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Experimental investigation on the effect of *n*-butanol blending on spray characteristics of soybean biodiesel in a common-rail fuel injection system

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HIGHLIGHTS

- We investigate the spray characteristics of soybean biodiesel with/without butanol blending.
- The total droplet number slightly decreases from the spray center line to the spray periphery while butanol blending makes the droplets more evenly distributed.
- Butanol addition leads to smaller Sauter Mean Diameter due to reduced viscosity and lower surface tension.

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ABSTRACT

In this work, the spray and atomization characteristics of neat soybean biodiesel fuel (BD100) and biodiesel/*n*-butanol blends (BDB80, 20% of *n*-butanol (wt.)), were investigated at room temperature and ambient pressure of 1 and 2 MPa. A high-pressure common-rail injection system was used to generate sprays from an injector (aperture 0.25 mm) at a maximum injection pressure of 100 MPa. High speed schlieren technique was used to record the highly transient spray penetration process, through which the spray macroscopic parameters such as spray tip penetration, spray cone angle, projected spray area and spray volume were deduced. In addition, droplet size, number density and its sauter mean values at specific location within the spray cone was analyzed, by using a particle/droplet image analyzing technique (PDIA). Results show that longer spray tip penetration and larger droplet diameters were observed for BD100, compared with BDB80, which was attributed to the lower viscosity and surface tension of BDB80. BDB80 has a spray volume less than BD100, the same trend is also observed in the spray tip penetration. BD100 presents bigger spray area than BDB80 under 1 MPa ambient pressure. This is mainly attributed to the bigger spray tip penetration of BD100. The results also show that droplets at the spray periphery have larger diameters than those in the center of the spray due to the effect of air entrainment at the spray periphery. The small particles of fuels are easily sucked into internal of spray. Furthermore, the droplets near the liquid core of spray have more small numbers, where the effect of viscosity is dominant.

1. Introduction

Fossil fuels such as natural gas, petroleum and coal have been meeting most industrial and commercial demands for relatively low cost, high energy density, transportable fuels for decades. However, being the main source of transportation fuels, petroleum is estimated to be running out within 50 years due to the limited storage under the stratum [1]. Because of the increasing fuel cost and stringent emissions, Biofuels, such as alcohols, DME, and biodiesel [2–6], have become an increasing attractive, efficient and less expensive fuels compared to gasoline. All these biofuels can be renewable resources instead of fossil feedstock.

As an alternative fuel, biodiesel has many similar or better properties than diesel fuel, such as cetane number, non-toxic, biodegradable and good inherent lubricity, which make it more suitable for diesel engines. Biodiesel fuels can be produced from various feedstocks. Some of them, especially soybean derived biodiesel fuels, have attracted attention due to its higher potential

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for a renewable source. Since soybean is more abundant in most of developed countries and oil derivation can be up to 20% by weight, its prices are generally more reasonable than the other feedstocks. Thus, soybean oil has become the main favorable feedstock for biodiesel fuel production. Mohamed et al. [7] conducted an experimental and theoretical study on a single cylinder, direct injection diesel engine fueled with different blends of soybean methyl ester (SME) and No. 2 diesel fuel. It was reported that the use of biodiesel produced lower smoke with a 14.65% higher brake fuel specific consumption (BSFC) compared to diesel fuel. The measured CO emissions of B20% SME and B100% SME were found to be 11.36% and 41.7% lower than that of diesel fuel respectively. All blends of SME were found to emit significantly lower UHC concentration compared to that of diesel over the entire load range. NOx emissions were observed to be higher for all blends of SME. Özener et al. [8] investigated the effect of soybean biodiesel addition on the engine combustion, performance and emissions. The results showed that when biodiesel was added, the brake torque was reduced by 1–4% and BSFC increased by 2–9% with the increase of the biodiesel blended ratio, when compared with diesel fuel. Furthermore, CO and HC emissions were found to be 28% and 46% lower but it was observed that NOx and CO_2 emissions increased by 17.62% and 5.03%, respectively. Their combustion analyses showed that the biodiesel addition to diesel resulted in the decrease of the ignition delay and the peak pressure of the premixed combustion.

