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Spray morphology transformation of propane, *n*-hexane and *iso*-octane under flash-boiling conditions

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ABSTRACT

Spray collapse has been widely observed under both flash-boiling and non-flash-boiling conditions when multi-hole gasoline direct injection (GDI) injectors with compact nozzle configurations were used. The main objective of this study is to further understand the collapse mechanisms by using liquids with appreciably different properties (propane, *n*-hexane and *iso*-octane). The tests were carried out in a constant volume vessel with ambient pressures ranging from 0.6 bar to 11.0 bar and fuel temperatures from 30 °C to 110 °C. Flashing propane sprays presented a non-collapse feature under elevated-ambient-pressures but flash-boiling conditions. By close-up examination of flashing propane sprays over a wide range of liquid temperatures and ambient pressures, it was found that there should be an ambient pressure threshold between 1.0 and 3.0 bar between the collapsed and the non-collapse sprays for propane. The spray collapse occurred as the ambient pressure is below the threshold. The non-collapse feature for flashing propane sprays under the ambient pressures beyond the threshold was attributed to the prohibition of nucleation and bubble growth under elevated ambient pressures.

1. Introduction

Flash boiling is a rapid phase change once a liquid is abruptly exposed to an environment with the ambient pressure lower than its local saturation vapor pressure. It has been widely found and used in the fields, such as desalination [1,2], ice slurry production [3], spray cooling [4–6] and so on, while several comprehensive reviews have also been made [7–9] to summarize the available experimental and numerical findings.

In the past years, flash boiling has been viewed as a promising way to enhance atomization and the potential in improving fuel economy and emissions of gasoline direct injection (GDI) engines. Thus, intensive studies have been carried out experimentally and numerically from the fundamental nucleation and bubble growth to external spray behaviors under the thermal conditions of GDI engines [10–20]. Zhang et al. [13,14] studied the effect of bubble formation inside a slit nozzle on the external breakup process of a superheated liquid jet and claimed that bubble number density was the main driving force for the breakup of a superheated jet. Serras-Pereira et al. [21] found that the in-nozzle flow regime is highly sensitive to the fuel temperature and reported that primary breakup and atomization quality could be enhanced by increasing superheated degree. Zeng et al. [11] examined the effect of fuel properties on the spray structure at varied superheated degrees and found that a good self-similarity could be achieved for comparable superheated degrees for different liquids. Li et al. [22] found that the change in ambient pressure could significantly influence the spray morphology. Araneo et al. [17] investigated the effects of fuel distillation curve on the flash boiling process using a multi-hole GDI injector. It was reported that P_{amb}/P_{sat} is a fundamental parameter for spray angle and that the experimental spray angle can be used to obtain the saturation pressure curve for liquid. Wang et al. [19,23] reported that flash boiling can considerably improve the atomization quality during the end of injection stage and impingement with split injection strategy. Guo et al. [24] also characterized the external flashing spray and found that nucleation rate and thermal energy were the key parameters influencing the jet expansion. Macroscopic spray behaviors and atomization characteristics of flash-boiling sprays in optically accessible GDI engines were also investigated [10,12,15].

However, the collapse of multi-jet flash-boiling sprays [11,15–17,19,20,25] would negatively influence the designed jet trajectories and fuel distribution. Furthermore, the longer penetration length as a result of the spray collapse could lead to wall impingement and lubricant dilution, which were believed as one of the sources for super-knock and engine damage [26]. With the increasingly stringent

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Nomenclature

GDI	Gasoline Direct Injection
JIC	Jet induced Collapse
CIC	Condensation induced Collapse
ASOI	After Start of Injection

emission regulations, wall impingement also becomes one of the main concerns on soot emissions [27–29]. The increase in superheated degree would enhance the collapse in a certain range of conditions [11,30,31]. The collapse was owing to the occurrences of jet overlap and low-pressure zone surrounded by the high-speed jets, but no consensus on the origin of the low-pressure zone have been achieved. Some researchers believe that the low-pressure zone was induced by the surrounding high-speed jets [30,32], which limited the gas exchange between the low-pressure zone and ambience. Recently, Li and Guo et al. [16,25] reported that the above-mentioned jet-induced low-pressure zone could not fully explain the collapse under flash boiling conditions using the proof by contradiction. They further proposed that the collapse was the consequence of vapor condensation based on a series of previous studies showing the liquid temperature at the nozzle exit instantly dropped to the ones below the local saturation temperature from the superheated state [33–36]. Furthermore, their latest study [37] demonstrated that the counteraction of radial momentum of vapor due to expansion could lead to the significant rise in static pressure and fulfill one of the necessary conditions for the vapor condensation. Besides, Li and Guo et al. [16,25,37] termed the collapse due to jet-induced low-pressure zone as Jet Induced Collapse (JIC) and termed the collapse under flash-boiling conditions as Condensation Induced Collapse (CIC). More details of the basic patterns of JIC and CIC can be described in Section 3.1.

