Applied Energy 145 (2015) 155–162

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Extensive analyses of diesel–vegetable oil–*n*-butanol ternary blends in a diesel engine

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HIGHLIGHTS

- Diesel–vegetable oil–*n*-butanol ternary blends were tested in a diesel engine.
- Canola, soybean, sunflower, corn, olive and hazelnut oils were the vegetable oils.
- Ternary blends increased BSFC as compared to diesel fuel between 21.45% and 24.67%.
- The ternary blends increased NO emissions as compared to diesel fuel.

ARTICLE INFO

Article history:
Received 21 October 2014
Received in revised form 14 January 2015
Accepted 17 January 2015
Available online 27 February 2015

Keywords:
Biofuels
Microemulsification
n-Butanol
Vegetable oil
Diesel engine

ABSTRACT

In this study, *n*-butanol (nB) was used as the common solvent and crude canola (Cn), soybean (Sb), sunflower (Sf), corn (Cr), olive (Ol), and hazelnut oil (Hn) as the vegetable oil components were used for making microemulsification of diesel fuel (D)-vegetable oil blends. The blend ratios of 70% vol. D, 20% vol. vegetable oil and 10% vol. *n*B were determined to increase concentration of biofuels in ternary blends. Six different ternary blends were prepared via the splash blending method. Engine performance tests of the ternary blends were carried out on a four-cylinder, four-cycle turbocharged direct-injection diesel engine at full load with various engine speeds. Test fuels were kept stationary at ambient temperature and the long-term stabilities were observed at 60 days. There were not any phase separations in the ternary blends. Fuel properties of the test fuels were examined and determined to be in agreement with the fuel standards. According to engine performance test results of the ternary blends, brake torque, brake power, brake thermal efficiency (BTE), brake mean effective pressure (BMEP) and exhaust gas temperatures decreased while brake specific fuel consumption (BSFC) increased as compared to those of diesel fuel. In terms of basic exhaust gas emissions, ternary blends increased nitric oxide (NO) and carbon monoxide (CO) emissions while reducing hydrocarbon (HC) and carbon dioxide (CO_2) emissions as compared to diesel.

1. Introduction

Renewable and alternative energy sources are becoming more demanding and necessary due to increases in crude oil prices and exhaust gas emissions due to fossil fuels throughout the world. The demand for fossil based fuels has increased rapidly in recent years because of worldwide industrialization and the increasing number of vehicles. Fossil fuels today represent 80% of primary energy consumption, wherein 58% of it is used in the transportation sector [1,2].

Biomass has the largest technical potential among alternative energy resources for diesel engines, which are the most commonly used devices in transportation. Among biomass energy resources are vegetable and animal origin biological substances for which carbohydrate compounds are the main components [1,3].

Utilization of vegetable oils and bio alcohols in diesel engines is advantageous because their biomass is easy to supply and they are renewable sources with lower exhaust gas emissions due to the oxygen in their chemical structures [4].

The main problem of using vegetable oils in diesel engines is the high viscosities of such fuels [5–9]. Chemical and thermal methods

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http://dx.doi.org/10.1016/j.apenergy.2015.01.071
0306-2619/

are the two techniques to reduce viscosities of vegetable oils. The thermal method uses preheating of fuels, which increases the temperature and reduces viscosity [10]. Chemical methods can be divided into dilution, pyrolysis, transesterification and microemulsion [8,9]. The widely used transesterification method has disadvantages during production and consumption stages. Such problems can be listed as high cost of biodiesel production; 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 [9,11–13].

Microemulsion mixes two immiscible liquids by using butanol, octanol or hexanol as a solvent and is a common method to ensure the required viscosity value for diesel engines for the ternary blends. In addition, these solvents can be mixed with vegetable oils and can provide new alternative fuels that are stable at lower temperatures [11,14–18].

Methanol and ethanol are the most commonly used alcohols for studies related to the utilization of alcohol–diesel mixtures in diesel engines. Ethanol is renewable and has more potential as compared to methanol. The miscibility problem of ethanol can be overcome by using biodiesel as a binder for diesel and ethanol mixtures [19]. However, phase separation occurs if ethanol and diesel fuel are used as a blended fuel in diesel engines under 10 °C [9,20]. Overall, butanol is an advantageous alternative alcohol to ethanol and methanol to use in diesel engines [21–23].

As compared to ethanol and methanol, *n*B (1-butanol), which is a straight chain molecular isomer of butanol, has advantages such as lower corrosion risk, higher calorific value, higher cetane number, lower polarity, and better solvent characteristics to mix with diesel and vegetable oils [16,24]. Due to these advantages, butanol is preferred to other common alcohols when mixing with diesel fuel. When studies related to utilization of alcohols in diesel engines are investigated in the literature, the use of nB as an alternative fuel is limited but becoming more important for diesel engines [16,25].

