Fuel 140 (2015) 116–125

Contents lists available at ScienceDirect

Fuel

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

Effect of di-n-butyl ether blending with soybean-biodiesel on spray and atomization characteristics in a common-rail fuel injection system

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HIGHLIGHTS

- We examine the effect of DBE addition on the spray characteristic recover.
- We investigate the macroscopic and microscopic spray characteristics of biodiesel, DBE/biodiesel.
- DBE addition significantly improves the spray characteristics due to its lower viscosity and surface tension.

ARTICLE INFO

Article history:
Received 15 June 2014
Received in revised form 18 September 2014
Accepted 25 September 2014
Available online 7 October 2014

Keywords:
Biodiesel
Di-n-butyl ether
Spray characteristics
Droplets size distribution

ABSTRACT

In this work, the spray and atomization characteristics of soybean biodiesel, di-n-butyl ether (DBE)/biodiesel blends and 0# diesel were investigated by using a high pressure common-rail injection system. The macroscopic spray characteristics such as the spray tip penetration (STP), the cone angle and the spray projected area were obtained from the spray images captured through high speed schlieren photography. The results show that as DBE is blended into biodiesel, the STP is decreased and the spray cone angle, projected area are increased and when the DBE volume fraction in the DBE/biodiesel blends reaches 30%, the STP, the spray cone angle and the projected area are comparable to that of diesel. For all the tested fuels, the microscopic spray characteristics such as the Sauter Mean Diameter (SMD) and statistical size distributions were measured by particle/droplet image analysis (PDIA) technique. The droplets number density distribution shows that for all the tested fuels, the region near the central of spray has the largest droplets number density and it decreases sharply as the position shifts from the center to the edge of the spray. As DBE is blended into biodiesel, smaller SMD is observed, which indicates that DBE addition can promote the atomization of biodiesel.

1. Introduction

Due to its very high compression ratio, the diesel engines have higher thermal efficiency when compared to regular petrol engines and are expected to reduce fuel consumption. Additionally, diesel engines typically have higher torque output and thus have been widely used in heavy road vehicles such as trucks, buses and ships. Though fossil fuels are still available for 50–100 years, their limited reserves are being depleted due to the increasing demands, thus research on alternative fuels have been attracting more and more attention. Biodiesel is the mono-alkyl esters of long chain fatty acids and can be produced from renewable and biodegradable resources. It can be derived from triglycerides by transesterification with alcohols. Due to its similar physico-chemical properties to those of fossil diesel, it can be directly used in the traditional diesel engines or with minor engine modifications and it has attracted great interest of researchers as an alternative fuel for diesel engines [1–3]. Compared to fossil diesel, biodiesel is renewable, nontoxic and contains no sulfur. The effect of biodiesel fuels on engine emissions was reviewed by Lapuerta et al. [4] in which biodiesel was shown to be potentially capable for the reduction of carbon monoxide (CO), carbon oxides (CO_2), unburned hydrocarbons (HC), and particulate matter (PM) emissions. However, biodiesel produces more nitrogen oxide (NOx) because of its higher oxygen content and high bulk modulus, which leads to an increased combustion temperature and NOx formation [5,6]. Practically, the exhaust gas recirculation (EGR) technique is introduced to reduce the combustion temperature thus to reduce the NOx emissions of the biodiesel fueled engines [7,8].

It is well known that the characteristics of fuel spray and the mixture formation are very influential on combustion process and final engine performance and emission characteristics.

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http://dx.doi.org/10.1016/j.fuel.2014.09.104
0016-2361/

Recently, some investigations have been carried out on the biodiesel spray characteristics. Lee et al. [9] studied the atomization characteristics of biodiesel-blended fuels and compared with the conventional diesel. Their results indicates that biodiesel-blended fuels have similar spray tip penetration (STP) but larger Sauter Mean Diameter (SMD) compared to the conventional diesel. Wang et al. [10] studied the spray characteristics of two biodiesels and diesel under high injection pressures. Their study shows that biodiesel gives longer STP and smaller spray angle, projected area and volume compared to diesel, and biodiesels give larger SMD than diesel because of their higher viscosity and surface tension. Gao et al. [11] studied the spray characteristics of biodiesel based on inedible oil and they found that spray is more concentrated and SMD of biodiesel-blended fuels is larger than that of diesel because of the higher viscosity and surface tension of biodiesel. These studies show that because biodiesel has higher surface tension and viscosity, biodiesel spray is relatively more difficult for evaporation and atomization. Additionally, biodiesel has a high pour point and fuel flow problems become significant at low temperatures [12,13].

