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Characteristics of trans-critical propane spray discharged from multi-hole GDI injector

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ABSTRACT

This paper is to investigate the characteristics of trans-critical propane spray compared with the flash boiling spray ejected from a multi-hole injector in a constant volume chamber by using the Schlieren and backlit imaging methods. The fuel temperature (T_f) is set from 30 °C to 120 °C, injection pressure (p_f) from 60 bar to 120 bar and ambient pressure (p_a) from 0.2 bar to 10 bar.

The results show that the trans-critical spray has longer vapor penetration and shorter liquid penetration than the flash boiling spray, but those two sprays have similar curve liquid boundaries near the nozzle. Several discernable collapsed shock structures near the nozzle are observed at T_f = 120 °C, p_f = 120 bar, p_a = 1 bar, but they disappear when p_f drops to 60 bar for the transition path may not enter the two-phase region, and the liquid phase hardly occurs. The Mach disk distance of trans-critical spray in this study is larger than that of the under-expanded ideal gas jet because of the collapse phenomenon. At T_f = 120 °C, p_f = 120 bar, the liquid length decreases when p_a increases from 0.2 bar to 2.5 bar and increases when p_a continues to rise.

1. Introduction

The fossil fuel is still the primary power source of the vehicles. However, the massive consumption of fossil fuel by vehicles contributes to air pollution [1] and global warming [2]. Particle matter (PM) and CO_2 are strictly limited by new emission standards and regulations. Low-carbon alternative fuels have the promising to reduce the exhaust emissions from motor vehicles. LPG comprises short-chain alkanes, e.g., propane and butane, and therefore LPG combustion produces lower CO and HC emissions [3] and helps with a CO_2 reduction in comparison with gasoline [4]. Furthermore, the higher research octane number (RON) of LPG [5,6] allows a high compression ratio to improve fuel economy and to reduce CO_2.

The gasoline direct injection (GDI) technique has advantages in achieving higher power, better fuel economy and overall emissions [7], favored by modern vehicles. Over the past years, GDI engines have occupied the majority of the market share of engines for passenger cars and hybrid vehicles [8]. However, compared with the conventional port fuel injection (PFI) engine, GDI engines generate more particles [9,10]. Previous studies have demonstrated that the combination of direct injection (DI) and LPG can efficiently resolve the PM emission problems of spark ignition engines [11–14]. The spray characteristics, which substantially determine the combustion process and thus the engine performance and emissions of a DI engine, are worthy of study. Flash boiling will happen in LPG spray under most engine operating conditions [15]. Propane, as the main component of LPG, has similar spray characteristics to LPG. A thorough understanding of the micro and macro characteristics of propane spray will contribute to the research of LPG spray in DI engines. Lacey et al. [16] experimented on the spray characteristics of propane under engine operating conditions using Mie scattering and the Schlieren method and concluded that the thermodynamic property should be taken into consideration for propane sprays.

The critical temperature and pressure of propane are 96.74 °C (369.89 K) and 42.5 bar [17], It is easy to make the trans-critical sprays possible, which may promote the mixing process and decrease exhaust emissions. According to Ref. [18], there are two types of trans-critical sprays: where a supercritical fluid is injected into subcritical surroundings and the fuel can be liquid or gas, or a high pressurized liquid with subcritical temperature is injected into an environment where the pressure is subcritical, but the temperature is supercritical. The first type may arise in propane sprays under engine conditions, which is the focus of this paper. Hereafter, the 'trans-critical spray' refers to the supercritical-to-subcritical fluid.

The studies on trans-critical sprays have attracted much attention in the aviation field. Wu et al. [19] investigated the characteristics of the

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Nomenclature

p_f	injection pressure
T_f	fuel temperature
p_c	critical pressure
T_c	critical temperature
p_a	ambient pressure
$h_{f,e}$	specific enthalpy at the nozzle exit
$u_{f,e}$	fluid speed at the nozzle exit
L_l	liquid penetration
$\bar{p}_r$	reduced injection pressure
$\bar{T}_r$	reduced fuel temperature
s_f	specific entropy of fuel
h_f	specific enthalpy of fuel
$p_{f,e}$	nozzle exit pressure
$a_{f,e}$	speed of sound at the nozzle exit
$Ma_{f,e}$	mach number at the nozzle exit
X_i	distance of Mach disk

