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Effect of di-*n*-butyl ether blending with soybean-biodiesel on the near-nozzle spray characteristics

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HIGHLIGHTS

- The near nozzle spray characteristics of biodiesel, DBE/biodiesel and diesel were investigated.
- More ligaments were found for DBE30 because of reduced viscosity and surface tension of DBE.
- DBE addition leading to larger micro projected area and spray cone angle due to better primary breakup.

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ABSTRACT

In this work, the near-nozzle spray 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 and the effect of experiment conditions and fuel physical properties on the near-nozzle spray structures were explored. Microscopic spray images at the near-nozzle field were captured by the high-resolution microscopy. The micro spray cone angle and micro projected spray area were obtained from the processed spray images for quantitative analysis. The results show that the initial spray of diesel is easier to breakup into ligaments and droplets because of smaller surface tension and viscosity compared to that of biodiesel under atmospheric condition. The spray with more ligaments was easily restrained by the ambient gas and promoted to evolve along the radial direction, leading to a wider micro spray cone angle of diesel. The breakup of liquid jet also tends to increase the micro projected spray area of diesel. When 30% of DBE was added into biodiesel, both the micro spray cone angle and projected spray area were increased due to the decreased surface tension and viscosity of the blended fuel. The initial spray images reveal that the high injection pressure favors the spray primary breakup while the high ambient pressure results in worse spray primary breakup. The quantitative analysis shows that the injection pressure has little influence on the micro spray cone angle but results in the increase in micro projected spray area, while both parameters increase significantly under high ambient pressures.

1. Introduction

Biodiesel, consisted of long chain alkyl esters, is typically produced through transesterification of vegetable oils, animal fats or waste cooking oils [1,2]. Biodiesel is renewable, and it has promising lubricating properties and comparable cetane rating to commercial diesel. Thus biodiesel is considered as a promising alternative fuel for diesel and its direct application in traditional diesel engines has been evidenced by extensive engine test studies [3–5]. These studies show that the combustion of biodiesel reduces total hydrocarbon (THC), carbon monoxide (CO), and particulate matter (PM) exhaust emissions, compared with diesel [6]. However, the high viscosity and surface tension of biodiesel inhibits its spray atomization performance [7], which retards further engine performance enhancement.

It is known that the mixture quality of injected fuel and ambient gases plays an important role in subsequent combustion process and the ultimate emission characteristics [8]. Recent studies on spray process have focused on the macro spray characteristics, such as spray tip penetration, cone angle, distribution of the liquid and the vapor phase that can be easily accessed with the high speed visualization [9,10]. In addition the macro spray characteristics, such as droplet size, velocity and number density distribution can be also qualitatively or even quantitatively detected, thanks to the progress of laser diagnostic techniques [11–15]. These studies have provided insightful understanding of the spray mechanism, but in the secondary breakup regime. Only a few studies have

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investigated the initial spray evolution process in the primary breakup zone. Shinjo and Umemura [16] has investigated the high speed liquid jet injection into still air with super high grid resolution direct numerical simulation and the mechanism of the ligament and droplet formation was discussed. Roisman et al. [17] has investigated the high speed spray breakup length and the effect of ambient pressure on the spray neck and tip region dynamics was investigated theoretically. However, the experimental exploration of the near nozzle spray tip dynamics has not been sufficiently reported. The difficulty of the near nozzle spray research is that the near nozzle spray is a highly transient process with a time scale of tens of micro seconds. In addition, the initial spray is very complex and is affected by the fuel properties, nozzle flow, cavitation and the interaction with the surrounding gas. Furthermore, the initial spray occurred near the nozzle outlet is very dense, which challenges the conventional optical diagnostic techniques.

Using optical long-distance microscopy is proven to be an effective way to investigate the initial spray performance and has been adopted in many previous studies. Bae and Kang [18] used a long-distance microscope to investigated the break-up zone of a valve-covered orifice nozzle under injection pressures of 39.5 MPa and 112 MPa and atmospheric ambient conditions. They found that the breakup process occurred simultaneously at the edge and center of the spray and ligaments were generated from the disturbed spray surface and droplets were formed at the end of the ligaments. Crua et al. [19] used a long range microscope to study the formation and breakup of diesel sprays at atmospheric conditions and injection pressures up to 160 MPa. A spheroidal cap was found immediately after the fuel jet leaving the nozzle and was found to consist of residual fuel trapped in the injector hole after the end of the injection process. The formation of ligaments was also observed close to the orifice. Deshmukh and Ravikrishna [20] used microscopic imaging to investigate the spray structure of diesel from a single-hole nozzle and they found that the ligaments become smaller and spread radially with increase in injection pressure.

