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Experimental analysis on spray development of 2-methylfuran–gasoline blends using multi-hole DI injector

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HIGHLIGHTS

- Two different spray patterns can be observed from experiment images.
- Flash boiling intensifies with the increase of MF mixing ratio.
- The spray cone angle with MF is increased at lower and higher pressures.
- Spray penetration decreases with increase of MF mixing ratio at high pressures.
- Spray area has a negative correlation with fuel temperature at low pressures.

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ABSTRACT

Confronting the situation of environment pollution and energy shortage, direct injection (DI) system has been commonly used in gasoline engines for its good performance in fuel economy, combustion efficiency, emissions and cold-start. Currently, 2-methylfuran (MF) has already been a more attractive biomass fuel in spark ignition (SI) engine, however, there is little knowledge about its spray behaviors in DI injector, especially when it is used as a gasoline additive. In this study, the spray characteristics of MF–gasoline blends M20 (20% volume fraction MF–gasoline blend fuel), M40 and pure gasoline from 6-hole DI injector are investigated under various ambient pressures and fuel temperatures using high-speed schlieren photography. The experimental results show that two different spray shapes, flash boiling and non-flash boiling, can be observed from experiment images. When flash boiling occurs at low ambient pressure, the level of flash boiling intensifies with the increase of MF mixing ratio which can make spray front collapse intensely. The spray area increases with the MF mixing ratio rising and it has a negative correlation with the fuel temperature at low ambient pressures. As for no flash boiling case, the spray penetration decreases with the increase of MF mixing ratio. Under the ambient pressure of 0.6 MPa and 0.85 MPa, the spray cone angle for same fuel increases with the increase in fuel temperature. On the other hand, at the same fuel temperature, spray area increases slightly with the increase of mixing ratio of MF blended in gasoline.

1. Introduction

Recently, energy crisis and environmental pollution lead to an increased demand for clean and high efficiency combustion engine. Engine downsizing and fuel diversification of spark ignition (SI) engine are of current interest and numerous attempts have been done by researchers around the world in the past decade [1]. Engine downsizing can achieve higher thermal efficiency and lower CO_2 emissions [2]. Direct injection (DI) technology with greater precision in fuel metering, allowing higher compression ratios and significant potential in fuel economy, is widely used in downsized SI engine [3,4]. Thus, in order to achieve good combustion characteristics and improve combustion efficiency in downsized SI engine, it is very important to study fuel spray characteristics and mixture formation process in different engine conditions (cylinder pressure, temperature, flow field and piston position) to achieve a good distribution of the stratified lean combustion or make a homogeneous mixture in each position of the cylinder [5–7]. For example, DISI injectors should inject fuel at conditions of low in-cylinder pressure, typically from ∼0.02 MPa at low load with early injection strategies for homogeneous mixture formation, to ∼0.5 MPa for late-injection strategies

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under stratified engine operation, or even more under supercharged operation (1 MPa). Additionally, fuel temperatures can vary from below 293 K at cold start engine conditions to over 423 K at the injector tip under high-load firing conditions [8]. This will become more complex and may lead to unacceptable levels of particulate emissions and unburned hydrocarbons if there is a fuel impingement in downsized SI engines. On the other hand, at low-load conditions with early injection strategies of DISI engines, there may be a flash boiling phenomenon that the atomization mechanism and spray structure are different with normal spray because of the change of a strong phase [9]. Fuel plumes collapse and converge into a single-plume structure in the axial direction of the injector when strong flash boiling occurs [10,11]. Thus the phenomenon makes the spray penetration increase and may result in wall/piston wetting. Additionally, boiling sprays consist of smaller drop sizes with an accelerated vaporization process [12,13] and are widely investigated in SI engines [14–16]. But it also results in a different spray distribution and destroys the designed directionality of the spray. It has serious implications to the latest design high-pressure multi-hole injectors located in close spacing arrangement with the spark plug. Therefore, in order to achieve the high-efficiency and clean combustion process, the spray characteristics of liquid fuel under different engine-like conditions should be in-depth investigated.

On the other hand, fuel surrogate in SI engine is also important aspect to strengthen sustainability and reduce emissions. Alcohols have widely used in SI engine as an alternative blending fuel because of their simple production process. Their higher Octane number can allow higher compressions ratios, resulting in higher thermal efficiency. And ethanol–gasoline blends have been widely used in many countries (E5 in UK, E10 in Germany and E25 in Brazil). However, at high ethanol content blends (E85, E100) issues may arise at cold-start engine conditions due to lack of fuel volatility and the volumetric energy density is also lower than traditional fuels which poses further challenges of controlling the injector pulse width [8]. For other alkyl alcohols, butanol and propanol was implemented rarely in practical engines because they might have some drawbacks in power or emission aspect. Therefore, looking for superior gasoline substitutes has become highly pronounced in the present context.

