Performance Optimisation of biodiesel fuelled Low Heat Rejection Diesel Engine using Response Surface Method

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Abstract: This work investigates the influence of injection timing on the performance and emission characteristics of Low Heat Rejection (LHR) diesel engine using 10, 20 and 30% biodiesel blends of Simarouba and Rubber seed oils respectively. Experiments were carried out at three injection timings (20° - Retarded, 23° - Rated and 26° – Advanced timing before top dead centre). Conventional engine is converted into LHR engine by coating 300 microns of Partially Stabilized Zirconia (PSZ) on piston crown. Response Surface Method is used to obtain models of the responses such as Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), Carbon monoxide (CO) and Oxides of nitrogen (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 injection timing. Optimisation of Injection Timing (IT), Brake Power (BP) 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, BP of 3.608 kW and 19.5% of fuel blend could be considered as the optimum parameters for the engine tested.

Key words: Biodiesel, Injection Timing, RSM, Response, Optimisation

1.Introduction

Industrialisation and exponential growth of population resulted in faster rate of fossil fuel depletion and environmental pollution. The demand of fossil fuel(s) 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 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 choice 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].

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 in to 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 conventional engine results is poor 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 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].

1. Materials and Methodology

Simarouba and rubber seeds were collected from commercial sources and crushed to extract the oils. The samples were converted into biodiesel by alkaline transesterification as Free Fatty Acid (FFA) of oils was less than 2%. Transesterification is the reaction of oil with an alcohol to form esters and glycerol. The fuel blends were prepared just before the experiments to get 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 (Fig. 1) is converted into semi adiabatic (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 injection timing (23^o btdc-rated injection timing, 20^o btdc-retarded injection and 26^o btdc- advanced injection). Load is applied from no load to full load in steps of 25% of maximum load using electric dynamometer to find performance parameters such as BP, BTE, BSFC, BSEC etc., combustion parameters like cylinder pressure rise and Heat Release Rate (HRR) and emission characteristics like 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 FSN is measured using AVL 415 variable sample smoke meter. 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 IT, 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 experiments.

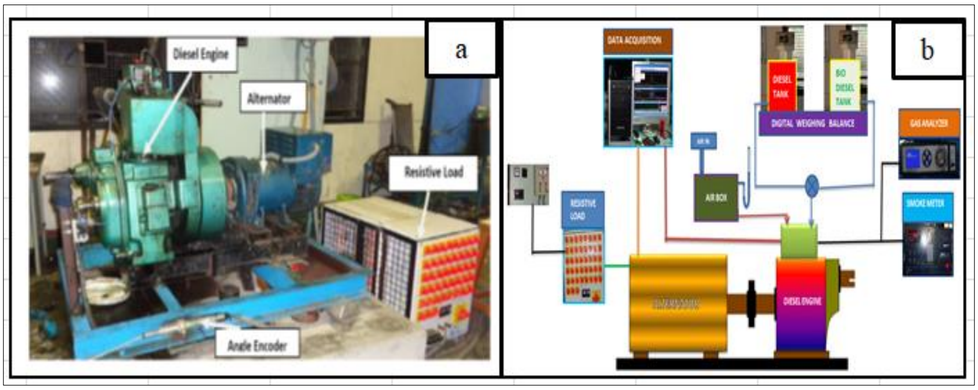

Fig 1 a) Engine test rig b) Schematic of experimental setup

2. Response Surface Methodology

Parameters of engine (IT, IP, different thickness of coating, % blend, compression ratio etc.) have considerable effect on the performance of diesel engine running on biodiesel(s). To improve BTE and reduce pollutants using biodiesel(s) in diesel engine, it is necessary to optimize either one or more parameters of the engine. Optimisation of parameters can be achieved using RSM. Models of second order polynomial (quadratic) equations are obtained and are useful in prediction of responses at optimised values. In the present investigation Load is varied at five levels (0, 1.1, 2.2, 3.31and 4.4 kW), blend is varied at 3 levels (10, 20 and 30%), and IT is varied at three levels (20^o, 23^o, 26^o btdc). Experimental results are used to analyse the effect of IT, BP and % blend using RSM in MINITAB

17 software. Sstability of models was validated by doing ANOVA. Based on this, empirical models of the present study are found to be significant as the value of 'p' is less than chosen reference limit of 0.05. 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 Table 2 for Simarouba blends. The values of R^2 and adjusted (R^2) 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.

