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Experimental investigation of engine performance and exhaust emissions of a diesel engine fueled with diesel–*n*-butanol–vegetable oil blends

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ABSTRACT

The aim of the present study was to evaluate the effect of using *n*-butanol in vegetable oil–diesel fuel blends on engine performance and exhaust emissions of a direct injection diesel engine operating at full load (100% throttle conditions) with different engine speeds without any engine modification. Neat canola-hazelnut-cottonseed oil (CHC) and neat sunflower–corn–soybean oil (SCS) blends were prepared as equal vol.% by splash blending method. Diesel fuel (70 vol.%) and *n*-butanol (10 vol.%) are added into CHC and SCS blends (denoted as DCHCnB and DSCSnB, respectively), simultaneously. Basic fuel properties of DCHCnB and DSCSnB are similar to those of diesel fuel. According to engine performance and exhaust emission test results of DCHCnB and DSCSnB, average values of brake torque (−6.08% and −6.67%), brake power (−4.12% and −4.59%), brake thermal efficiency (BTE) (−10.80% and −11.66%), exhaust gas temperature (−15.11% and −14.99%), carbon dioxide (CO_2) (−1.12% and −2.30%) and hydrocarbon (HC) (−36.71% and −32.28%) are lower, while brake specific fuel consumption (BSFC) (18.43% and 19.58%), oxides of nitrogen (NO_x) (27.27% and 30.36%) and carbon monoxide (CO) (41.57% and 26.89%) are higher than those of diesel fuel.

1. Introduction

Due to declining petroleum resources and increasing energy consumption, growing interest is being shown in biofuels as diesel engine fuels. Biofuels are known as a potential renewable and sustainable energy sources in satisfying environmental and economical concerns [1]. Renewable fuels, vegetable oils and alcohols have been evaluated by reason of desirable fuel properties and exhaust emissions for diesel engines used in transportation, agricultural and industrial applications.

Vegetable oils are easily available and many studies have focused on the use of these fuels as an alternative fuels [2–4]. Different types of vegetable oils as substitutes for diesel fuels are considered in different countries depending on the climate and soil conditions. For instance, soybean oil in the USA, rapeseed (canola in Canada) and sunflower oils in Europe, palm oil in South-east Asia (mainly Malaysia, Indonesia and Thailand), coconut oil in the Philippines and cottonseed oil, which is classified as non-edible oil, in Greece and Turkey are being produced [5].

Likewise, hazelnut oil and sunflower oil are grown widely in Turkey. Turkey is the main hazelnut producer country (approximately 80% of hazelnut production in the world); hazelnut oil can be used as an alternative diesel fuel especially by the farmers around the Black Sea region which is the main production area [6].

Vegetable oils can be obtained from oilseed plants and have physical characteristics close to those of diesel fuel and therefore behave like similar fuels [5,7]. However, there are some disadvantages related to the use of vegetable oil in diesel engines primarily because of their high viscosity [8].

In order to overcome the problem of high viscosity, the microemulsification method, which is of low production cost, of simple and easy implementation, and requires minimal fuel processing, is widely used. The microemulsification method involves mixing two immiscible fluids, a vegetable oil–diesel, using alcohol to stabilize the mixture [3].

Alcohols have been widely investigated as alternative fuels and oxygenated additives for many years [9–12]. There are many studies performed on diesel engines to observe engine performance and exhaust emissions by using alcohol fuels (methanol and ethanol) blended with diesel fuel [13]. However, there are still many drawbacks of using such fuels [13–16]. Butanol is one of the

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Nomenclature

A/F	air/fuel ratio	ISO	international organization for standardization
BSFC	brake specific fuel consumption	$k_{h,D}$	correction factor for humidity
BTDC	before top dead center	kW	kilowatt
BTE	brake thermal efficiency	m_{fc}	actual measured fuel consumption
C	carbon	N_2	nitrogen
°C	centigrade	NO	nitric oxide
CFPP	cold filter plugging point	NO_2	nitrogen dioxide
CHC	neat canola-hazelnut-cottonseed oil blends	NO_x	nitrogen oxides
CN	cetane number	nB	*n*-butanol
CO	carbon monoxide	O_2	oxygen
CO_2	carbon dioxide	P_e	brake power
C/H	carbon/hydrogen ratio	ppm	parts per million
D	diesel fuel	RH	relative humidity
EN	european norm	rpm	revolutions per minute
G_{EXHW}	exhaust gas average molecular weights	SCS	neat sunflower-corn-soybean oil blends
h	hour	T_a	temperature of the intake air
H_a	humidity of the intake air	TS	turkish standard
HC	hydrocarbon	w_R	total percentage uncertainty