In spite of the intensive investigations on multi-jet flash boiling sprays, the mostly used liquids were gasoline and gasoline-like fuels, e.g. *n*-hexane, methanol, ethanol and *iso*-octane, which showed certain similarity in terms of spray morphology against R_p (pressure ratio of saturation pressure over ambient pressure) under certain conditions [11,17,31,38] and Zeng et al. [11] reported that the multi-jet flash-boiling sprays completely collapsed at $R_p > 3.3$. Recently, using propane as the injected substance, Lacey et al. [39] found that the flashing propane collapses at R_p much larger than 3.3, indicating the less generality of R_p in correlating spray morphology under flash boiling conditions for liquefied gas (i.e. propane). They further also proposed a new criteria for the collapse taken into account the geometrical parameters and liquid thermodynamic properties.

The present study is inspired by one case with ambient pressure of 1000 kPa in the study by Lacey et al. [39], which showed that the flashing propane sprays did not collapse. This finding may support the deduction in our previous study [16] that disruptive evaporation and thus massive vapor could eliminate the generation of jet-induced low-pressure zone if the jet-induced low-pressure zone intended to formulate. (i.e. JIC cannot fully explain the collapse under flash boiling conditions.) Therefore, the first purpose in this study is to double-check whether the non-collapse feature of flashing propane sprays would still be observed or not when the nozzle configuration is changed. Then, what's more important, the second one is to conduct the flashing propane spray tests with wider operating conditions to further understand the non-collapse process of flashing propane sprays, which is finally conducive to understanding the collapse behaviors of gasoline-like liquids. Herein, flashing propane sprays were studied in comparison with flashing sprays of *iso*-octane and *n*-hexane using a five-hole GDI injector. The ambient pressure ranged from 0.6 bar to 11.0 bar and the fuel temperature ranged from 30 °C to 110 °C. In contrast to the results by Lacey et al. [39], similar phenomena were found given the similar boundary conditions, but more interesting and worth noting results were delivered and a new understanding on the non-collapse feature of flashing propane sprays was proposed.

2. Experimental setup

Fig. 1 shows the schematic of the experiment set-up. The experiment was carried out in a constant volume vessel. The injector was mounted at the top of the vessel, and two quartz windows were mounted oppositely. The fuel temperature was realized by the heaters around the injector, and monitored by the thermocouple near the injector. The sub-atmospheric pressures were achieved by an Agilent HS452 centrifugal pump and the elevated ambient pressures were realized by high-pressure gas bottle. Two Omega pressure gauges (DPG409-025HG and DPG409-002BG) were used to monitor sub-atmospheric and elevated pressures, respectively. A high-speed camera (Photron SA X2) was utilized to capture the spray development of liquid phase using backlit method. The camera speed was set as 12,500 frame/s and the spatial resolution was 38 μm/pixel. A five-hole gasoline direct injector with the hole diameter of 0.18 mm was used, and the spray footprint is shown in

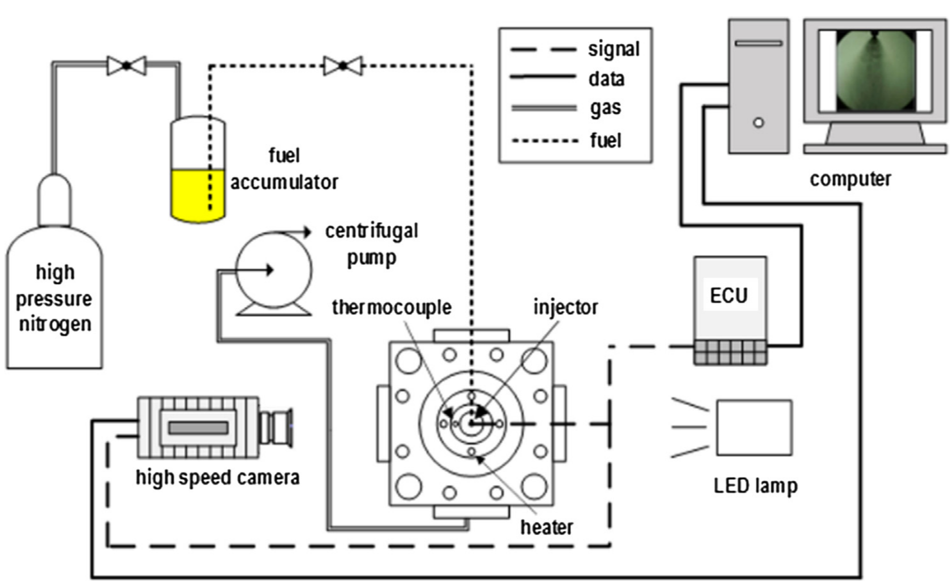

Fig. 1. Experimental setup.