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Research Paper

An exploration on collapse mechanism of multi-jet flash-boiling sprays

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HIGHLIGHTS

- Collapse of multi-jet flash-boiling sprays was caused by vapor condensation.
- Jet overlap was a necessary condition for collapse of flash-boiling sprays.
- Collapse under high P_{amb} was caused by low-pressure induced by high-speed jets.
- Rapid bubble bursting caused local static pressure rise at the balance position.

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ABSTRACT

The main objective of this study is to understand the mechanism of the spray collapse during flash boiling using multi-hole injectors. The spray characteristics of a five-hole gasoline direct injection (GDI) injector were investigated over a range of ambient pressures and fuel temperatures with high-speed imaging and phase Doppler particle measurement techniques. Spray collapses under both flash-boiling and non-flash-boiling (elevated ambient pressure) conditions were observed, but due to different mechanisms. In order to prove that the vapor condensation near the nozzle exit is the primary cause for the collapse under flash boiling conditions, careful analysis to examine the two necessary conditions for vapor condensation in multi-jet flash-boiling sprays was conducted: (1) existence of sub-cooled droplets and (2) existence of saturated vapor. The first condition could be supported by the previous studies and the other condition was numerically and experimentally demonstrated in the present study. It was found that the local static pressure significantly increased at the balance position, where the radial momentums of the droplets and vapor issued from the five holes could be counteracted. The increased static pressure was beyond the local saturation pressure, fulfilling the condition for vapor condensation. Furthermore, the bimodal size distribution under flash boiling conditions and the condensation core inside the spray observed under much reduced ambient pressure also prove the occurrence of vapor condensation at the nozzle exit.

1. Introduction

In recent years, flash boiling has been widely studied due to its great potential in improving spray atomization quality [1–3] and impingement [4] for gasoline direct injection (GDI) engines. A recent report has shown that up to 99% of all the injections during New European Driving Cycle and 95% during 'Real Driving Emissions' tests in mid-range cars were superheated [5]. Therefore, the flash-boiling spray should be fully understood because of its significant impact on atomization and its frequent occurrence in real GDI engines.

Flash-boiling can be achieved by elevating liquid temperature or depressurizing ambient pressure to make the liquid superheated. The superheated degree can be expressed by the temperature difference between the liquid temperature and the saturation temperature at local ambient pressure, or by the ratio of the ambient pressure over the saturation pressure. The superheated fluid inside the nozzle undergoes the processes of nucleation and bubble growth. The mechanisms of nucleation and bubble growth have been investigated and several models have been proposed [6–8]. In order to correlate the inside bubble formation and external superheated jet breakup, a number of studies have been conducted. Zhang et al. [9,10] studied the effect of bubble formation inside a nozzle on the external breakup process of a superheated liquid jet. They found that the bubble number increased with the superheated degree and claimed that bubble number density

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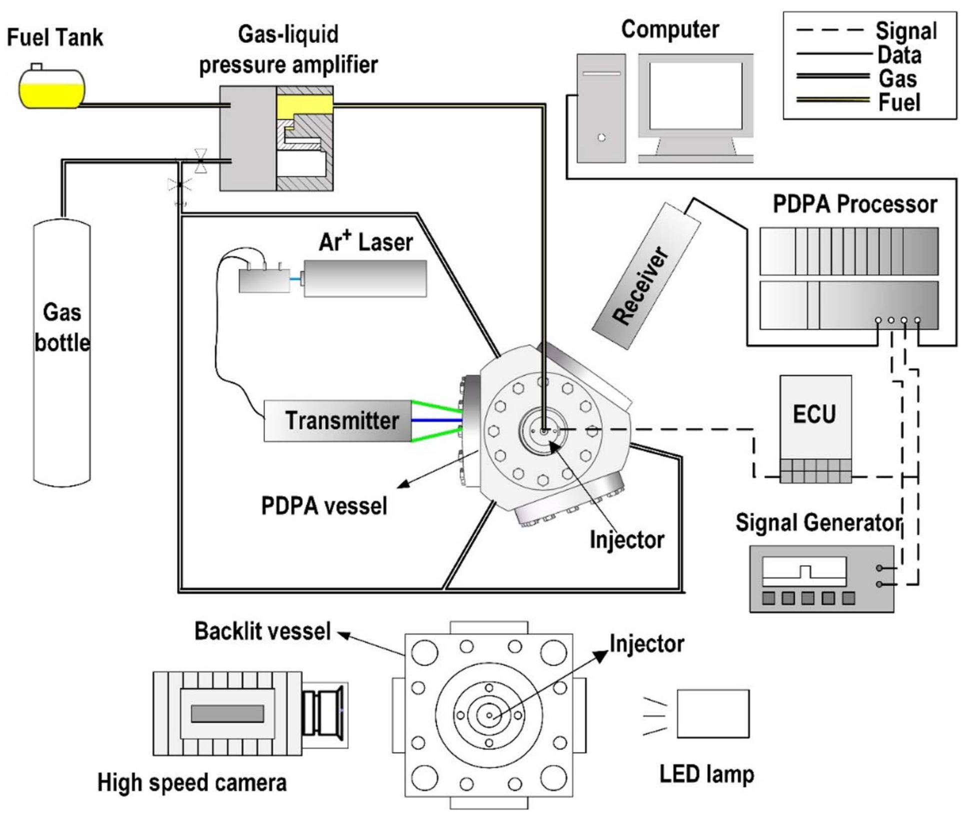