$BTE = 9.46 + 11.296 * BP + 0.402 * B - 0.682 * IT - 1.5722 * BP * B - 0.01251 * B * B + 0.0166 * IT * IT - 0.00847 * BP * B + 0.0077 * BP * IT + 0.00406 * B * IT$	(i)
$BSEC = 37933 - 11435 * BP - 302 * B + 6 * IT + 1440.9 * BP * BP + 7.85 * B * B - 6.9 * IT * IT + 1.81 * BP * B + 50.4 * BP * IT + 0.47 * B * IT$	(ii)
$CO = 0.293 + 0.0042 * BP + 0.00115 * B - 0.0242 * IT + 0.00505 * BP * BP + 0.000004 * B * B + 0.000602 * IT * IT + 0.000561 * BP * B - 0.001667 * BP * IT - 0.000104 * B * IT$	(iii)
$NO_x = 3962 + 194 * BP - 9.4 * B - 428 * IT - 73.8 * BP * BP - 0.009 * B * B + 10.55 * IT * IT + 0.84 * BP * B + 20.08 * BP * IT + 0.465 * B * IT$	(iv)
$HC = 143.3 - 6.70 * BP - 1.292 * B - 8.36 * IT + 0.826 * BP * BP + 0.0112 * B * B + 0.139 * IT * IT - 0.0379 * BP * B + 0.202 * BP * IT + 0.0250 * B * IT$	(v)

Current research work uses desirability approach of RSM [10] to optimize input parameters like IT, BP and % of biodiesel blends. Fig 2(a) show optimisation plot for Simarouba biodiesel and Fig 2(b) show optimisation plot for Rubber seed biodiesel respectively.

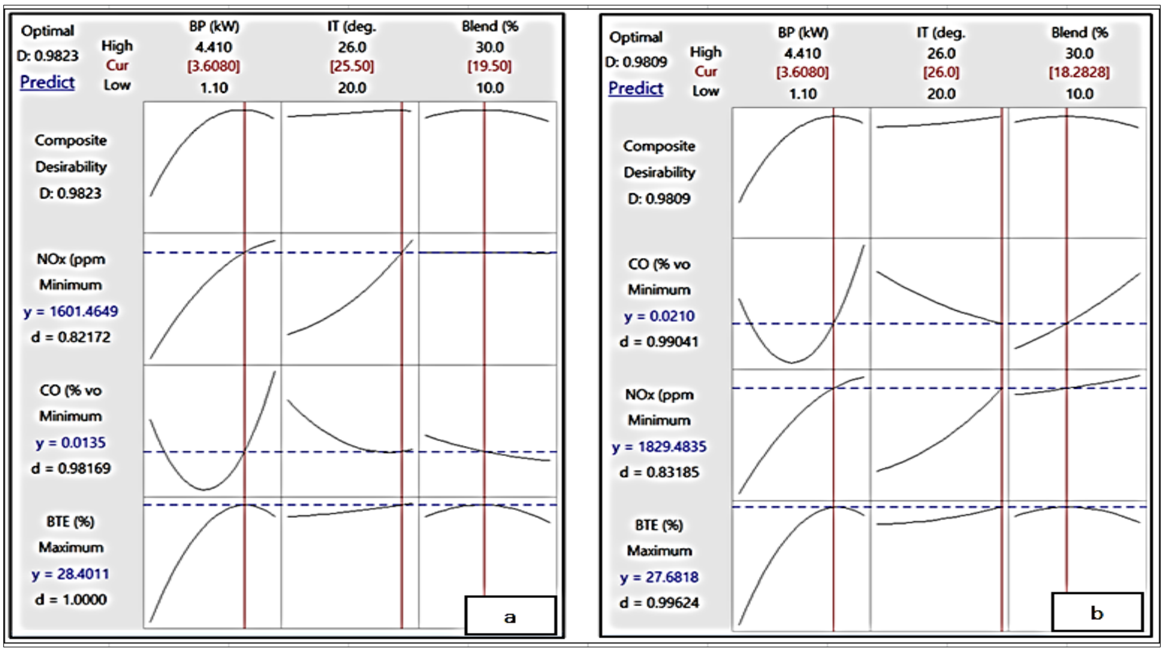

Fig 2 a) Optimisation plot for SRBD blends b) Optimisation plot for RSBD blends

Amongst SRBD and RSBD blends tested, results of SRBD are highly encouraging and showed improved performance compared to conventional engine. Models of BTE, BSEC, CO and NO_X are discussed for Simarouba biodiesel.

Fig 3(a) indicates a surface plot drawn between BTE, IT and % blend at optimum brake power of 3.608 kW. It is found that optimum BTE of 28.4% is obtained at optimised blend, BP and IT of 19.5%, 3.608 kW and 25.5^{o} btdc respectively by RSM analysis. During optimisation suitable weightages and responses are assigned to each of the responses considered [10]. Brake thermal efficiency is higher with early advanced (early) injection timing. This could be because of higher peak pressure due to early start of combustion; higher temperature and maximum heat rerelease rate and longer combustion duration resulting in efficient combustion. Start of Combustion and combustion duration is shown in Fig 4 (a) and (b) in terms of crank angle degrees. Apart from this inherent oxygen present in the biodiesel will also accelerate combustion.

Fig 3(b) shows a surface plot drawn between BSFC, IT and % blends. From the plot it is observed that BSFC decreases with advanced injection timing and the same is evidenced by increase in BTE.

