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Experimental study on the diesel and biodiesel spray characteristics emerging from equilateral triangular orifice under real diesel engine operation conditions

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ABSTRACT

The triangular spray has a potential to accelerate air-fuel mixing rate and undergo axis-switching during the injection process, which both are beneficial for improving the atomization quality. This paper presents an experimental investigation on the macro-spray characteristics and the mechanism of axis-switching with diesel and biodiesel emerging from equilateral triangular orifice of diesel nozzle, by using shadowgraph technique, under various injection pressures (50 MPa, 70 MPa, 90 MPa) and backpressures (1 MPa, 2 MPa, 3 MPa). Two CCD cameras were set to capture the macro spray images at the minor and major view planes simultaneously. Macro spray characteristics values were processed from the spray images in different view planes by MATLAB. The results indicated that the spray width of biodiesel was larger than that of diesel at all conditions from all view planes. In addition, both diesel and biodiesel emerging from equilateral triangular orifice underwent axis-switching during the spray progress even under the typical diesel engine operation conditions. Moreover, the difference of equilateral triangular spray widths between minor plane and major plane decreases as the backpressure increases for both fuels, it is expected that the increasing of backpressure enhances the aerodynamic effects, resulting in inhibiting the spray axis-switching. Furthermore, the difference of diesel spray widths between the major plane and minor plane was much higher than that of biodiesel. Because the higher surface tension and viscosity of biodiesel can cause smaller surface-instabilities and also resist the spray deformation, which are conductive to suppress the biodiesel spray axis-switching, and thus ultimately lead to narrowing the difference of biodiesel spray widths between minor plane and major plane. Finally, the spray tip penetration of biodiesel was consistent longer than that of diesel, while the spray cone angle of biodiesel was smaller than that of diesel, and also there was an interaction between major and minor view planes for diesel spray cone angle values at the backpressure of 1 MPa, but it didn't happen for biodiesel during the whole injection process. The present results indicated that the diesel spray was much easier to undergo axis-switching. The higher probability of axis-switching, larger spray cone angle and spray width of diesel demonstrated better air-fuel mixing quality than biodiesel.

1. Introduction

The upgrade emission regulations put more stringent requirements on diesel engine emission performance, especially for soot and NOx emissions. Biodiesel fuel as a renewable clean energy was widely used because of its potential ability in reducing soot emissions [1–3]. However, biodiesel has poorer air-fuel mixing quality than that of diesel due to its higher surface tension and viscosity. Traditionally, air-fuel mixing quality was improved by increasing injection pressure and decreasing injector orifice diameter [4,5]. Nevertheless, benefits from these traditional methods were too difficult and expensive to achieve further gain due to limits on material strength and machining capabilities. In addition, under the extreme high injection pressure, fuel leakage and energy loss of fuel injector will increase sharply [6,7]. Findings from a preliminary studies [8–10] suggested that the spray discharging from non-circular orifice has the potential to enhance air entrainment and

Abbreviations: A, Nozzle exit area; ASOI, After Start Of Injection; CCD, Charge Coupled Device; CN, Cetane Number; DBE, Di-n-Butyl Ether; LED, Light Emitting Diode; LMD, Laser Micro-Drilling; P, Wetted perimeter; SMD, Sauter Mean Diameter

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boost spray characteristics greatly, which was helpful to improve the diesel engine performances. Specially, triangular orifice as a kind of non-circular orifice has attracted much attention from experts and scholars. Because the triangular spray has a potential to accelerate air-fuel mixing rate significantly and undergo axis-switching during the injection process, which both are beneficial for improving the atomization quality greatly [11,12]. Therefore, it is necessary to characterize the effects of biodiesel fuel emerging from triangular orifice on spray characteristics at typical diesel engine conditions.

Investigations of the influences of biodiesel properties on spray behaviors. Agarwal et al. [13] investigated the in-nozzle flow and spray characteristics for diesel and biodiesel, their results provided that the atomization and evaporation quality of mineral diesel was superior than that of biodiesel fuel. Mo et al. [14] experimentally studied the spray behaviors with biodiesel with or without butanol blending, they found that the Sauter Mean Diameter (SMD) of biodiesel were larger than that of biodiesel and *n*-butanol blends, because the biodiesel and n-butanol blends hold lower viscosity and surface tension than biodiesel. Lee et al. [15] analyzed the effect of karanja biodiesel and its blends on spray characteristics, the results show that the spray cone angle of biodiesel was narrower than that of diesel, while the spray tip penetration of karanja biodiesel 40% blend was longer. However, under the high back pressure of 4 MPa, the macro-spray behaviors for diesel and karanja biodiesel were similar. Guan et al. [16] conducted the spray characteristics of soybean biodiesel, di-n-butyl ether (DBE) or biodiesel blends and diesel. They found that di-n-butyl ether blended ratio of biodiesel could lead to smaller SMD, which indicates that di-n-butyl ether addition is helpful to increase the atomization quality of biodiesel. Yu et al. [17] presented the macro-spray characteristics combine with internal flow parameters with diesel and biodiesel, the results provided that the spray tip penetration of biodiesel was longer than that of diesel, while the aerodynamic spray cone angle of biodiesel was narrower than that of diesel. Xie et al. [18] compared the macro spray characteristics of biodiesel and diesel under different injection conditions. They found that the spray cone angle decreases as the blend ratio of biodiesel increases.