As a biomass-based renewable fuel, *n*-butanol has many advantageous properties, such as better miscibility in diesel, higher energy content and higher cetane number. These properties, make butanol an attractive alternative fuel or blending component to diesel fuel compared with other alcohols, such as methanol and ethanol. Recently, some investigations have been carried out on the combustion and emission characteristics about *n*-butanol/biodiesel blends. Specifically Tüccar et al. [9] studied the engine performance and exhaust emissions of diesel–microalgae biodiesel(MB)–butanol blends on a four-cylinder diesel engine. Their results showed that the power and torque output of engine reduced slightly when butanol was added to the diesel–MB blends. CO and NO_x emission and smoke opacity values decreased with the addition of butanol. Rakopoulos [10] studied the combustion and emissions of cottonseed oil and its biodiesel in blends with *n*-butanol or diethyl ether in high-speed direct injection (HSDI) diesel engine. Their results showed that the tested blended fuels produced lower smoke, NO_x and CO emission but higher HC emission than neat biodiesel. The BSFC decreases with the usage of these fuel blends, compared with the neat biodiesel, and the corresponding brake thermal efficiencies increase. Yilmaz et al. [11] studied the effect of butanol–biodiesel blends on the emissions and performance characteristics using an indirect-injection diesel engine. Their results showed that butanol blended fuels produced lower NOx emissions and higher CO and HC emissions than neat biodiesel. Furthermore, butanol blended fuels produced lower CO and higher NOx emissions than diesel fuel for low concentrations of butanol (5% and 10%), but there was no significant change in terms of HC emissions. The biodiesel blend with the highest concentration of butanol (20%) produced higher CO and HC emissions but lower NO_x emission than diesel.

It is well known that fuel spray characteristics and atomization have an important effect on combustion process and final engine performance and emission. In some studies, the experimental and numerical investigation on spray atomization characteristics of biodiesel fuel have been conducted [12–20]. Park et al. [14] investigated the spray atomization characteristics of soybean oil methyl ester (SME) compared with that of diesel fuel in a diesel engine. Their results showed that the spray tip penetration of biodiesel fuel had almost similar behavior pattern compared with that of diesel fuel at various experimental conditions. The spray area of biodiesel fuel decreases when the ambient pressure increases. Furthermore, the Sauter Mean Diameter (SMD) of biodiesel fuel decreases along the spray axis, and biodiesel fuel had a slightly larger droplets size than diesel fuel. Deshmukh et al. [17] studied the high pressure spray characterization of Straight Vegetable Oils (Jatropha and Pongamias). Their results showed that Pongamias oil had higher injection delays at low injection pressures and this is attributed to its higher viscosity. The spray tip penetration for Pongamia and Jatropha is less than that of diesel. Deshmukh and Ravikrishna [20] studied the high pressure spray characterization of Pongamis oil and its blends with diesel under various ambient pressures. Their results showed that the spray cone angle for biofuels was lower than that of diesel. The Pongamia had 200% higher SMD than that of diesel. The spray atomization performance was typically characterized by the droplet size. Because there were large number of droplets within the spray, there have been several methods to characterize the average droplet size. Among these definitions, SMD is the most commonly used. However, studies on the spray atomization characteristics of *n*-butanol blending with diesel and biodiesel are not sufficient so far. Liu et al. [21,22] studied the effects of volatility on butanol–biodiesel–diesel spray characteristics. The results indicated that for the non-combusting case, the tip of the spray jet erupted into a plume sometime after injection for the butanol–biodiesel–diesel blend at an ambient temperature of 1100 K. Such phenomenon was not seen with the biodiesel–diesel blend, neither with the same fuel but at a lower ambient temperature of 900 K. It is concluded that micro-explosion could occur under particular conditions for the butanol–biodiesel–diesel blend. Wu et al. [23] conducted an experimental study of spray characteristics of different fuel mixtures and analyzed the influence of different proportions of acidic oil biodiesel and *n*-butanol on the macroscopic parameters of spray. The results show that after adding *n*-butanol in acidic oil biodiesel and diesel mixture fuel, the surrounding air entrainment is enhanced, and spray front end widen. With the increasing of mixing ratio, spray penetration increasing first, then decreases. The spray cone angle increases after adding *n*-butanol, and decreases with the increase of mixing ratio. The results show that adding *n*-butanol can be used as one of the methods to improve biodiesel spray characteristics. In the research of Liu et al. [24], the spray, flame natural luminosity and soot quantitative measurement by fueling *n*-butanol and soybean biodiesel on a constant volume chamber were investigated. Results demonstrate that the transient liquid penetration length of *n*-butanol is less affected by the downstream flame and is shorter than that of biodiesel under similar conditions. Compared to biodiesel, the flame luminosity of *n*-butanol is lower and its propagation and distribution is less sensitive to ambient temperatures. Ambient temperature is confirmed as the dominant impact on the soot emissions as the net soot increases for both tested fuels with elevated ambient temperature. No soot emission is detected for either *n*-butanol or biodiesel at low ambient temperature of 700 K. The soot starts to appear at both downstream of the jet and near wall regions from 800 K for biodiesel whereas the soot do not emerge until 900 K for *n*-butanol. The higher soot formation

Table 1
Physical properties of test fuels.

Fuel	Density (kg/m^3) (40 °C)	Kinematic viscosity (mm^2/s) (40 °C)	Surface tension (mN/m)
Biodiesel	871.853	5.288	29.23
20% *n*-Butanol of biodiesel blend	854.665	3.870	29.16
n-Butanol	809.8	3.64	24.6