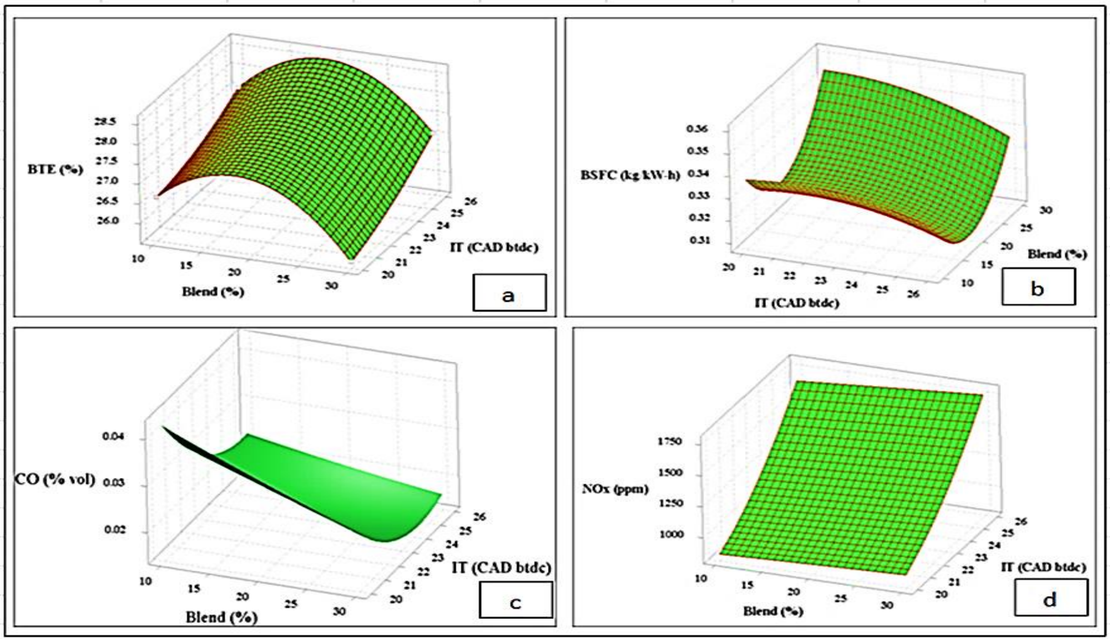

Fig 3 surface plot of a) BTE with blend and IT b) BSFC with blend and IT c) CO with blend and IT d) NO_X with blend and IT

Fig 3(c) shows surface plot of CO emission with IT and % biodiesel blends. From the plot it is noticed that CO emission decreases with advanced injection timing. This is because of combined effect of higher in-cylinder gas temperatures in combustion chamber due to coating and advanced injection timing which result in better mixing of air and fuel due to early start of combustion (Fig 4, a) and hence improved combustion efficiency.

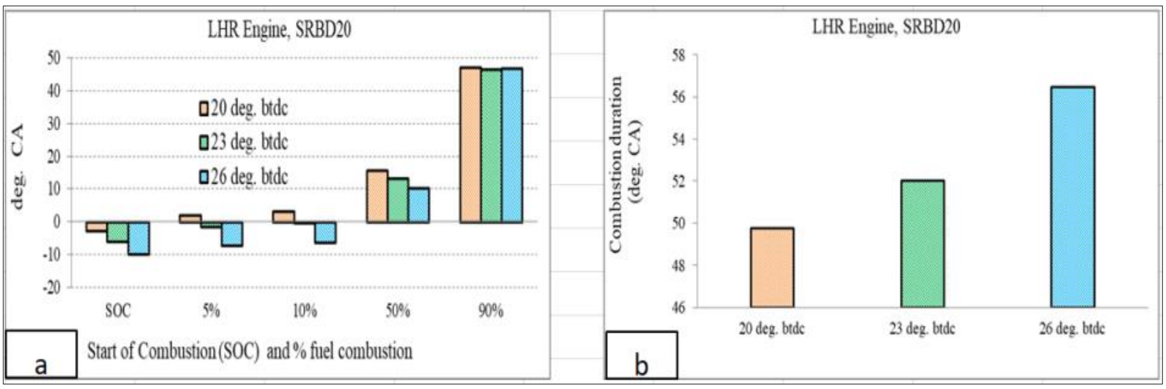

Fig 4 a) Start of combustion b) Combustion duration

Fig 3(c) shows surface plot for CO variation with IT and biodiesel blend. Advanced timing provides better oxidation reactions between carbon and oxygen molecules due to early start of combustion followed with 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.

Fig 3(d) shows surface plot of NO_X variation with IT and % blend. It is observed that NO_X emission is increasing with 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 takes 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.

3. Validation of Optimised Results

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

Table 3: Experimental results, predicted (RSM) results 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	0.00
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

4. Conclusion

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

i. Simarouba and Rubber seed biodiesels can be regarded as an alternative fuel to diesel fuel

ii. RSM technique was helpful to obtain empirical models of responses in terms of IT, Brake Power and % blend of biodiesel

iii. Advancing the injection timing helped in increased

BTE and decrease in CO emission

iv. The maximum BTE of 28.4% was achieved with 20% blend of and was higher than that of diesel at 3.6 kW of power.

v. The desirability of approach of RSM was found to be the simple and effective optimisation technique. A high composite desirability of 0.98 was achieved at optimum injection timing of 25.5º btdc, fuel blend of 19.5%, and 3.608 kW of brake power.

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