh hectares of cultivated land. A study by rubber board showed that approximately 75,000 tonnes of rubber seeds are produced annually. The seeds which go waste can be converted into a useful potential biofuel and will fetch income for the farmers. The percentage of oil in rubber seed is about 40-50 % [6].

Even after transesterification viscosity of biodiesel is higher than diesel and use of biodiesel in the conventional engine results is poor in performance. An approach in which heat energy is trapped in an engine cylinder by insulating parts such as piston crown, cylinder head, combustion chamber walls, exhaust valves, cylinder liner with a ceramic material which can withstand high temperature and minimize coolant heat loss is called Low Heat Rejection (LHR) engine [7]. Although number of ceramic materials have been used as coatings, amongst them Partially Stabilized Zirconia (PSZ) has proved good due to its physical properties like lower thermal conductivity, higher mechanical strength, chemical stability and higher thermal expansion coefficient [7, 8&9].

2. MATERIALS AND METHODOLOGY

Simarouba and rubber seeds were collected from the commercial sources and crushed to extract oil. The samples were converted into biodiesel by alkaline transesterification as FFA of oils was less than 2%. Transesterification is the reaction of the oil with an alcohol to form esters and glycerol. The fuel blends were prepared just before the experiments to get a homogeneous mixture of diesel with biodiesel. The fuel properties have been determined as per IS standards. The single cylinder, four stroke, 4.41 kW Kirloskar TAF1 diesel engine (Figure 1) is converted into semi adiabatic also called as Low Heat Rejection (LHR) engine by coating the piston crown with 300 microns of PSZ by plasma spray technique and used for conducting the experiments. Experiments are conducted using Simarouba Biodiesel (SRBD) blends and Rubber Seed Biodiesel (DSBD) blends of 10, 20 and 30% by volume by varying the injection timing (23°btdc-rated injection timing, 20°btdc-retarded injection and 26°btdc-advanced injection). Load is applied from no load to full load in steps of 25% of maximum load using an electric dynamometer to find the performance (BP, BTE, Brake specific Energy Consumption-BSEC), combustion (cylinder pressure rise and Heat Release Rate-HRR) and emission characteristics (CO, UBHC, NO_x and Filter Smoke Number-FSN) of different blends tested. The AVL Digas 444 analyser is used for measuring exhaust gases and Filter Smoke Number is measured using AVL 415 variable sample smoke meter. Response Surface Method (RSM) is applied to optimise injection timing, brake power and % of biodiesel blend for the fuels tested. Surface plots are drawn to study the effects of variables like injection timing, BP and % biodiesel blend on engine responses such as BTE, BSEC, emissions and combustion parameters. Confirmation experiments are carried out at optimised values and results are compared with RSM models in order to validate the experimental results.

Figure 1: a) Engine Test Rig b) Schematic of Experimental Setup

3. RESPONSE SURFACE METHODOLOGY

Parameters of engine (injection timing, fuel injection pressure, level of LHR such as different thickness of coating, percentage blends, compression ratio etc.) have a significant effect on the performance of a diesel engine running on biodiesel. In order to improve thermal efficiency and reduce emissions using biodiesel in diesel engine, it is necessary to optimize either one or more parameters of the engine. RSM can be used in optimizing non-linear systems and can be modelled by a second order polynomial (quadratic) equation. In the present research work full factorial experiment was conducted to study the effect of biodiesel blends in semi adiabatic (LHR) engine. Load varied at five levels (0, 1.1, 2.21, 3.31 and 4.41 kW), blends varied at 3 levels (10, 20 and 30%), and injection timing varied at three levels (20°, 23°, 26°btdc). Experimental results are used to analyse the effect of injection timing, power output and percentage blends using response surface method in MINITAB 17 software package. Empirical relations are obtained from the responses. Stability of models obtained from semi adiabatic diesel engine running with biodiesel blends is validated by using ANOVA. Based on this, models of the present study are found to be significant as the value of ‘p’ is less than the chosen reference limit of 0.05. If the value of ‘p’ is less than 0.05 it implies that the model of response obtained is significant at 95% confidence level. Table 1 shows the values of ‘p’ of predicted response models. The values of the regression statistics, goodness of fit (R^2) and the goodness of prediction (adjusted R^2) are shown for some model samples (BTE, CO and NO_x) in the Table2 for Simarouba blends. The ‘ R^2 ’ value indicates the total variability of response after considering the significant factors. The value of adjusted ‘ R^2 ’ accounts for the number of predictors in the model. Both the values indicate that the models fit the data very well.