Lujaji et al. used blends of croton oil, *n*-butanol and diesel fuel in a diesel engine to investigate fuel characteristics, engine performance and engine emissions. Experimental results indicated that brake specific energy consumption increased and thermal efficiency decreased as the engine load increased. Butanol containing blends showed higher cylinder pressure, cylinder temperature and heat release on higher engine loads. As compared to D2 fuel, the blends indicated lower CO and smoke emissions and higher HC emissions, and no significant difference in NO_x. It was reported that fuel blends had no phase separation and vegetable oils improved characteristics of fuel blends [26].

Atmanli et al. investigated the effect of temperature and component concentration on phase stability of diesel fuel, cotton oil and *n*-butanol ternary blends by performing titration method at five temperatures. Based on the phase diagram at the lowest test temperature (−10 °C) and no indication of separation, the ternary blend of 70% diesel fuel, 20% cotton oil and 10% *n*-butanol by volume (DCtOnB) was evaluated in a diesel engine for engine performance and emissions. Engine performance tests of DCtOnB showed lower brake torque, brake power, brake thermal efficiency, brake mean effective pressure and exhaust gas temperature, and higher brake specific fuel consumption. Especially at lower engine speeds, CO and CO_2 emissions decreased, and NO_x and HC emissions increased. It was noted that DCtOnB was a suitable alternative to diesel fuel due to its performance at cold temperatures and lower exhaust emissions [11].

Considering the limited number of studies in the literature, ternary blends of diesel fuel, *n*-butanol and various vegetable oils (Cn, Sb, Sf, Cr, Ol, Hn) were tested and the blend of 70% D, 20% vegetable oil and 10% nB was determined as an alternative based on the desire to increase biofuel ratio in fuel blends and the European Union (2003/30/EC) directive on May 8, 2003 that endorsed 20% share of biofuels by 2020. Test blends were evaluated in a four-cylinder, four-stroke, turbocharged, direct-injection diesel engine for engine performance characteristics and emissions. Performance parameters were compared to those of the reference fuel.

2. Experiment and procedure

2.1. Experimental setup

The engine dynamometer coupled to the engine was hydraulic-type (BT-190) with a maximum brake power of 119 kW, a maximum engine speed of 7500 rpm and a maximum torque of 745 N m. The load cell capacity was 2500 N and the brake water pressure was 1–2 kg/cm^2. The schematic of the engine dynamometer setup is seen in Fig. 1. The test engine was a four-cylinder, four-stroke, turbocharged, direct injection, Land Rover 110 diesel engine. Technical specifications of the test engine are given in Table 1.

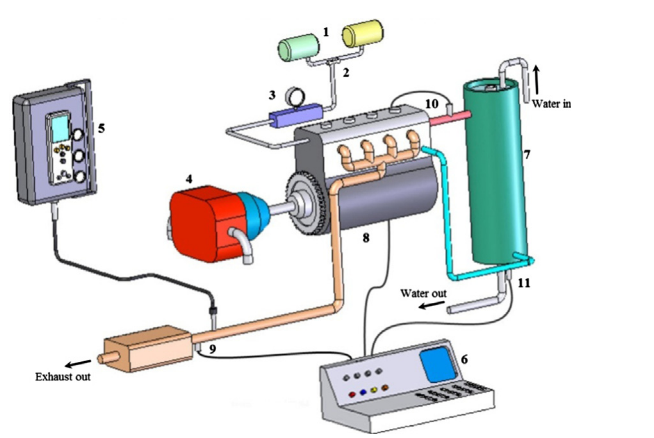
Exhaust gas emissions were measured using a Testo 350 exhaust gas analyzer which determines CO, NO, NO_2, CO_2 and HC emissions within the ranges of 0–10000 ppm, 0–4000 ppm, 0–500 ppm, 0–50 vol.% and 100–40000 ppm, respectively. Uncertainty analyses for engine performance parameters were performed using the propagation of errors. The overall uncertainty was calculated using Eq. (1).

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{\frac{1}{2}} \quad (1)$$

where R is a given function of the independent variables $x_1, x_2, \ldots, x_n$ and $w_1, w_2, \ldots, w_n$ are the uncertainties of the independent variables [27]. Table 2 shows accuracy and uncertainty values of measured and calculated quantities.

2.2. Test fuels

For the blends of three fuels, diesel fuel, *n*-butanol and various vegetable oils were used. *n*-Butanol can be made of renewable resources, is miscible with diesel fuel, and has fuel properties closer to diesel fuel than other alcohols such as ethanol and methanol.



1. Fuel tanks.
2. Two-way, hand controlled valve.
3. Fuel meter.
4. Hydraulic dynamometer.
5. Exhaust gas analyzer.
6. Control panel.
7. Cooling water tank.
8. Diesel engine.
9. K-type thermocouple.
10-11. PT-100 temperature sensor.

Fig. 1. Engine test setup.