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Experimental study on injection characteristics of fatty acid esters on a diesel engine common rail system

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HIGHLIGHTS

- Injection of methyl oleate, ethyl oleate, and methyl laurate are investigated.
- Difference in injection delay is found among test fuels.
- Pressure oscillation damps more rapidly for methyl oleate and ethyl oleate.
- Fatty acid esters have lower volume but higher mass injection quantity than diesel.

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ABSTRACT

The injection processes of three fatty acid esters (methyl laurate, methyl oleate and ethyl oleate) are investigated on a high pressure common rail injection system and compared to that of diesel fuel. The cycle injection rate, cycle injection quantity and pressure fluctuation at the injector inlet during and after the injection event are studied across a range of injection pressure and injector energizing time. Test fatty acid esters show smoother rising slopes at the start of injection and lower injection rates at the stable injection period in the volumetric injection rate curves, but the mass injection rates among all test fuels are quite close. Fatty acid esters have longer injection delay than diesel fuel; while increased injection pressure causes reduced injection delay but prolonged injection duration. Injector energizing time significantly influences the shape of injection rate curve and the pressure fluctuation at the injector inlet. After the needle valve closure, pressure oscillation damps more rapidly for methyl oleate and ethyl oleate, due to their high density, viscosity and bulk modulus of compressibility.

1. Introduction

Biodiesel can be produced via a variety of biomass feedstock [1,2] and is compatible with the currently existing petroleum fuel application devices like internal combustion engines, thus is considered as a potential renewable and alternative automotive fuel. The injection, spray and combustion characteristics of biodiesel in diesel engines and other combustion vessels have been widely investigated [3–10], and an increase in NOx emissions is generally recognized when biodiesel is used [11–13].

Fuel injection process in compression ignition engines places an important impact on the in-cylinder mixture formation, ignition, combustion processes and subsequently the emissions. Some researchers tried to confirm the relationship between increased NOx emissions burning biodiesel fuel with changed injection features. Boehman et al. indicated that increased bulk modulus of compressibility of biodiesel advances the actual injection timing on mechanical injection systems, contributing to the increase in NOx emissions [14,15]. Kegl et al. investigated injection characteristics of diesel, rapeseed biodiesel and their blends experimentally and numerically on a mechanical injection system, with focus on parameters such as fuelling amount, mean injection rate, peak injection pressure, injection timing, injection delay and injection duration. It is found that increased biodiesel content leads to increased fuelling, injection duration and injection pressure, but shortens injection delay and advances injection timing [16–18]. On the contrary, through analyzing the pressure history in the injection pipe of a pump-line-nozzle injection system, Caresana concluded that the usage of biodiesel does not necessarily cause higher maximum injection pressure than diesel, and the extent of injection timing advance by biodiesel on a mechanical injection system has been overestimated [19]. On the same test facility as used by Kegl et al. [16], Torres-Jimenez et al. further investigated the effects of ethanol addition to biodiesel on the injection process, and found the biodiesel and ethanol blends share similar proper-

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ties with diesel fuel, thus producing close injection characteristics to those of diesel fuel [20].

Seykens et al. investigated the injection characteristics, including injection rate, pressure and injector control plunger displacement of diesel and rapeseed methyl ester (RME) on a common rail using a one dimensional model. It is found that RME only results in a marginally reduced flow rate but not any influences on injection timing [21]. Boudy and Seers studied the effects of fuel density, viscosity and bulk modulus on injection characteristics of different injection strategies on a common rail injection system. It was reported that the fuel property changes in their study slightly influence the fuel injection characteristics in a single injection strategy, but remarkably influence the post injection event due to the change in the friction coefficient and pressure wave fluctuation in a multiple injection strategy [22].

However, all abovementioned researches are based on real biodiesel fuels, which are mixtures of different fatty acid alkyl esters. Due to the differences in biodiesel feedstock sources, it is inevitable that their physical and chemical properties have remarkable variances [23]. These variances are possible reasons leading to different research findings. To identify the effects of biodiesel composition on injection characteristics, this paper aims to investigate the injection characteristics of several major fatty acid alkyl esters in biodiesel on a common rail injection system. In this study, two typical long-chain fatty acid esters in biodiesel sourcing canola, rapeseed, palm and jatropha oil [23], methyl oleate and ethyl oleate, are studied. Meanwhile, methyl laurate, a significant amount of which is contained in coconut biodiesel but with shorter carbon chain [24], is also investigated. The injection rate characteristics and pressure fluctuation at the injector inlet of these fatty acid esters are studied across a range of injection pressure and injector energizing time, and compared to those of petroleum diesel. These obtained injection characteristics of fatty acid esters with different properties are necessary for the in-cylinder mixture formation control and combustion optimization in biodiesel engines, and could also provide precise boundary conditions for the simulation of biodiesel spray processes.

