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Optimization of diesel–butanol–vegetable oil blend ratios based on engine operating parameters

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ABSTRACT

The rule of thumb in literature is that 20% of biodiesel is the most acceptable blend ratio in alternative fuel blends. This work focuses on in-depth mathematical optimization analyses of ternary blends of diesel–butanol–vegetable oil (cotton oil), based on engine operating parameters using RSM (response surface methodology). It is critical to achieve the maximum power and torque for customers while keeping the emissions low enough due to government regulations and certifications. Thus, three optimization studies were conducted at 2200 rpm, which corresponds to the maximum brake torque, and engine emissions were fixed at a maximum possible value based on emission standards, for all three studies. In order to understand the impact of other engine parameters on the blend ratio, as well, various combinations of BTE (brake thermal efficiency), maximum brake power, maximum brake torque, BSFC (brake specific fuel consumption) and BMEP (brake mean effective pressure) were fixed, which correspond to Opt-1 (optimization 1) (BTE and exhaust emissions), optimization 2 (BTE, brake power and exhaust emissions), and optimization 3 (BTE, brake power, brake torque, BSFC, BMEP and exhaust emissions). Optimization studies used experimentally determined emissions and performance data of a diesel engine based on 7 different concentrations of diesel–butanol–cotton oil blends. Optimum values of the blends corresponding to the optimization studies were mathematically determined as Opt-1 (optimization 1) (61.7 vol.% diesel, 34.75 vol.% butanol, 3.55 vol.% cotton oil), Opt-2 (optimization 2) (64.5 vol.% diesel, 28.7 vol.% butanol, 6.8 vol.% cotton oil), and Opt-3 (optimization 3) (65.5 vol.% diesel, 23.1 vol.% butanol, 11.4 vol.% cotton oil). When compared to diesel, BSFCs of Opt-1, Opt-2 and Opt-3 blends at 2200 rpm increased 41.57, 33.87 and 24.53%, respectively. In terms of basic exhaust gas emissions, optimum fuel blends decreased NO_x (oxides of nitrogen), CO (carbon monoxide) and HC (hydrocarbon) emissions as compared to diesel.

1. Introduction

Fossil fuel reserves, the vast majority of the World's energy resources, have been increasingly used due to high global energy demands. As a result of large scale production and consumption of these fuels, air pollution and harmful emissions increase in the World. The most important way to reduce air pollution caused by fossil fuels is to develop new alternative fuels that would satisfy the demands of the transportation sector, which is the largest consumer of fossil fuels [1,2]. Because of that, the European Union and the U.S. target 20% and 25% share of biofuels by 2020 [3].

Diesel engines have been increasingly used in the transportation sector due to their efficiency and performance. Thus, utilization of biodiesel blends in diesel engines is important from the perspectives of efficiency, performance, environment and economics [4].

Vegetable oils and alcohols that can be produced from biomass are important alternative fuels for use in diesel engines. Utilization of vegetable oils and alcohols are advantageous because their biomass is easy to supply and they are renewable resources with lower exhaust gas emissions due to the oxygen in their chemical structures [5,6].

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The main problem of using vegetable oils in internal combustion engines is the high viscosities of such fuels [7,8]. There are thermal and chemical methods to reduce the viscosities of vegetable oils. The thermal method uses preheating of these fuels, which increases the temperature and reduces viscosity [9]. Chemical methods are dilution, pyrolysis, transesterification and micro-emulsion [10]. Transesterification is the mostly commonly used method that has disadvantages such as high production cost; additional energy cost to convert glycerin, which is released during production, to a valuable product; poor cold flow characteristics under 0 °C; and higher NO_x emissions as compared to diesel fuel [11,12]. On the other hand, the microemulsion method is easy to apply and requires no significant cost. This method is based on mixing two immiscible liquids by using butanol, octanol or hexanol as a solvent. It is a commonly used method to reduce the viscosity of alternative fuel blends to the level required in diesel engines. In addition, these solvents can be mixed with vegetable oils to provide stable alternative fuels at lower temperatures [13–15].

For microemulsion, butanol is advantageous over methanol and ethanol due to a lower corrosion risk, higher calorific value, higher cetane number, lower polarity and the quality of being a common solvent [16,17]. However, the miscibility problem of ethanol and methanol can be overcome by using biodiesel as a binder for diesel–ethanol–biodiesel and diesel–methanol–biodiesel mixtures [18].

Because of the promising potential of butanol, the effect of diesel fuel–butanol binary blends on engine performance and exhaust emissions in diesel engines were extensively examined [19–23]. However, there are fewer studies with regards to diesel fuel–vegetable oil–butanol ternary blends in literature [3,20,24,25]. These studies showed butanol as a promising and safe alternative fuel that can be used in diesel engines with high blend ratios.

