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Microscopic investigation of near-field spray characteristics of 2-methylfuran, ethanol and isooctane under flash boiling conditions

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ABSTRACT

Atomization of fuel sprays is a key factor in the control of combustion quality in direct-injection engines. In the present work, the near-field spray patterns of 2-methylfuran (MF), ethanol (ETH) and isooctane (ISO) under non-flash boiling and flash boiling conditions were investigated using an ultra-highspeed imaging technique. Fuel was injected from a single-hole solenoid injector into an optically accessible constant volume chamber at the injection pressure of 40 MPa. Various conditions were tested, ranging from non-flash boiling conditions (ambient) to flare-flash boiling conditions with fuel temperatures of 20 °C and 80 °C and different back pressures. High-speed imaging was performed using a long-distance microscope coupled with an ultra-highspeed camera (1 million fps). Results showed that under flash boiling conditions, near-nozzle spray patterns changed significantly and clear radial expansion was observed due to bubble formation and explosion. Among the three fuels, MF showed the most intense flash boiling behavior due to it having the highest vapor pressure. The effects of different non-dimensional numbers were also considered and it was found that saturation ratio and cavitation number were the two main governing factors for the near-nozzle spray behaviors. During the end of the injection process, the low effective pressure led to poorly atomized spray with a compact liquid column and large ligaments; this could result in poor air/fuel mixing and thus higher HC and particle emissions. Significant improvements were observed at Rs = 0.2 where flash boiling greatly promoted the spray atomization, even with low fuel velocity.

1. Introduction

Direct-injection spark-ignition (DISI) internal combustion engines have been studied worldwide in recent decades due to their practical advantages over the traditional port fuel injection (PFI) engines. As liquid fuel is directly injected into the combustion chamber, DISI engines provide opportunities to precisely control the injected fuel amount and its distribution [1] and to implement a higher compression ratio due to better charge cooling.

Precise control of spray characteristics is one of the keys to achieving the advantages of DISI engines. However, it is difficult as the thermal conditions vary greatly inside the combustion chamber, which could significantly affect fuel distribution [2,3]. Flash boiling occurs when a superheated fuel spray is exposed to sub-saturation pressure. It is commonly observed in the homogeneously charged combustion with early injection mode of DISI engines, where the absolute cylinder pressure can go down to 0.02 MPa. Droplet behavior changes significantly under flash boiling conditions, where much smaller droplet sizes can be obtained [4]; thus, contributing to better air/fuel mixing and combustion performance. This is mainly attributed to the formation and explosion of vapor bubbles, allowing better atomization of fuel spray [3]. Spray deformation is another noticeable feature generally observed for multi-hole flash boiling sprays [4–7]. Wall impingement by spray deformation may lead to the deterioration in fuel/air mixture preparation [8]. Further, lubricating oil diluted by fuel impingement was also viewed as a source for super-knock [9].

Superheat degree is an important parameter to describe the spray transition during the flash boiling process [6,7]. Zeng et al. [6] performed extensive studies of macro spray behavior under a wide range of superheated conditions and found that the saturation ratio (ambient

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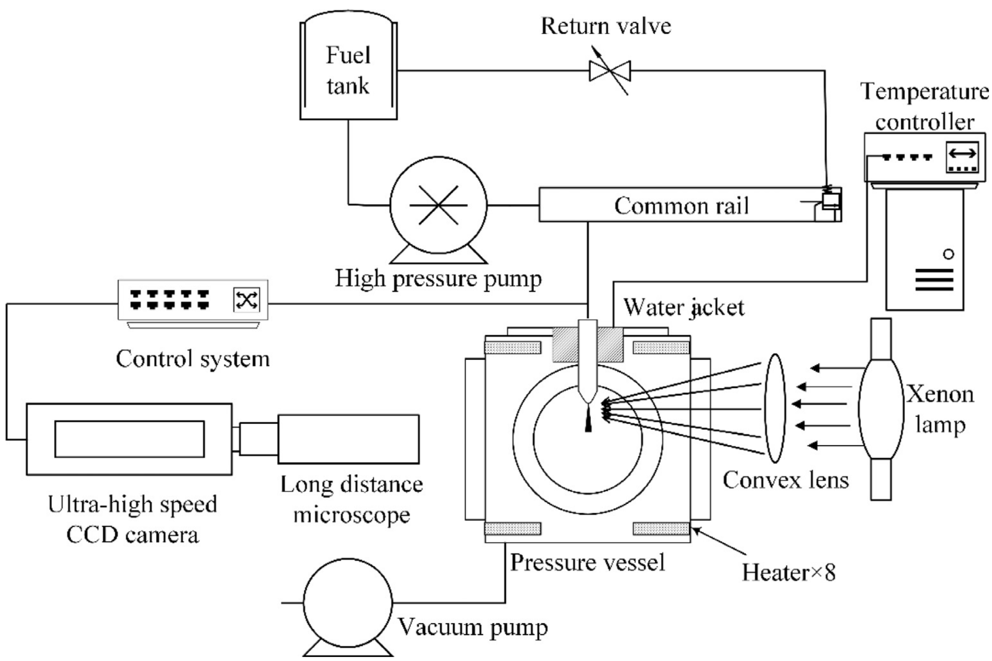

