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Experimental study on spray characteristics of ethanol-aviation kerosene blended fuel with a high-pressure common rail injection system

Lanbo Song, Tao Liu, Wei Fu, Qizhao Lin*

Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Jinzhai Road, Hefei 230026, China

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Partial replacement of fossil fuels by biomass based alternative fuels is considered as a possible option toward sustainability in aviation applications. The present work aims to study the changes in the spray characteristics in a pressure vessel when operated with aviation kerosene and ethanol-aviation kerosene blended fuel in a high-pressure common rail injection system. This research proposes the concept of adding a certain percentage of ethanol to aviation kerosene, creating ethanol-aviation kerosene blended fuel, which can decrease our reliance on fossil fuels on some level. The spray characteristics of the blended fuel, like spray tip penetration, spray cone angle and spray area, are studied in our work. Through the analysis, we can find that the atomization conditions have a significant impact on the spray characteristics of the aviation kerosene. Similarly, the experimental results show that the addition of ethanol has certain effect on the spray characteristics of the aviation kerosene. And the empirical equations applied in this study to predicting spray tip penetration and spray tip velocity provide a good agreement with the experimental data in the error-allowed range.

1. Introduction

The sustainable replacement of finite fossil fuels as novel strategies are intensely pursued in fundamental research, which are widely applied in science and industry. Establishment of the renewable fuel production systems is a global challenge to the environmental, social and economic problems. Aviation fuels constitute a large sector for the consumption of fossil fuels with a market value of $207 billion in 2012 [1]. According to the Airbus' report that globally there are approximately 15,750 aircraft, and it is projected to reach 32,000 by 2028 [2]. This means that the influence of the aviation to the environment will attach more and more attention, such as the emissions of NO_x, H_2O, sulfate and particulate matter from aviation as radiative forcing. The available alternative fuels can be categorized into two main parts: the operational stability and security or environmentally friendly. Blakey et al. [3] summarized the development of aviation alternative fuels, such as the commercially available process technologies to produce aviation alternative fuels, the flight testing program and the research on combustion characteristics for alternative fuels, and they also discussed the prospects for future fuel development.

Bio-ethanol, as a sustainable and renewable source, is taken into account as many states' strategy, its basic point is the beneficial to environment and the objective point is the permanent [4]. As we know, ethanol is a colorless volatile flammable liquid formed, the molecular weight is 46.07 g and the density is 789 kg/m^3 at 294 K. Thermal and transport properties are given in Table 1. Brazil and the United States produce about 80% of the world's ethanol, more than 20% of Brazilian cars can run on pure ethanol rather than as additive to fossil fuels, a much higher percentage of bioethanol (top 85%) can be used in flex-fuel vehicles in the USA [6].

The use of alternate liquid fuels toward developing bio-derived renewable fuel had received more and more social attention from different industrial sectors. During the last century, many researchers had studied the characteristic parameters of the liquid fuel spray, such as spray tip penetration, spray cone angle and the mean drop diameter which have significant effects on the combustion behavior in engine

* Corresponding author. 96 Jinzhai Rd, Hefei, Anhui 230026, China. Fax: +86 551 63606459.
E-mail address: qlin@ustc.edu.cn (Q. Lin).
URL: http://combustion.ustc.edu.cn.

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Table 1
The thermophysics and transport properties parameters of absolute ethanol [5].

Boiling point	351.37 K
Flash point	289.6 K
Auto-ignition temperature	698 K
Heat of combustion	26,800 kJ/kg
Latent heat of vaporization	926 kJ/kg
Coefficient of thermal conductivity	0.1644 W/(m k)
Kinematic viscosity	1.5115×10^{-6} m^2/s
Dynamic viscosity	1.1931×10^{-3} Pa s
Surface tension	0.0224 N/m