Currently, furan-based fuels has already been studied as a novel potential gasoline substitute [17,18,23] since the breakthrough of its production methods, which were reported by the Nature and Science [19,20]. 2-Methylfuran (MF) has similar energy density and higher Octane number (RON 100.7), hence better resistance to engine knock that can allow higher compression ratios and greater engine thermal efficiencies. In addition, as biomass fuel, it is beneficial to slow down greenhouse effect. Table 1 summarizes the relevant fuel properties with data taken from Refs. [21–24]. The lower heating value (28.5 MJ/L) of MF is much closer to gasoline (31.05 MJ/L) and 35% higher than ethanol (21.09 MJ/L). What's more, the high density of MF leads to a lower heating value, which comes close to the heating value of gasoline when compared on a volumetric basis. Much lower enthalpy of vaporization for MF (389 kJ/kg) as against ethanol (919.6 kJ/kg) can avoid the engine cold-start problem. Moreover, MF is an attractive fuel candidate with regard to engine startability at low ambient temperatures because it has a lower boiling temperature (337 K) than ethanol (351 K) and gasoline (314.5–446.5 K). Above superior physico-chemical properties make MF a promising bio-fuel and worldwide interest has been triggered in recent years. Wei et al. [25] have investigated the combustion and emissions characteristics of M10 experimentally in a single-cylinder four-stroke SI engine and found that there is a good engine performance when M10 is used. The output torque and brake power increase slightly than E10. Regulated gas emission of HC and CO is lower than gasoline. Thewes et al. [23] have analyzed the impact of MF on in-cylinder spray formation and evaporation as well as engine performance using a direct-injection single-cylinder spark-ignition engine. The results showed that MF has quicker evaporation than ethanol, lower HC emission (reduction of at least 61% compared to conventional fuel), and good knock resistance compared to RON95. All of above indicated that MF is a promising potential biofuel candidate than ethanol except a drawback of higher NO_X emissions. However, there is still little knowledge about the spray performance of MF–gasoline blends with DI injector under the DISI engine conditions.

Therefore, the main objective of this work is to investigate the spray characteristics of MF–gasoline blends and gasoline using multi-hole DI injector in details. Experiments are conducted in a constant volume vessel using high-speed schlieren photography with the different fuel temperatures and ambient pressures. The characteristics of the spray are investigated in this study, such as spray tip penetration, cone angle and spray area, in which the flash boiling of MF–gasoline blends is also studied. This work is believed as a necessary preliminary research for the further analysis of internal mixture formation, and consequent combustion using the MF–gasoline blends into DISI engines. Also, this work is helpful to offer a comprehensive database for spray properties of the MF–gasoline blends.

In the following sections, the experimental setup and conditions are briefly discussed. And the results involve four parts to explain the spray properties, including spray morphology, spray tip penetration, spray cone angle and spray area. In each part, the comparative analysis of blended M20, M40 and gasoline sprays in different ambient pressure and fuel temperature is performed. Finally, major conclusions from this work are drawn in the last section.

Table 1
Fuel properties [19–22].

Parameter	Gasoline	2-Methylfuran	Ethanol
Density (kg/m^3, 293 K)	744.6	913.2	790.9
Viscosity (mPa s, 293 K)	0.37–0.44	4.00	1.08
Surface tension (mN/m, 293 K)	20.0	25.51	22.10
Boiling temperature (K)	314.5–446.5	337	351
Enthalpy of vaporization (kJ/kg)	351	389	919.6
Stoichiometric air requirement	14.14	10.08	8.98
Lower heating value (MJ/kg)	42.13	31.2	26.84
Lower heating value (MJ/L)	31.05	28.5	21.09
Research octane number	95	100.7	108.6
Motor octane number	85	82.4	89.7

2. Spray experimental

2.1. Experimental apparatus and test conditions

This experiment was carried out in a constant volume vessel equipped with a high-speed schlieren photography system, shown as the schematic of the experimental setup in Fig. 1. The entire experimental system consists of a constant volume vessel, a high-speed schlieren photography system, a temperature control system, a fuel injection system, an intake and exhaust system and a synchronization controller, etc. The constant volume vessel is a closed cylindrical cavity with inner diameter of 100 mm and volume of 2.32 L. There are two windows mounted on the front and back walls which are made of quartz glass to provide optical access with thickness of 50 mm. The windows are circular with 80 mm diameter. The HDEV (high drive electric valve) 5.1 type injector (6 holes, diameter 0.193 mm) of Bosch was chosen and mounted at the top of the chamber. Air was pumped into the