Investigations of the effects of triangular orifices on spray characteristics. Mi et al. [19] investigated the effects of nine different geometry orifices on the jets characteristics. The results indicated that the jet mixing rate of triangular orifice was the greatest among all the nine jets. Quinn et al. [20] presented an experimental study on free jets discharging from two triangular orifices and circular orifice under the still air condition. It was observed that the equilateral triangular jet had the fastest mixing rate, and also the energy spectra results indicated that the equilateral triangular jet has the most energetic. Lee et al. [21] conducted an experiment to analyzed the jet flow characteristics discharging from equilateral triangular orifice. They found that kinetic-energy loss coefficients of the triangular jet are much smaller than those of circular jets, and the triangular geometry orifice with an outlet lip is helpful to increase the initial spreading angle. Azad et al. [22] compared the free jets behaviors discharging from isosceles triangular orifices with different apex angles and a round orifice under the still air conditions. It was found that the jet discharging from the triangular orifice with the apex angle of 10 exhibited the highest mixing rate, while the circular orifice held the lowest mixing rate. Sharma and Fang [23] studied experimentally the liquid breakup and atomization of free jets discharging from non-circular orifices under the still air conditions (Backpressure of 0.1 MPa). Their results showed that the triangular jets underwent axis-switching during the injection progress, and also the mixing rate of triangular orifice nozzle was faster than that of circular orifice. Rajesh et al. [24] conducted a series of experiments to better quantify interfacial oscillation of liquid jets discharging from elliptical, equilateral triangular, and square shaped orifices under the backpressure of 0.1 MPa. They found that the liquid jet discharging from the equilateral triangular exhibits shorter wave segment than that of orifice elliptical orifice, and also the square orifice exhibits shortest wave segment among all jets. Wang et al. [25] studied the water breakup sprays under low pressure conditions with circular, rectangular, squire and triangular orifices with the same exit sectional area. They found that triangular and square orifices were much easier to enhance the jet instabilities than that of the circular one, which was beneficial for increasing the spray and atomization quality.

Based upon the above brief review, it is found that extensive studies were conducted on the biodiesel spray characteristics and triangular orifice sprays under low pressure conditions so far. Moreover, the review showed that triangular orifice can both enhance the spray instabilities and improve the air-fuel mixing quality, and also revealed that the triangular spray underwent axis-switching during the injection process. It can be determined that the triangular spray quality was much better than that of the circular spray. However, the sizes of triangular orifice used in all the previous works were most with equivalently diameters in range of 0.3–5 mm quite far from the standard diesel nozzle diameters (from 0.1 mm to 0.2 mm), and also the injection pressure and backpressure were also much less than that of typical diesel engine operation conditions. Moreover, the mechanisms of triangular spray and axis-switching phenomenon for diesel and biodiesel with smaller equivalently diameters orifice nozzle under higher injection pressure and backpressure provided to be quite different from that under the traditional scale conditions. In addition, it is hard to find works that extensively comparative study the mechanism of spray behaviors and the axis-switching phenomenon of biodiesel and diesel emerging from equilateral triangular orifice under the real diesel engine operation conditions. Therefore, the main purpose of this research work is, to comparative study the macro spray characteristics and the axis-switching phenomenon for diesel and biodiesel emerging from equilateral triangular orifice by using shadowgraph technique under different injection pressures (50 MPa, 70 MPa, 90 MPa) and backpressures (1 MPa, 2 MPa, 3 MPa).

2. Experimental method

2.1. Orifice geometry

The experimental study was performed with a equilateral triangular geometrical orifice nozzle, The equilateral triangular orifice was drilled by the Laser Micro-Drilling (LMD) machining method [26], which can ensure the precision of machining satisfactorily (± 0.1 μm). In Fig. 1, the different topologies of the tested nozzle are depicted.Table 1 describes the geometric parameters of equilateral triangular orifice. Other geometric parameters, such as orifice length, wetted perimeter and hydraulic diameter, are also concerned. The hydraulic diameter was calculated by $4A/P$, where A is the nozzle exit area and P is the wetted perimeter of equilateral triangular orifice.

2.2. Spray image acquisition system

Fig. 2 shows the experimental equipment diagram for capturing the spray images from two different directions. The image acquisition consists of two 2D image recorder systems. Two CCD cameras were adopted to capture the macro spray images at the minor and major plane simultaneously. These two cameras were operated at 500 frames per second with a resolution of 1600 × 1200 pixels sat an exposure time of15 μs. Two light sources (LED lights) were used to illuminate the spray. Before the injection of fuel, the constant-volume chamber was filled with nitrogen (99% purity) and its pressure was controlled by an electronic valve. The temperature inside the chamber was kept at 300 K throughout the experiment. The delay time among the two CCD cameras, injector and the light was set by a delay controller. The shutters of the two cameras were triggered at the same time at each test condition to capture spray images at the nozzle's major plane and the minor plane simultaneously. Ten repeated spray images were captured at each injection condition. Based on these ten images, spray width, spray tip