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A nonlinear regression based multi-objective optimization of parameters based on experimental data from an IC engine fueled with biodiesel blends

N. Maheshwari, C. Balaji*, A. Ramesh

Indian Institute of Technology Madras, Department of Mechanical Engineering, Chennai 600036, India

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ABSTRACT

This study reports the results of an experimental investigation of the performance of an IC engine fueled with a Karanja biodiesel blends, followed by multi-objective optimization with respect to engine emissions and fuel economy, in order to determine the optimum biodiesel blend and injection timings complying with Bharat Stage II emission norms. Nonlinear regression has been used to regress the experimentally obtained data to predict the brake thermal efficiency, NO_x, HC and smoke emissions based on injection timing, blend ratio and power output. To acquire the data, experimental studies have been conducted on a single cylinder, constant speed (1500 rpm), direct injection diesel engine under variable load conditions and injection timings for neat diesel and various Karanja biodiesel blends (5%, 10%, 15%, 20%, 50% and 100%). Retarding the injection timing for neat Karanja biodiesel resulted in an improved efficiency and lower HC emissions. A tradeoff relationship between the NO_x and smoke emissions is observed, which makes it difficult to determine the optimum blend ratio. The functional relationship developed between the correlating variables using nonlinear regression is able to predict the performance and emission characteristics with a correlation coefficient (R) in the range of 0.95–0.99 and very low root mean square errors. The outputs obtained using these functions are used to evaluate the multi-objective function of optimization process in the 0–20% blend range. The overall optimum is found to be 13% biodiesel-diesel blend with an injection timing of 24°bTDC, when equal weightage is given to emissions and efficiency.

1. Introduction

Compression ignition engines are widely used for transportation, rural agricultural applications and in the industrial sector. However, with increasing environmental concerns and legislated emissions standards there is a need to search and find ways of using complementary fuels, which are renewable and also emit low levels of gaseous and particulate pollutants. Current diesel engine research is focused on simultaneous reduction in soot and (oxides of nitrogen) NO_x emissions, while maintaining reasonable fuel economy. This problem is handled as multi-objective optimization as there are tradeoff relationships between the thermal efficiency, NO_x and soot [1].

Biodiesel is a diesel-equivalent processed fuel derived from biological sources (such as vegetable oils), which can be used in unmodified diesel engines [2,3]. However, biodiesel has higher flash point temperature, higher cetane number, lower sulfur content and lower calorific value than that of petroleum diesel fuel [4]. A comparison of important properties of Karanja biodiesel with diesel is shown in Table 1.

* *Corresponding author*. Tel.: +91 44 2257 4689.
E-mail address: balaji@iitm.ac.in (C. Balaji).
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Nomenclature

B	Blend ratio, %
bTDC	Before Top Dead Center
BMEP	Brake Mean Effective Pressure
BSFC	Brake specific fuel consumption
BTE	Brake Thermal Efficiency
BSU	Bosch smoke unit
HRR	Heat Release Rate
I	Injection timing, °bTDC
P	Power, kW
R	Correlation Coefficient
R^2	Coefficient of Determination
RMS	Root Mean Square error
UHC	Unburnt Hydrocarbon

A significant improvement in the performance and emissions even with neat Jatropha oil is observed by increasing the injector opening pressure (IOP). Optimization of the injection rate and injection timing is essential with biodiesel [5,6]. To reduce the emissions, use of exhaust gas recirculation (EGR) and oxidized biodiesel have been tried. Oxidized biodiesel results in lower HC and CO emissions with insignificant effect on the NO_x emissions [7]. EGR reduces NO_x emissions, but it results in increase in the HC, CO and particulate emissions [8].

Biodiesel is generally blended in definite proportions with diesel and used. In case of Karanja biodiesel, as the content of Karanja biodiesel in the fuel was increased, a corresponding reduction in NO_x, HC and CO emissions were noted for blends upto 40% by volume (B40) [9,10]. The influence of injection timing and fuel blends on exhaust emissions has been experimentally investigated by using methanol-blended diesel [11]. It was reported that NO_x and CO_2 emissions decreased, smoke opacity, UHC and CO emissions increased for the retarded injection timing. In terms of BSFC (Brake specific fuel consumption) and BTE (Brake Thermal Efficiency), retarded and advanced injection timings gave negative results for all fuel blends for all engine loads. The influence of injection timing and blend ratio on the exhaust emissions of ethanol-blended diesel has also been studied. Retarding the injection timing resulted in lower emissions [12]. It has been concluded that the performance characteristics can be improved with biodiesel by re-designing the injection system and determining the optimum biodiesel-diesel blend. To develop a good injection system, a parameter search to determine the influence of design parameters on both the performance and exhaust emissions should be performed. However, when this parameter search is executed experimentally, it involves a huge expenditure of money and time. For this reason, the optimization of parameters by simulations based on limited experimental data followed by optimization on a computer is very useful.

In the past, Artificial Neural Network (ANN) has been used to predict the performance and exhaust emissions of blended fuels [13,14]. It was reported that ANN can predict engine performance, exhaust emissions and exhaust gas temperature quite well with correlation coefficients in the range of 0.983–0.996 [15,16]. Linear regression analysis has been used to establish an empirical equation between the cetane number (CN) and fatty acid methyl ester (FAME) composition with an accuracy of 88% [17]. The analysis of variance and nonlinear regression approach was used to express the engine performance parameters like power output, BSFC and torque in terms of blend and speed. Statistical analyses showed that the fuel blends had a significant linear effect, whereas engine speed had a significant fourth order polynomial effect on power output ($R^2 = 0.94$) and torque ($R^2 = 0.9702$). There was a significant quadratic trend effect of fuel blends on CO emissions ($R^2 = 0.7977$) and on HC ($R^2 = 0.9881$) emissions. A regression analysis performed on smoke emissions data showed a significant linear effect of the fuel blend ($R^2 = 0.9971$) [18,19]. Simulation tools like ANN and nonlinear regression can predict emission levels and performance and these outputs can be used to evaluate the objective function of the optimization process, which can be performed with a GA approach [20].

From a review of literature, it seen that while a lot of work has been carried out to improve the performance of biodiesel fueled compression ignition engines, studies on multi-objective optimization to determine the most suitable set of operating variables with modern optimization techniques are not many. Hence, the goal of the present investigation is to set up a multi-objective optimization framework for reducing emissions without significantly sacrificing the fuel economy. Experiments were conducted on a diesel engine running on biodiesel (from Karanja oil) and diesel blends to generate data required for the optimization and finally the optimized configuration was validated experimentally with the same engine.

Table 1 – Properties of diesel and biodiesel.

Properties	Diesel	Karanja
Density@15°; C, kg/m^3	840	887.6
Kinematic Viscosity at 40°c,cSt	4.59	5.460
Calorific value (kJ/kg)	42,500	39000
Flash Point (PMCC)°C	75	155
Cetane Number	45–55	57.5
Carbon Residue, Percent by mass	0.1	0.25

2. Experimental set up and measurements

A single cylinder, four stroke, direct injection, air cooled diesel engine normally used for agricultural applications was employed. Table 2 gives the details of this engine. Fig. 1 shows a schematic diagram of the experimental setup. The engine was coupled to an eddy current dynamometer to provide brake load. Karanja biodiesel was injected into the engine through the existing injection system. The fuel consumption was measured with the aid of a precision weighing machine and stopwatch on mass basis. Air consumption was measured with the help of a turbine type air flow meter and stopwatch. A chrome–alumel thermocouple was used along with a digital