primary alcohol types, which has more advantages than ethanol and methanol as an alternative fuel for diesel engines [13,17]. Butanol as a higher alcohol can also be used as a blend component, owing to its properties, such as hydrophobic, latent heat of vaporization and cetane number, which are closer to that of diesel than that of lower alcohols [17–20]. Many researchers indicated that butanol possessing similar latent heat of vaporization with added advantages of complete miscibility in diesel fuel and higher heating value provides complete combustion characteristic in diesel engines [9,11,21,22]. Therefore, butanol as a potential second generation biofuel is a very competitive alcohol to be applied in diesel engines and is becoming popular recently [11,13,17,23–26].

Engine performance and exhaust emissions in diesel engines fuelled with diesel-*n*-butanol blends were investigated by many researchers [9,11,13,24–30]. However, the current literature reports only a few papers regarding the use of diesel fuel-vegetable oil-*n*-butanol ternary blends in diesel engines and its effects on their engine performance and exhaust emissions.

The effects of diesel fuel-cotton oil-*n*-butanol ternary blend on phase stability, engine performance and exhaust emissions in a diesel engine were investigated by Atmanli et al. [31]. 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. According to engine performance test results, ternary blend of 70 vol.% diesel fuel, 20 vol.% cotton oil, 10 vol.% *n*-butanol (DCtOnB) decreased brake torque, brake power, BTE, exhaust temperature, CO and CO_2 emissions, while increasing NO_x and HC emissions.

Sharon et al. [17] conducted experiments on a diesel engine with diesel-used palm oil-butanol blends. They reported CO, CO_2, NO_x emissions and smoke opacity of the blends decreased while HC and BTE increased with increasing butanol content in the blends.

It was reported by Weerachanchai et al. [21] that the blending of the palm kernel bio-oil with diesel by using *n*-butanol as a cosolvent showed better characteristics of phase behavior and fuel properties than the use of ethanol.

Lujaji et al. [20,24] examined the effects of croton mogalocarpus oil-*n*-butanol-diesel fuel ternary blends on engine performance, combustion, and emission characteristics. They reported that fuel properties of vegetable oils were improved by the ternary blends, presence of *n*-butanol in the blends results in increased brake specific energy consumption, cylinder pressure and heat release rate, while decreasing BTE, CO_2 and smoke emissions.

These experimental studies show that next generation promising fuel, *n*-butanol, can be used safely and advantageously, both from the viewpoints of thermal efficiency and exhaust emissions, in the diesel engines using high blending ratios with diesel fuel. In comparison to ethanol–diesel blends, *n*-butanol requires no cetane enhancing additive or solubilizer due to its relatively high cetane number, high solubility, no phase separation in the diesel fuel [9,13,25,28–30,32].

A competitor alcohol based fuel is *n*-butanol, which has not been qualified with diesel engines in a wide range of operative conditions in spite of many advantages mentioned in the above of *n*-butanol as an alternative diesel fuel [17,18,20,24,27,31,33,34].

Therefore, it is made obvious that a major gap exists in the open literature regarding the basic fuel properties and engine performance of these promising biofuels (vegetable oils and *n*-butanol) in their two combinations in diesel engines. Filling this gap, this research is focused on the use of diesel fuel (70 vol.%) and *n*-butanol (10 vol.%) as an additive in two groups of vegetable oil, CHC and SCS, blends. Hazelnut, cottonseed and sunflower oils are produced from oil seed crops affiliated with the temperatewarm climates in Mediterranean region especially in Turkey, unlike corn, soybean and canola oils produced in the USA and Central Europe.

The main objective of this study is to use a rather high blending ratio (totally 30 vol.% in ternary blends) of both alternative biofuels (vegetable oils and *n*-butanol) with the diesel fuel, in order for the differences to be more prominent and the underlying mechanisms better understood. The investigation of effect of the addition of diesel fuel and *n*-butanol added into CHC and SCS simultaneously as well as the component type on basic fuel properties and conduct comprehensive bench tests of the engine for the analysis engine performance and exhaust emissions when operating alternately on DCHCnB and DSCSnB over a wide range of engine speeds.

2. Materials and methods

2.1. Engine test setup and procedure

As shown in Fig. 1, the arrangement of the test equipment consisted of a hydraulic-type dynamometer, a fuel meter, fuel tanks, a cooling water tank, an exhaust gas analyzer, and control panel monitoring systems. The diesel engine used for the present study was a Land Rover 110 type, turbocharged direct injection; its