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Full Length Article

Macroscopic and microscopic spray characteristics of fatty acid esters on a common rail injection system

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HIGHLIGHTS

- Macroscopic and microscopic spray features of three fatty acid esters are studied.
- Light intensity distributions of different fuel sprays are compared.
- Macroscopic spray parameters are influenced by fuel physical properties.
- Droplets of methyl laurate are of smaller SMD than methyl oleate and ethyl oleate.

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ABSTRACT

The composition of biodiesel is significantly influenced by the feedstock sources. This variation in biodiesel composition may cause changes in fuel physiochemical properties and further affect the engine operation processes such as the fuel injection and spray processes. In this study, the macroscopic and microscopic spray parameters of diesel fuel and three biodiesel components (methyl laurate, methyl oleate and ethyl oleate) on a diesel common rail injection system are investigated at conditions of different injection pressures and ambient pressures. The macroscopic spray parameters, including the tip penetration distance, projected spray area, spray front velocity, spray cone angle, and the maximum spray width, of different fatty acid esters are characterized and compared to those of diesel fuel. Further, the images of fuel spray development obtained by the high speed camera are converted to grayscale ones, and the grayscale values within the spray contours are extracted to evaluate the light intensity level and distribution characteristics for different fuels. Finally, the microscopic spray characteristics of test fuels measured using a split laser particle size analyzer indicated that fuel properties also play an important role in the droplet sizes, and the droplets of methyl laurate and diesel have smaller SMD than methyl oleate and ethyl oleate.

1. Introduction

Biodiesel could be made from renewable feedstock and as such is considered as a potential alternative for the petroleum-based fuels used in transportation sectors, especially as concerns about the worldwide climate warming and petroleum shortage are gradually increasing. The utilization of biodiesel in internal combustion engines does not require any engine structure modification, and can improve incomplete combustion products such as soot, hydrocarbon and carbon monoxide emissions, only with a slight sacrifice in NOx emissions [1–4]. Therefore, many researchers tried to investigate the injection [5–7], spray [8–10], combustion and emissions characteristics [11,12] of biodiesel in diesel engines.

Biodiesel fuels are produced by the transesterification process of a variety of biomass oils/fats with alcohols, forming mixtures of many different fatty acid esters, and their compositions are significantly influenced by the feedstock sources. For example, rapeseed, palm and jatropha biodiesel contain a large amount of long-chain fatty acid esters, the carbon chain of which generally have more than sixteen carbon atoms; in contrast, coconut biodiesel contains large fractions of light fatty acid esters such as methyl laurate (C12:0) [13]. The differences in biodiesel composition may cause changes in fuel physiochemical properties and further affect the engine operation processes. Therefore, it is necessary to identify the effects of biodiesel composition on their physical and chemical properties and on the engine performance and emissions.

Knothe et al. [14,15] investigated the cetane numbers of fatty acid esters with different carbon chains, degree of unsaturation and ester structures. It was found that the number of CH_2 groups and double bonds had the most pronounced impacts on the cetane

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number, while the structure of ester moiety did not greatly influence ignition properties. To characterize the chemical effects of fatty acid esters on fundamental combustion properties, the auto-ignition delay times [16,17] and propagating flame speeds [18] of different fatty acid esters were also investigated using different kinds of experimental facilities. These studies proved that the different ester structures caused changed fuel decomposition pathways, thus exhibiting changed global combustion features. Schöborn et al. [19,20] studied the effects of molecular structure (fatty acid carbon chain length, degree of unsaturation and alcohol moiety length) of fatty acid esters on the NOx emissions on a single cylinder engine. It was found that increased carbon chain length of fatty acid or alcohol moiety, and increased saturation resulted in a reduction in ignition delay time and decreased premixed burn fraction, which led to reduced NOx emissions provided the same injection time or ignition time for all fuels. However, as the ignition delays of all test fuels were maintained constant by selectively adding some ignition promoters, the adiabatic flame temperature played the dominant role in NOx formation. Further, Hellier et al. [21] systematically investigated the engine combustion phasing and emissions formation features of a series of stearic acid esters with varied alcohol moiety structures, by changing straight carbon chain length or carbon chain branching. The authors concluded that the alcohol moiety structure did not apparently influence the ignition quality, but pose influences on NOx given the same ignition delay time. Mueller et al. [22] suggested that the biodiesel effects on NOx emissions mainly originated from the change in equivalence ratio of the reacting mixture at the premixed auto-ignition zone. When the biodiesel fuel structure produces near-stoichiometric premixed mixture, the thermal NOx formation is promoted due to the increased local and average temperature, the reduced radiative heat loss, and the advanced combustion phasing. Pham et al. [23] investigated the effects of fatty acid methyl ester profiles on the engine-out particulate emissions, observing that lower power-based specific particulate emissions in mass and number were produced as the carbon chain length decreased and the degree of unsaturation increased. However, given the mass of particle emissions, the particle number was observed to increase with shorter carbon chain length and higher molecular oxygenate content. Barrientos et al. [24] analyzed the oxidative reactivity of soot from biodiesel surrogates with different chemical structures, and they found that soot generated from fatty acid methyl esters with shorter alkyl chain showed higher oxidative reactivity.