Fig. 1. Schematic of experimental setup.

pressure/saturated vapor pressure), as an indication of superheat degree, can be successfully used as a parameter to describe the spray behaviors under flash boiling conditions. The criteria of flash boiling is at Rs = 1. With a lower saturation ratio, the spray's cone angle will first increase; when continuing to reduce the saturation ratio to 0.3, flare flashing would happen and the spray will collapse and form a single-plume [6]. With regard to the collapse mechanism, Guo et al. [7] proposed that it was caused by vapor condensation near the nozzle, termed as condensation-induced collapse rather than the previous understanding that it was led by jet-induced low pressure zone.

The near-nozzle field spray behavior has attracted much research attention since it provides initial information for the spray and atomization process. Solid knowledge of the flow behavior in this region is required to potentially understand and predict the mixing process downstream and subsequently, the combustion. Though some optical work has been carried out trying to capture the near-nozzle spray behaviors, either by highspeed imaging [10,11] or by X-ray techniques [12], very limited studies are available under flash boiling conditions. Serras-Pereira et al. [13] experimentally studied the impact of various factors including fuel properties, back pressure and fuel temperatures on near-nozzle spray behavior with a real-size optical direct-injection nozzle. Fuel temperatures used were at 20 °C and 90 °C and back pressures were chosen at 0.5 bar and 1.0 bar. They reported that spray behaviors were greatly influenced by the interaction between the cavitation and flash boiling. Cavitation would provide a plentiful source of vapor bubbles which act as nucleation sites to enhance the flash boiling process. However, due to the limited camera speed (50 k fps) and view field, detailed information of the transient spray development is missing in their study.

On the other hand, fuel surrogate in DISI engines is also an important aspect to strengthen sustainability and reduce emissions. Extensive and intensive research has been carried out on bio-fuels in the past, such as bio-ethanol [14,15]. Due to its simple production process and high octane number, extensive study has been done on the application of bio-ethanol in both SI and diesel engines [16,17]. However, bio-ethanol suffers from several limitations such as low energy density and high energy consumption in its production process. Furan-based fuel has attracted research attention since the breakthrough of its production method as reported in Nature [18] and Science [19]. Some work has been done to investigate the combustion and emission performance of MF and its blends with gasoline [20–23]. The results highlighted the potential of MF for being a substitute for conventional gasoline fuel, with a steadier combustion performance and better resistance to engine knock; however, its high NOx emission is still a problem to be solved.

A very important factor in achieving the successful application of bio-fuels in DISI engines is to characterize their fuel spray. Due to very different physical properties compared to those of conventional fuels, such as much higher volatility and lower viscosity, the spray behavior of MF is expected to be quite dissimilar to that of gasoline fuel. Recently Wei et al. [24] studied the spray behavior of MF-gasoline blends using a multi-hole DI injector and found that increasing the MF blending ratio would increase the spray area and make the spray more sensitive to temperature change. Ding et al. [25] studied the droplet behavior of MF and MF50 compared to ISO with a Phase Doppler Particle Analyzer and found that MF had the lowest penetration rate and smallest droplet size. Despite its great importance in subsequent spray development and CFD modelling, study of the MF flow behavior in the near-nozzle region is not available in the literature. These uncertainties make the accurate control of the MF spray and its CFD modelling a challenging task. To extend the use of MF and optimize its injection control in current engine systems, the effect of MF on the near-field spray development needs to be thoroughly understood.

Therefore, the main objective of this work is to investigate and understand the dynamic near-field spray characteristics under both non-flash boiling and flash boiling conditions with different saturation ratios. The fuels used are MF, ETH and ISO. Ultra-high injection pressure of 40 MPa was applied as it is a trend for future SI systems [26]. The high velocity of the fuel spray and small area of interest makes the imaging of the near-nozzle region a challenging task. To observe the near-nozzle spray behaviors, an ultra-highspeed camera equipped with a long-distance microscope was employed to capture the dynamic spray development up to 1.6 mm downstream of the nozzle exit during both initial (0–60 μs) and quasi-steady stages (500–550 μs).

2. Experiment set-up

2.1. Optical set-up

The set-up of the backlit photography is shown in Fig. 1. An ultra-