trans-critical injection of ethylene with a customized single-hole injector using Schlieren. The experiment results showed that the flow was choked at the nozzle exit and there was a shock structure nearby; the trans-critical jet was similar to the under-expanded ideal gas jet when the fuel temperature was much higher than the critical temperature. The same research group then experimented with the expansion process of under-expanded supercritical ethylene jets into the superheated environment [20]. It was observed that higher ambient temperature reduced the length of the fuel condensation core, but it could not eliminate the core because of the limited heat transfer rate from the ambient gas to the spray plume. Star et al. [21] conducted a simulation on the same spray conditions, giving a well-matched simulation result. They found out that the masking effects of fuel condensation covered the Mach disk structure and the amounts of condensate increased with the increase of chamber pressure. Lin et al. [22,23] presented a database of the trans-critical injection of a methane/ethylene mixture into sub-critical nitrogen and analyzed the structure and phase transition of this kind of injection. As for the research of automobile engines, the application of trans-critical spray did not appeal to researchers until recently when much higher injection pressure was applied to reduce the emissions in direct injection engines. Boer et al. [24] applied trans-critical gasoline injections in a GDI engine, and as a result, the emissions including PN, PM, BSHC, and CO dramatically decreased due to the increased mixture homogeneity. Zhang et al. [25] investigated the trans-critical spray characteristics of a multi-hole GDI injector by using high-speed imaging. They found that the trans-critical spray plumes collapsed and merged into one bigger jet, similar to the multi-jet flash boiling sprays [26]; when the initial fuel temperature was high enough, there was a Mach disk structure near the nozzle. There is an increasing interest in understanding the characteristics of the trans-critical sprays which have the potential to decrease the PM emission, and more detailed investigations are required to have a better understanding of the trans-critical spray discharged from multi-hole GDI injection.

This paper aims to investigate the difference between the trans-critical spray and the flash boiling spray of propane and the influence of fuel condition and ambient pressure on the macroscopic characteristics of the trans-critical sprays of propane. The main parameters, including liquid penetration, vapor penetration, liquid length and Mach disk distance, were obtained by using speed backlit and Schlieren imaging methods. A *p-s* diagram was used to account for the injection process. The visible shock structures appeared, and the normalized Mach disk distance of the trans-critical spray was discussed to compare the trans-critical spray with the under-expanded ideal gas jet.

2. Experiment apparatus and conditions

2.1. Experimental set-up

The systems for high-speed backlit and Schlieren imaging are shown in Fig. 1(a) and (b), respectively. In Fig. 1(a), the LED lamp (150 W) and the high-speed camera (PhotronSA-X2) were placed on the opposite sides of the constant pressure. The full liquid spray can be captured by using this set-up with a Nikon 105 mm lens, while the spray near the nozzle tip was captured by a Nikon 180 mm lens. In the Schlieren system, a DC halogen tungsten lamp (24 V, 300 W) was used as the light source. Those two types of experiment were conducted separately. Both the high-speed backlit and Schlieren imaging used the same high-speed camera, and the camera speed was set at 40,000 fps with a resolution of 512 × 584 pixels. The exposure time was 1/100,000 s for the backlit imaging and 1/416,999 s for the Schlieren imaging.

The propane was pressurized by high-pressure air in a storage tank. A fuel accumulator surrounded by several heaters was connected to the storage tank as the fuel rail, which can heat up the fuel to the target temperature and stabilize the injection pressure. The temperature of the fuel in the accumulator was regarded as the fuel temperature, it was measured by a thermocouple and controlled by a temperature

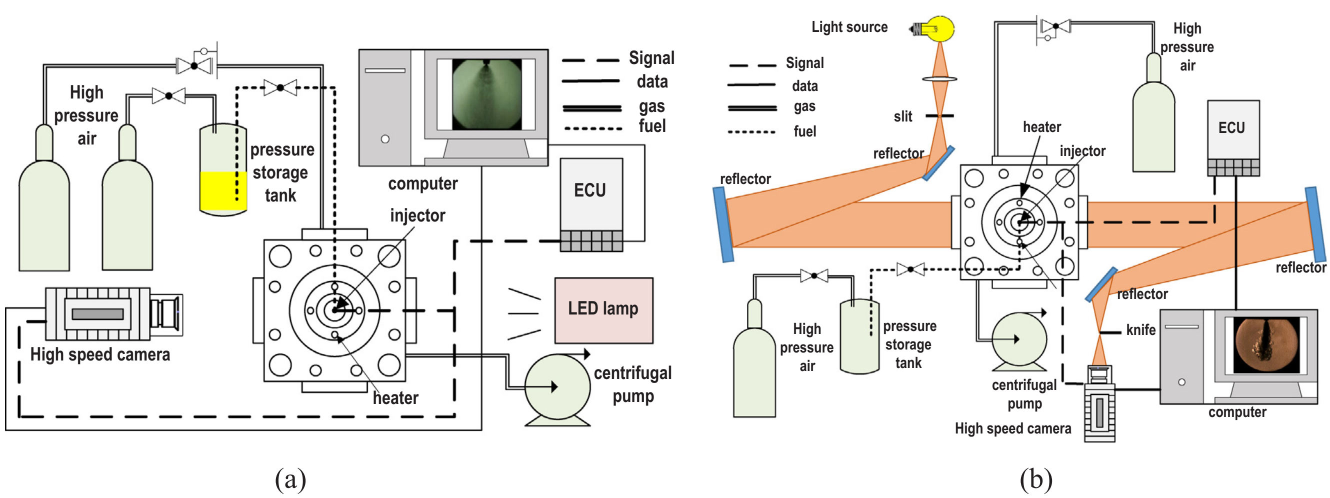

Fig. 1. Schematic of (a) high-speed imaging and (b) Schlieren detection system of trans-critical propane spray.