Table 1: ‘p’ Values of Response Models Obtained by ANOVA for SRBD Blends

Coefficients of Models	BTE	CO	NO_x
BP	*0.000	*0.000	*0.000
B	*0.000	0.069	0.736
IT	*0.000	0.070	*0.000
BP x BP	*0.000	*0.000	*0.000
B x B	*0.000	0.718	0.852
IT x IT	0.192	0.079	*0.000
BP x B	0.119	0.122	0.516
BP x IT	0.662	*0.011	0.000
B x IT	0.136	0.311	0.804

* indicates the significant terms (‘p’ value less than 0.05)

Where BP: Brake Power (kW), B: Biodiesel blend (%), IT: Injection Timing (deg. btdc)

Table 2: Response Surface Model Evaluation for Simarouba Blends

Model	BTE	CO	NO _x
Mean	23.60	0.022	960.31
SD	0.31	0.0097	90.81
R ²	99.52	82.47	97.28
Model degree	Quadratic	Quadratic	Quadratic
Adjusted R ²	99.35	76.4	96.33
Predicted R ²	99.15	66.66	94.02

The different models of the responses developed by RSM for Simarouba biodiesel blends are shown in equations (i) to (v). These equations are valid for input variables ranging from 23° to 26°btdc injection timing, 1.1 to 4.41 kW of power output and 10 to 30% of biodiesel blends respectively.

$$BTE = 9.46 + 11.296 * BP + 0.402 * B - 0.682 * IT - 1.5722 * BP * B - 0.01251 * B * B + 0.0166 * IT * IT - 0.00847 * BP * B + 0.0077 * BP * IT + 0.00406 * B * IT \quad (i)$$

$$BSEC = 37933 - 11435 * BP - 302 * B + 6 * IT + 1440.9 * BP * BP + 7.85 * B * B - 6.9 * IT * IT + 1.81 * BP * B + 50.4 * BP * IT + 0.47 * B * IT \quad (ii)$$

$$CO = 0.293 + 0.0042 * BP + 0.00115 * B - 0.0242 * IT + 0.00505 * BP * BP + 0.000004 * B * B + 0.000602 * IT * IT + 0.000561 * BP * B - 0.001667 * BP * IT - 0.000104 * B * IT \quad (iii)$$

$$NO_x = 3962 + 194 * BP - 9.4 * B - 428 * IT - 73.8 * BP * BP - 0.009 * B * B + 10.55 * IT * IT + 0.84 * BP * B + 20.08 * BP * IT + 0.465 * B * IT \quad (iv)$$

$$HC = 143.3 - 6.70 * BP - 1.292 * B - 8.36 * IT + 0.826 * BP * BP + 0.0112 * B * B + 0.139 * IT * IT - 0.0379 * BP * B + 0.202 * BP * IT + 0.0250 * B * IT \quad (v)$$

Figure 2: a) Optimisation Plot for SRBD Blends b) Optimisation Plot for RSBD Blends

Current research work uses desirability approach of RSM [10] to optimize input parameters like injection timing, power output and percentage of biodiesel blends. Figure 2(a) shows an optimisation plot for Simarouba biodiesel and

Figure 2(b) shows an optimisation plot for Rubber seed biodiesel respectively.