Reducing the viscosity and surface tension to improve the mixture formation process has been receiving increased attention recently [21,22]. In our previous study [13], the spray atomization characteristics of Di-*n*-butyl ether (DBE)/biodiesel blends were experimentally investigated and the results show that the addition of 30% DBE by volume into biodiesel could improve the spray atomization performance effectively.

The aim of this work is to study the initial spray structure of diesel, biodiesel and DBE/biodiesel blend fuel from a common rail injection system. Microscopic images of the initial spray were obtained by using a long distance microscope and high-power short duration laser such that good space and time resolved images during the evolution of the primary breakup region of the spray. Micro spray cone angle and projected area were obtained from the captured microscopic images for quantitative analysis. The effects of injection and ambient pressures, as well as the fuel physical properties on the initial spray characteristics were experimentally studied for further understanding the initial spray formation and primary breakup.

2. Experimental setup and procedure

The spray generation system with accurately controlled injection pressure and ambient pressure has been described in detail previously [13], and here only a brief introduction is given. Fig. 1 is a sketch of the present experimental system. It consists of the fuel injection control module, the constant volume chamber and the imaging system which is synchronized with the fuel injection. The fuel injection control module is a subassembly of commercial fuel supply system from Bosch China, which includes a fuel tank, high pressure pump, and a common rail. The injection pressure is monitored by a pressure transducer mounted on the common rail and the injection pressure is adjustable by monitoring the electronic control unit (ECU). A Bosch second-generation common rail injector with a modified single hole nozzle was used. The geometry and dimension of the single hole nozzle was shown in the inset figure. The constant volume chamber is filled with nitrogen to the desired pressure, and two opposite sides of the chamber are mounted with glass windows to allow for optical access.

The light source used in this study is a Nd: YAG laser with the wavelength of 532 nm and pulse duration of 4 ns. A fluorescence diffusor is attached at the head of the laser and employed for the homogeneous illumination. The diameter of the lens at the head of the diffusor is 120 mm, which is larger than the chamber window, so as to ensure the homogeneous illumination of the spray flow field. A CCD camera (ImagerProSX 5 M, 2456 pixel × 2058 pixel) connected with a long distance microscope (Queststar QM1) and a magnifying lens with an amplification factor of 2 was used to capture the initial spray images. A scaling plate with minimum scale of 25 μm and total length of 5 mm is employed for calibration of the image size. After calibration, the field of view is $1679 \times 1407\ \mu m^2$ for the initial spray images and micro spray cone angle measurement, and $3660 \times 3067\ \mu m^2$ for the micro projected spray area measurement. The CCD camera and the long distance microscope are mounted on an electric positioner MC600. The precise displacement control (1 μm) ensures the accuracy of the image capturing position. When capturing the spray images near the nozzle outlet, the position of the CCD camera and long distance microscope were adjusted to the place where the nozzle just appeared at the top of the field of view.

The trigger signals of the injector, the Nd: YAG laser and CCD camera are synchronized by an optical diagnostic controller OD2301. Fig. 2 shows the pulse sequence of the camera, the injection and the laser. The exposure time of the CCD camera (2 ms) is much larger than the pulse duration of the Nd: YAG laser (4 ns). By adjusting the delay time of the Nd: YAG laser illumination with respect to the injector trigger pulse, the initial spray images at different phases after the start of injection can be obtained. The duration of the injection was fixed to 1 ms in this study.

In this study, three fuels were tested, including the soybean biodiesel (B100), DBE30 (30% di-*n*-butyl ether in vol. in the biodiesel/DBE blends) and 0# diesel. Physical properties of the fuels are listed in Table 1. The density, viscosity, surface tension were measured according to Chinese national standard GB/T 1884-1992, GB/T 265-1988 and GB/T 6541-1986, respectively. The surface tension, viscosity and density of biodiesel are larger than those of diesel and these parameters decreased with the addition of DBE into biodiesel.

3. Experimental results and discussion

In this section, a series of high resolution images illustrating the spray tip evolution at the near nozzle region at different test conditions will be presented. In addition, the spray cone angle and the projected spray area of B100, DBE30 and diesel will be presented. Injection pressures P_{inj} are 800 and 1200 bar and ambient pressures P_{amb} are 1, 20 and 40 bar. The ambient temperature is 293 K. We note that all the following experimental data and analysis were focused on the near nozzle region, say, less than 5 mm from the injection nozzle exit.

3.1. Spray tip evolution: effect of fuel property, ambient pressure and injection pressure

3.1.1. Effect of fuel property

Fig. 3 shows the typical images of the spray evolution at the immediate nozzle downstream ($z < 4.5$ mm) at $P_{inj} = 800$ bar and