Fig. 1. Schematic of the experiment setup for PDPA and backlit.

could be the main driving force enhancing the superheated liquid jet breakup. With a real-size transparent injector nozzle, Serras-Pereira et al. [3] found that the in-nozzle flow regime was highly sensitive to fuel temperature and the increase in superheated degree dramatically improved primary breakup and atomization. Wang et al. [11] studied the near-field spray characteristics of 2-methylfuran, ethanol and *iso*-octane under flash boiling conditions and reported that saturation ratio and cavitation number were the two dominant factors for the near-nozzle spray behaviors.

It has been widely observed that spray collapse would occur under flash-boiling conditions when multi-hole GDI injectors were used [1–3,12–15]. The occurrence of spray collapse could lengthen spray tip penetration, lead to the fuel film buildup on the cylinder wall and piston crown [16], and increase soot emissions. Furthermore, fuel impingement would also dilute the lubricating oil, which was believed to be one of the sources inducing super-knock [17]. Zhang et al. [12] studied the flow field of the multi-jet flash-boiling sprays and found that the superheated degree was the predominant factor in determining the structure and flow field. Mojtabi et al. [13] studied the effects of fuel properties, superheated degree and nozzle configuration (different envelop cone angles) on the flash-boiling sprays and found that superheated degree and nozzle configuration were the two key parameters affecting spray collapse. Based on experimental results with different liquids and injectors, Kramer et al. [5] suggested that the trajectory deviation could be induced by flash-boiling or increasing nozzle hole number. Yang et al. [14] investigated spray collapse under flash-boiling conditions, and suggested it was attributed to low-pressure zone caused by the high speed jets and the jet overlap. Aori et al. [15] investigated the effect of nozzle configuration on the macroscopic characteristics of flash-boiling sprays, and revealed that the spray collapse was enhanced for nozzles with more holes and symmetrical configuration. They also claimed that the spray collapse was induced by the low-pressure zone enclosed by the high-speed jets.

However, spray collapse could also be observed at elevated ambient pressures (non-flash-boiling conditions) [18–21]. It is worth noting that the spray collapse under non-flash-boiling conditions was also attributable to the generation of low-pressure zone enclosed by high-speed jets [18,20,21], which was used to explain the collapse under flash-boiling conditions as well. Recently, Guo et al. [22] compared the collapse of multi-jet sprays under elevated ambient pressure with the collapse under flash boiling conditions. They found that the spray collapse became much weaker as the ambient pressure decreased from 10.0 bar to 1.0 bar and the spray even slightly expanded as the ambient pressure further decreased to 0.5 bar with the liquid temperature fixed at 20 °C. In other words, the jet-to-jet interaction was very weak at low ambient pressures. This phenomenon can be observed in the current study (Fig. 6). Considering that flash boiling in GDI engines normally occurred at sub-atmospheric pressures, it is unlikely that the collapse under flash boiling conditions was just caused by the jet-to-jet interactions, or to be more precise, the low-pressure zone enclosed and induced by the high-speed jets could not be produced under flash boiling conditions. Thus, Guo et al. [22] further proposed that the spray collapse at elevated ambient pressures was caused by the low pressure zone enclosed and induced by the high-speed jets, while the collapse under flash boiling conditions was caused by the low pressure zone induced by the vapor condensation at the nozzle exit. The two collapse mechanisms with different inner physical process were termed as jet-induced spray collapse and condensation-induced spray collapse, respectively. The proposal of condensation-induced spray collapse was based on a series of findings, which demonstrated that the temperature of the initial superheated liquid immediately dropped below the local saturation temperature at the nozzle exit [23–25]. A recent study from Li et al. [26] reported that the near-field spray width was quite sensitive to P_{amb} under flash boiling conditions. With the increase in superheated degree, relatively larger P_{amb} could enhance the spray collapse while relatively small P_{amb} could enhance the expansion. They suggested that relatively larger P_{amb} be conducive to increasing local vapor concentration via vapor coagulation and enhancing the condensation intensity, leading to stronger collapse, whereas, relatively small P_{amb} may lead to relatively weaker collapse due to the dilute vapor concentration