Amongst Simarouba and Rubber seed biodiesels tested, the results of Simarouba are highly encouraging and showed improved performance compared to conventional engine. Models of BTE, BSEC, CO and NO_x are discussed for Simarouba biodiesel.

Figure 3(a) indicates a surface plot drawn between BTE, injection timing and percentage blend at optimum brake power of 3.608 kW. It is found that optimum BTE of 28.401% is obtained at optimised blend of 19.5%, BP of 3.608 kW and injection timing of 25.5°btdc by RSM analysis by defining suitable weight ages and responses to each of the responses considered for optimisation [10]. Brake thermal efficiency is higher with early (advanced) injection timing. This could be because of higher peak pressure, maximum heat release rate and longer combustion duration (Figure 4, b) resulting in better combustion of biodiesel. Apart from this small amount of oxygen (in the form of water content) present in biodiesel will also enhance combustion.

Figure 3 (b) shows a surface plot drawn between BSFC, injection timing and percentage blends. From the plot it is observed that BSFC decreases with early injection timing (above the rates, timing of 23°btdc) and the same is evidenced by the increase in BTE.

**Figure 3: a) Surface Plot of BTE with Blend and IT
b) Surface Plot of BSFC with Blend and IT
c) Surface Plot of CO with Blend and IT
d) Surface Plot of NO_x with Blend and IT**

Figure 3(c) Shows variation CO emission with injection timing and percentage biodiesel blends. From the plot it is noticed that CO emission decreases with early injection timing. This is because of the combined effect of higher in-cylinder gas temperatures in the combustion chamber due to coating and advanced injection timing.

Figure 3 (c) shows the surface plot for CO variation with IT and biodiesel blend. Advanced timing provides better oxidation reactions between carbon and oxygen molecules due to the early start of combustion followed by longer combustion duration as shown in. CO emission is higher with retarded injection timing. It is because of incomplete combustion due to late burning of the fuel and loss of power.

Figure 4: a) Start of Combustion b) Combustion Duration

Figure 3(d) shows the surface plot of NO_x variation with IT and % blend. It is observed that NO_x emission is increasing with the increase in percentage of biodiesel in the blend and early (advancing) injection timing. The possible reasons for NO_x formation can be higher peak cylinder pressures and peak temperatures and more residence time (longer combustion duration) available for reaction to take place. With injection timing advanced, cylinder peak pressure and temperature will rise quickly and this causes nitrogen to react with oxygen to form more NO_x .

4. VALIDATION OF OPTIMISED RESULTS

In order to validate the optimized result, the experiments were performed at the optimum Injection timing, power and % biodiesel blend. Actual responses were calculated from experimental results. Table 3 summarises experimental values, predicted values and the percentage of error. The validation results indicated that the model developed was quite accurate as the percentage of error in the prediction was in a good agreement.

Table 3: Experimental values, predicted (RSM) values and % error

Sl. No	Parameter	Predicted	Experimental	% Error
01	IT (deg. btdc)	25.5	26.0	1.92
02	BP (kW)	3.608	3.616	0.22
03	Blend (%)	19.5	19.5	0
04	BTE (%)	28.40	27.84	-2.01
05	CO (% vol.)	0.0135	0.02	--
06	NO_x (ppm)	1601.46	1648.00	2.82

5. CONCLUSIONS

Based on the results of this study, the following conclusions were drawn

- Simarouba and Rubber seed biodiesel can be regarded as an alternative fuel to diesel fuel
- RSM technique was helpful to obtain empirical models of the responses in terms of IT, power output and % blend of biodiesel
- Advancing the injection timing helped in an increased BTE and decrease in CO emission
- The maximum BTE of 28.4% was achieved with a 20 % blend of and was higher than that of diesel at 3.6 kW of power.
- The desirability of the approach of RSM was found to be the simplest and efficient optimization technique. A high

desirability of 0.98 was achieved at optimum injection timing of 25.5°btdc, a fuel blend of 19.5%, and 3.608 kW of power.

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