Lujaji et al. [26,27] evaluated the engine performance, combustion, and emission characteristics of a diesel engine fueled with croton megalocarpus oil–n-butanol–diesel blends. They observed that brake specific energy consumption, cylinder pressure and heat release rate of ternary blends increased, while CO_2 (carbon dioxide) and smoke emissions decreased in comparison to diesel fuel. Ternary blends emitted similar NO_x (oxides of nitrogen) emission values except at 100% load condition with those of diesel fuel. In addition they declared that fuel properties of vegetable oils are improved by the blending of vegetable oil, n-butanol, and diesel fuel. It was reported by Weerachanchai et al. [28] that palm kernel oil–diesel fuel–n-butanol (cosolvent) ternary blend is a promising alternative diesel fuel in terms of avoiding the problems related to direct use of palm kernel oil in a diesel engine. This study indicates that the use of n-butanol as a cosolvent showed better characteristics of phase behavior and fuel properties than the use of ethanol. Atmanlı et al. [24] produced one kind of micro-emulsions consisting of diesel, cotton oil and n-butanol, and investigated the phase stability, fuel properties, engine performance and exhaust emissions. It was reported that n-butanol is a very competitive renewable fuel and is increasing its content in ternary blends decreased insolubility and improved low temperature behavior of the blends. Experimental results show that a ternary blend of DCtOnB (70 vol.% diesel fuel, 20 vol.% cotton oil, 10 vol.% n-butanol) decreased brake torque, brake power, BTE (brake thermal efficiency), exhaust temperature, CO (carbon monoxide) and CO_2 emissions, while increasing NO_x and HC (hydrocarbon) emissions. They concluded that DCtOnB is a promising candidate for renewable fuels at the expense of increasing BSFC (brake specific fuel consumption), NO_x and HC emissions. Sharon et al. [29] studied the effect of diesel-used palm oil–butanol ternary blends on engine performance and emission characteristics and reported CO, CO_2, NO_x emissions and smoke opacity of the ternary blends decreased while HC and BTE increased with increasing butanol content in the blends.

There are a few studies in literature with regards to the investigation of optimum blends ratios of biodiesel blends [30–32]. One area that is missing in the literature is the investigation of the optimum diesel–butanol–vegetable oil ternary blend ratio corresponding to higher engine efficiency and lower exhaust emissions. The main advantage of optimization of fuel blend ratios is to improve engine performance and exhaust emissions and to utilize the best possible blend ratios in a diesel engine without any engine modification such as injector pressure, nozzle diameter or injection time. In order to establish the optimum fuel blend ratios based on engine operating parameters, design of experiments techniques, namely RSM (response surface methodology), Taguchi method, and factorial design can be used. RSM is used for modeling nonlinear relations between the input factors and the outputs or responses. Factorial design is used for modeling linear relations, and the Taguchi method determines only the best combination of factors for the previously determined factor levels at the beginning of the investigation [33,34]. RSM is advantageous over the other methods because it provides a high level of information with fewer experiments and less data and can change parameters simultaneously during optimization.

Because the relations between responses and input factors are nonlinear, RSM based optimization analyses of ternary blends of diesel–butanol–vegetable oil (cotton oil) were carried out based on engine operating conditions. Three optimization studies were conducted at 2200 rpm, which corresponds to the maximum brake torque, and engine emissions were fixed at a maximum possible value based on emission standards, for all three studies. Optimum values of the blends corresponding to the optimization studies were mathematically determined as optimization 1 (61.7% diesel, 34.75% butanol, 3.55% cotton oil), optimization 2 (64.5% diesel, 28.7% butanol, 6.8% cotton oil), and optimization 3 (65.5% diesel, 23.1% butanol, 11.4% cotton oil). The optimum fuel blends were evaluated in the diesel engine and performance and emission characteristics were experimentally compared to diesel fuel as functions of the engine speed.

2. Experimental setup and procedure

Experiments were carried out using a four-cylinder, four-stroke, direct injection, turbocharged Land Rover 110 diesel engine. Table 1 shows the technical specifications of the test engine. Engine performance characteristics were determined using a hydraulic dynamometer (BT-190) with a maximum brake power of 119 kW, a maximum speed of 7500 rpm, a load cell capacity of 2500 N and a

Table 1
Technical specifications of the test engine.

Model	Land Rover 110
Cylinder bore (mm)	90.47
Stroke (mm)	97
Volume (cm^3)	2495
Compression ratio	19.5:1
Maximum torque (Nm) at 2200 rpm	235
Maximum power (kW) at 3800 rpm	82
Maximum speed (rpm)	4400 (+40,−20)
Fuel injection system	Turbocharged direct injection
Injection pump type	Bosch Rotary R509
Injector type	Bosch KBAL90P37
Injection pressure (kg/cm^2)	200
Injection timing	15° BTDC
Turbocharge-delivered pressure (kg/cm^2)	0.8–1
Emission standard	Euro III