With respect to the physical properties, Lopes et al. [25] measured the speeds of sound, which are related with isentropic bulk modulus and have important impacts on the fuel injection timing, in fatty acid methyl esters of different carbon chain lengths and degrees of unsaturation. Han et al. [26] characterized the injection rates, injection quantities and injector inlet pressure fluctuation characteristics of methyl laurate, methyl oleate and ethyl oleate on a common rail injection system. They found that the changed fuel physical properties could result in slight injection delay times, shapes of injection rate curves and pressure fluctuations at the injector inlet. As mentioned above, in spite of plenty of research work on the engine ignition and combustion characteristics for fatty acid esters, the spray development processes of different fatty acid esters have received little attention [27]. In a direct injection compression ignition engine, the fuel spray and atomization characteristics directly determine the in-cylinder fuel/air mixture formation, and further substantially influence the in-cylinder combustion quality, engine emissions and thermal efficiency. Therefore, in this study, the macroscopic and microscopic spray characteristics of three fatty acid esters, including methyl laurate, methyl oleate and ethyl oleate were experimentally obtained on a diesel common rail injection system and compared to those of diesel fuel.

2. Experimental methods

2.1. Test facility

As described in Fig. 1, the test facility used for the spray development observation mainly consisted of a diesel common rail injection system, a two-stage fuel pump, an electronic control unit, a constant volume vessel and a FASTCAM-series high speed photography system with a halide lamp as the light source. A high pressure nitrogen gas bottle was connected to the constant volume vessel to set up the ambient pressure and scavenge the residual fuel after each test condition. The fuel injector mounted on the top of the constant volume vessel was a single-hole injector of 0.28 mm diameter. The quartz windows on three sides of the vessel for the spray development observation had areas of 8×16 cm^2. The spray images were captured in 15,000 fps (frames per second), with 66.7 μs interval between two consecutive recorded images. The image resolution was 1024×128 pixels and the camera shutter rate was set to 1/15,000 s. A split laser particle size analyzer was used for droplet size measurement, in which the particle sizes were evaluated by analyzing the spatial distribution of diffraction and scattered lights. The measurement range of the laser particle size analyzer is 0.5–1000 μm. The trigger signals for the high speed camera and the injector were synchronized using a digital delay/pulse generator (Stanford Research Instrument, Model DG535). The test was conducted at the ambient temperature of 293 K and 0.1 MPa, 0.5 MPa and 1.0 MPa ambient pressures, with the ambient gas density being 1.15 kg/m^3, 5.75 kg/m^3 and 11.5 kg/m^3, respectively. The injection pressures were 40 MPa and 60 MPa, respectively and the energizing pulse width was held at 1.0 ms. Spray development processes for each test fuel and condition were measured three times and the macroscopic spray parameters were calculated and averaged based on the captured images.

2.2. Test fuels

The spray development processes of three fatty acid esters, including methyl laurate, methyl oleate, ethyl oleate were investigated in this study and compared to diesel fuel. The methyl oleate and ethyl oleate are typical long-chain constituents in canola, rapeseed, palm and jatropha biodiesel fuels [13], while methyl laurate, with a shorter carbon chain, is a major content in coconut biodiesel [28]. The purity of test fatty acid esters is above 98%. The fuel molecular structure, density, kinetic viscosity, surface tension and vapor pressure are listed in Table 1. Fuel densities of different fatty acid esters are similar but higher than that of diesel; meanwhile, methyl oleate and ethyl oleate have higher viscosity and surface tension than diesel and methyl laurate.

2.3. Definition of spray parameters

Macroscopic spray parameters derived from the acquired high-speed images include the spray tip penetration distance, the spray cone angle, the spray front velocity, the projected spray area, and the maximum spray width. The definition of the abovementioned parameters is as follows and shown in Fig. 2: the vertical distance from the nozzle tip to the farthest spray front is defined as the spray tip penetration, and the angle included between the two lines connecting the nozzle tip and the two periphery points at the half of the tip penetration distance from the nozzle tip is defined as the spray cone angle. Spray front velocity is calculated from the derivative of the spray tip penetration distance versus time. The area of total cells covered by the spray contour is defined as the projected spray area. Also, the original images obtained by the high speed camera are converted to grayscale images. Further, these grayscale images