2. Experimental setup and test fuels

2.1. Experimental setup

The injection characteristics measurement of test fuels was carried out on a high pressure common rail fuel injection test system, which includes a fuel pump bench, a mono injection qualifier, a fuel pressure measurement system, an electronic control unit (ECU) and a data acquisition system. The schematic of the experimental setup is described in Fig. 1. As is shown, test fuel from a tank flows sequentially through a fuel filter, a two-stage fuel pump, a fuel rail and finally enters an injector. An ECU is used to control the rail pressure and injection pulse width profile. The fuel injection rate and quantity during a fuel injection cycle are measured by the mono injection qualifier, which is synchronized with the fuel pump by an encoder. The energizing current during an injection cycle is recorded by a current probe (Tektronix A622) and fuel pressure at the injector inlet is measured by a pressure transducer (Kistler 4067A3000 with measurement range of 0–300 MPa) and amplified by a charge amplifier (Kistler 4068). The energizing current, fuel pressure, injection rate and encoder clock signals are recorded by a Yogogawa DL750 data acquisition device with sampling frequency of 20,000 Hz.

The high pressure common rail injection system used in this study can generate high rail pressure up to 140 MPa. The fuel rail volume is 30 cm^3, and the fuel pump displacement is 3.62 cm^3/rev. The nozzle has 7 holes, and the diameter of each hole is 0.157 mm. The calculation of injection rate and quantity using the mono injection qualifier is based on the displacement measurement of a piston located in a closed chamber. During the injection period, the drain valve of the mono injection qualifier is closed, so fuel is injected into this closed injection chamber and falls on the piston, forcing the piston to move downwards. Therefore, the piston position is related with the volume injection quantity. Also, a temperature sensor is used to calculate the fuel density and thus the mass quantity can be obtained by multiplying the fuel density and volumetric quantity. The injection rate curve is evaluated based on the derivative of the instantaneous piston displacement. The measurement range of the mono injection qualifier is 0–600 mm^3, with relative measurement accuracy of 0.1%.

2.2. Test fuels

The injection characteristics of diesel, methyl laurate, methyl oleate, ethyl oleate were investigated in this study. The purity of test fatty acid esters are above 98%. Some properties including density, viscosity and bulk modulus of these four test fuels are listed in Table 1. As can be seen, fatty acid esters have similar fuel density with each other but higher than diesel; the viscosities and bulk modulus of compressibility of methyl and ethyl oleate are higher than diesel and methyl laurate.

2.3. Test conditions

Tests were conducted at a room temperature 303 K and the fuel temperature in the mono injection qualifier was controlled within a range of 306 ± 3 K. Injection pressure varied from 45 MPa to 100 MPa and three energizing durations (0.5 ms, 1.0 ms and 2.0 ms) were selected. The back pressure was held at 0.1 MPa and fuel pump rotation speed was maintained at 120 rpm to ensure sufficient time that the pressure fluctuation in fuel pipe and rail could sufficiently diminish before the next injection event. The results of 100 injection cycles were recorded and averaged for the following analysis.

Mass based cycle injection quantities and relevant coefficients of variance for all test fuels versus injection pressure and energizing time are illustrated in Table 2. Methyl laurate generally has the highest mass cycle injection quantity among all test fuels. Coefficient of variance is observed to be strongly related with energizing time: at the short energizing time when the needle valve is not fully opened, the cycle injection quantity is mainly influenced by the transient needle motion and has relatively high variance. However, as the energizing time is sufficiently extended, the needle valve could be fully opened, and the coefficient of variance of the cycle injection quantity is dramatically reduced to below 1%.

3. Results and discussion

3.1. Definition of injection process

The parameter definition of the fuel injection process in this study is shown in Fig. 2. The location of rise of energizing current (start of energizing) defines the zero point in time on the axis. The location of injection rate rising to 1 mm^3/ms defines the start of injection and the location of injection rate curve falling to zero defines the end of injection. Injection delay is the interval between the start of injection and the start of energizing; the injection duration is the time interval between the start and the end of injection. The fluctuation of fuel pressure at injector inlet is also monitored during and after the injection event.

3.2. Injection rate characteristics of different fuels

Fig. 3 compares the volumetric and mass injection rates of different test fuels, at 45 MPa injection pressure and 1.0 ms