combustors [7–10]. Huang et al. [11] visually researched the spray atomization, evaporation and combustion processes of ethanol–diesel blend under LTC conditions. The effect of the size of the droplets on the combustion efficiency of the liquid fuel also had been discussed in many literatures [12,13]. Through Datta and Som's numerical research [14], they found that the best combustion efficiency can be achieved by obtained an optimum size of the spray droplets in a gas turbine combustor. Cheng et al. [15] researched the characteristic of diesel spray combustion and soot formation by using laser-induced incandescence (LII). They found that the soot production decreases with the increase of the injection pressure for the diesel jet spray. And likewise, there were many studies about the combustion and emission performance of biofuel engines. Hyuntae et al. [16] studied the effects of bio-butanol and bio-butanol–diesel blends on combustion and emission characteristics in a passenger car diesel engine with pilot injection strategies. Cencerrado et al. [17] described a method for the analysis of flame images based on two-dimensional distributions and important flame dynamic features in a semi-industrial scale combustor operating on pulverized fuel. According to their research, a similarly system was used by Sun et al. [18] to monitor the stability and characteristics of combustion flames in a heavy oil burner. On the whole, the combustion performance and pollutants like CO, CO_2, NO_x and HC emissions characteristics of the alternative fuels reflected the better practicality and superiority [19,20]. In other words, the conventional combustors can achieve the good fuel applicability and maintain high performance for the alternative blended fuel without any modifications.

Previous studies had shown that the addition of ethanol can improve fuel spray and atomization characteristics. In Park et al.'s study [21], better spray behavior and smaller SMD was found when ethanol was blended into biodiesel. At the same time, the resistance to auto-ignition of ethanol leads to prolonged ignition delay and the ethanol has higher oxygen content [22]. Because of these, the significant reduction of smoke emission and increasing of combustion efficiency when the certain concentration ethanol is blended into kerosene is due the joint effects of longer mixing time, faster mixing rate and higher fuel oxygen fraction. Jitendra et al. [23] introduced a set of laboratory equipment which can research the flame characteristics and combustion performance of the ethanol-kerosene blended fuel, the combustion performance would be preliminarily identified. Mendez et al. [24,25] studied the performance and emission characteristics of the ethanol-Jet A blended fuel and the butanol-Jet A blended fuel in a gas turbine engine, they found that the engine achieved even lower exhaust emissions with the addition of ethanol and butanol. In the present work, we have mainly studied the spray characteristics of kerosene and ethanol blends experimentally in a constant-volume pressure vessel. Ethanol is added in a certain percentage to the parent aviation kerosene fuel to observe the effects on the penetration, angle and area of the spray and so on. On the basis of the study, it was obtained the influence of operation parameters on quantitative and instantaneous physical characteristics of the spray process with the numerical calculation.

2. Experimental and theoretical models

2.1. Setup and methodology

The schematic diagram of the testing system is shown in Fig. 1. The system mainly has three components: the pressure vessel, schlieren system (Fig. 2) and the injection system, which separately adjust the ambient pressure and injection pressure. The constant-volume pressure vessel has three transparent quartz observation windows ($D = 80$ mm) and the designed maximum working pressure is 15 MPa. The high-pressure common rail injection system is used to provide experimental injection pressure.

The experimental spray pictures are captured by utilizing the method of Schlieren system, and a high speed camera (FASTCAM SA5 1000 K-M3, photron) is applied in the image data recorder. The spray characteristics parameters are obtained by analyzing the gray-value of experimental images deformation. In this paper, the macroscopic spray characteristics parameters, such as spray tip penetration, spray cone angle, and spray area were measured. In order to avoid the duplication errors of experimental information, the glossary definitions were put forward in the following description (Fig. 3). The hole-diameter of injector nozzle for our experiment is 0.15 mm.

2.2. Test fuels

The aviation kerosene is a multi-component fuel with a carbon chain length of C8–C16 [4] which is developed from lamp oil, and the composition of aviation kerosene used in our tests can be seen in Table 2. The physico-chemical characteristics of test samples is shown in Table 3, four different samples are considered, viz., pure aviation kerosene (E0), aviation kerosene blended with 10% (E10), 20% (E20) and 30% (E30) ethanol, respectively.

2.3. Hiroyasu and Arai model

Many papers give the empirical formula for determine the spray characteristics of liquid jet based on theoretical study and practical data of various oil fields [26]. Hiroyasu and Arai [27] proposed a model which commonly used to estimate the spray tip penetration as a function of time, two main evolution stages can be distinguished in terms of the breakup theory. The model represented in Eqs. (1) and (2), separates

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