We propose that the addition of less viscous fuels with smaller surface tension into biodiesel is potentially capable to recover the deteriorated spray characteristics, compared to diesel. Previously, Yoon et al. [14] added up to 20% (by volume) of ethanol into biodiesel (BE20), and the spray characteristics of fuel blends were studied with spray visualization and droplet size analyzing techniques. Their results show that the spray penetrations of BE10, BE20 and diesel are similar, but the SMD of diesel is larger than those of BE10 and BE20. Shi et al. [15] studied the effects of biodiesel/ethanol addition on the emission characteristics of a heavy duty diesel engine and their results show that both PM and total hydrocarbons (THC) emissions are decreased but NOx emissions are slightly increased. The amount of unregulated emissions such as acetone, aldehyde and ethanol are also found to be increased. Ethers like dimethyl ether (DME) and diethyl ether (DEE) have shown to be promising in terms of soot reduction and combustion enhancement [16,17]. Another ester of interest is di-n-butyl ether (DBE), which can be produced from lignocellulosic biomass with promising material efficiency [18] through a series of bio-chemical processes. Additionally, DBE is the so called second generation biofuel which does not threaten the food supply and biodiversity. Compared to biodiesel, it has lower density, surface tension and viscosity, but has higher cetane number (up to 100) [19–21]. Very limited studies have been conducted on the use of DBE as alternative fuel. Nabi et al. [22] investigated the effect of DBE blending into diesel on emissions and engine noise characteristics in a direct injection diesel engine. Their results show that significant reductions in smoke, CO, NOx, and THC are simultaneously achieved with the increase of DBE blending ratio, and engine noise is also reduced because of better ignitibility of DBE. Beeckmann et al. [23] studied the effect of DBE blending (up to 20% by volume) on the spray characteristics of CEC (Coordinating European Council) reference diesel at the ambient pressure of 50 bar and temperature of 800 K. They reported that addition of DBE is potentially capable to improve the atomization process and ultimately the engine performance. Additionally, the ignition delay times are significantly reduced as DBE is added into the CEC diesel because of its high cetane number and they stated that blending DBE into diesel might enhance the premixed charge compression ignition (PCCI) combustion process which would result in a significant reduction in both soot and NOx.

Since compared to diesel, the higher viscosity of biodiesel deteriorates the spray characteristics, we attempt to adopt DBE as an additive into biodiesel and to see if the spray characteristics of the biodiesel/DBE blends (with certain DBE blending ratio) are comparable to that of diesel. As far as it is known, there has been no study on the spray atomization and fuel–air mixing of DBE/biodiesel blends. In the following, the experimental setup and procedures will be specified in detail. The macroscopic spray characteristics of biodiesel/DBE blends at different injection pressures and ambient pressures in terms of spray tip penetration, spray angle and projected area will be examined from the spray images captured through high speed schlieren photography. Additionally, microscopic and statistical spray characteristic parameters such as SMD and the droplets number density distribution of different biodiesel/DBE blends will be compared.

2. Experimental setup and procedure

2.1. Apparatus and procedure

Fig. 1a shows the sketch of the spray visualization apparatus. A high-pressure, constant volume chamber is designed for the spray visualization and is filled with nitrogen gas. The ambient pressure is adjusted by a manual intake and exhaust valves that connects on the chamber and the maximum pressure is 50 bar. Two quartz windows with the diameter of 100 mm on two sides provide an optical access for the spray visualization.

The fuel-injection facility consists of the fuel tank, the high pressure pump, the common rail, the injector and the electronic control unit. A pressure transducer mounted on the common rail

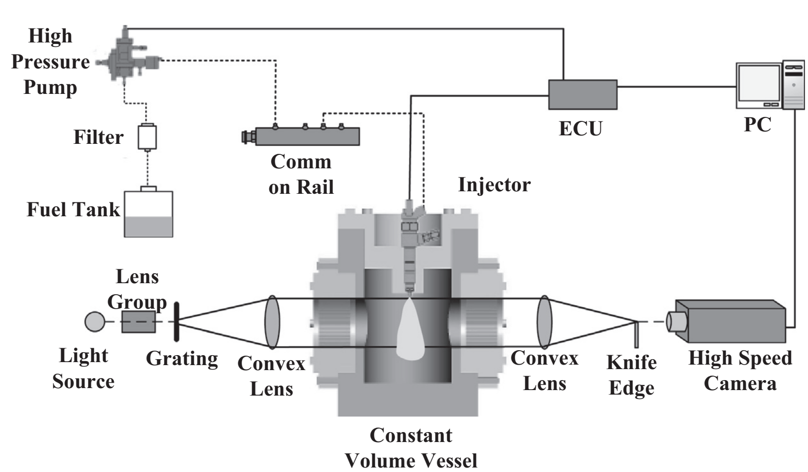

Fig. 1a. Experimental setup for STP and cone angle measurements.