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Characteristics and correlation of nozzle internal flow and jet breakup under flash boiling conditions

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ABSTRACT

Flash boiling sprays utilize superheated fluid to enhance spray breakup via eruption of flash boiling bubbles near the nozzle exit. Extensive efforts have been made to interpret the underlying complex phase change physics associated with flash boiling sprays. However, the dynamic interaction between the gas phase and liquid phase of the flash boiling sprays has not been adequately investigated yet. This work adopts a two-dimensional optical transparent nozzle to study in-nozzle multiphase flow characteristics as well as spray characteristics outside of the nozzle. Both high-speed and low-speed measurements were carried out using optical diagnostic methods, and flash boiling sprays at different superheat levels were studied. With the experiments, the correlation between the internal flow and spray liquid jet breakup is established and the impact of the gas-liquid correlation on the properties of flash boiling sprays is presented. Furthermore, dynamic interaction between the gas phase and liquid phase in the nozzle and out of the nozzle is analyzed with a center of mass scheme. It is found that the dynamic features of the flash boiling sprays are closely connected with the dynamics of the in-nozzle flow. Such observation suggests that modifying flash boiling bubble characteristics can potentially be utilized to actively control flash boiling sprays for improved spray performance.

1. Introduction

Flash boiling fuel sprays are created by injecting superheated fuel into a low-pressure environment, which would cause fierce evaporation and spray breakup. Flash boiling sprays have been extensively investigated because of their excellent atomization capabilities. Flash boiling may substantially decrease droplet size [1,2], increase spray cone angle [3–5], enhance air-fuel mixing [6], and improve liquid jet breakup at a low injection pressure with an elevated fuel temperature. Therefore, flash boiling sprays are considered to have the potential in improving liquid fuel combustion and engine emission [7–15].

Despite of its potential advantages, fundamental interpretation and theoretical analysis of flash boiling spray are still inadequate, partially due to the complexity of flash boiling phenomenon. For instance, dealing with liquid-gas multiphase flow and high optical depth across the spray is challenging for diagnostics in obtaining accurate measurements. It has been widely recognized that the complex in-nozzle multiphase flow would greatly impact flash boiling spray characteristics [16–29]. To visualize the flash boiling process (both in-nozzle and also out-nozzle) as well as investigate near nozzle effects, a feasible experimental approach is to utilize two-dimensional transparent slit nozzles, which has been well documented in many studies. Henry et al. [30] adopted two glass blocks to create a thin slot for in-nozzle cavitation bubble observations. Short pulsed white light source and Nd: YAG laser was used to capture cavitation effects for non-flash boiling sprays. Sou et al. [31] used a similar experimental setup utilizing thin stainless steel plates to precisely control the thickness of the slit. Backlit measurement as well as laser Doppler velocimetry (LDV), enabled by doping silicon carbide (SiC) particles, were performed for cavitation analysis of non-flash boiling sprays. Wu et al. [19] further adopted this technique for flash boiling bubble analysis, and the impacts of different two-dimensional nozzle geometries were studied [17].

Existing research has demonstrated the effect of in-nozzle bubbles from cavitation and flash boiling, for instance, experimental data clearly indicates that flash boiling bubbles could significantly enhance spray breakup near the nozzle since flash boiling mainly occurs near the nozzle exit. However, in-depth analysis regarding how the degree/strength of flash boiling impacts spray features is still lacking. Previous studies had primarily focused on internal flow and near nozzle spray characteristics by bubble fraction, as well as spray width or spray angle analysis. Such attempts could

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not fully reflect the detailed physics related phenomena of flash boiling sprays. Therefore, the goal of this work is to investigate the properties of the two-dimensional flash boiling spray with controllable valve motions in studying cycle-to-cycle variations and breakup process.

Furthermore, it is also desired to investigate the dynamic interactions between flash boiling bubbles and sprays, so that flash boiling induced spray breakup can be better understood. There have been several preliminary theoretical analysis on the physics of flash boiling sprays. Senda et al. [32] proposed a numerical model for flash boiling sprays while this model lacked sufficient analysis of spray breakup induced by flash boiling. Zeng et al. [33] established a flash boiling evaporation model based on fundamental analysis, however, no detailed breakup experiment was carried out to thoroughly validate the breakup mechanisms proposed. Serras-Pereira et al. [34] aimed at investigating the evaporation and breakup process of flash boiling sprays experimentally, while the study only briefly demonstrated that flash boiling could accelerate spray breakup without detailed analysis. Successful realization of detailed, time-resolved flash boiling spray measurements may reveal the mechanism of bubble-spray interaction of flash boiling sprays and contribute to the numerical efforts of modeling the flash boiling process.

For the said purposes, a precise solenoid valve was adopted to accurately control valve timings so that repeatable flash boiling sprays were enabled. With controlled experiments, this work will focus on dynamic analysis of flash boiling sprays with both low-speed and high-speed optical measurements. The rest of this paper is organized as followed: Section 2 depicts the experimental setup with both high-speed and low-speed backlit measurements. Section 3 exhibits in-nozzle and out-nozzle measurements at various fuel temperatures/superheat indices and the dynamic interaction between the in-nozzle and out-nozzle phases. Finally, Section 4 concludes this investigation.

2. Experimental setup

Fig. 1 depicts the experimental schematic for this investigation. A constant volume chamber was used to generate a controlled ambient environment for fuel spray injections. N-hexane was chosen as the fuel in this work for its relatively low boiling temperature for generating flash boiling sprays. The physical property of n-hexane is close to that of gasoline, with a density of 653.35 kg/m^3, surface tension of 0.017948 N·m, and dynamic viscosity of 295.92 μPa·s. The change of physical properties under different temperatures was also accommodated with reference to standard NIST table. We chose a single component fuel of n-hexane since multi-component evaporation and flash-boiling is not the goal of this work. The injection pressure was controlled by a nitrogen-driven accumulator and the temperature of the fuel was controlled by a heat exchanger and an additional heating source. In this work, fuel temperature varied from 63 °C to 138 °C to cover different superheat degree levels with a constant chamber pressure of 1.0 bar. Different injection pressures of 0.7 MPa, 3 MPa, and 5 MPa were chosen to reveal the effects of injection pressure on the internal flow. In order to minimize spray vaporization and condensation induced by heat transfer, the ambient temperature in the chamber was set to be the same temperature as the fuel injected to minimize the temperature gradient across the ambient and fuel. A precise magnetic valve was installed to reduce any flow fluctuation caused by valve instability. The use of the precise magnetic valve also enables transient measurements of pulsed injections under different conditions. In this study, the injection duration of the precise magnetic valve was set to 20 ms to achieve fully-developed sprays as well as limit fuel temperature drop caused by insufficient heating time as the fuel was flowing through the heating system.

In this investigation, a two-dimensional transparent nozzle was adopted to visualize the cavitation/flash boiling bubbles in the nozzle. The transparent nozzle consists of two optical glass blocks and a precise slit with a thickness of 40 μm, which enables a two-dimensional flow with the same thickness of 40 μm. The purpose of such design is to eliminate bubble overlapping and optical diagnostic challenges posed by three-dimensional nozzle geometries. The upstream width of the nozzle was 15 mm, the length of the nozzle was 10 mm with a width of 2 mm. This design was sufficient to separate cavitation bubbles from flash boiling bubbles as verified previously in other experiments. It is worth noting that in this work, we only focus on the phenomenon associated with

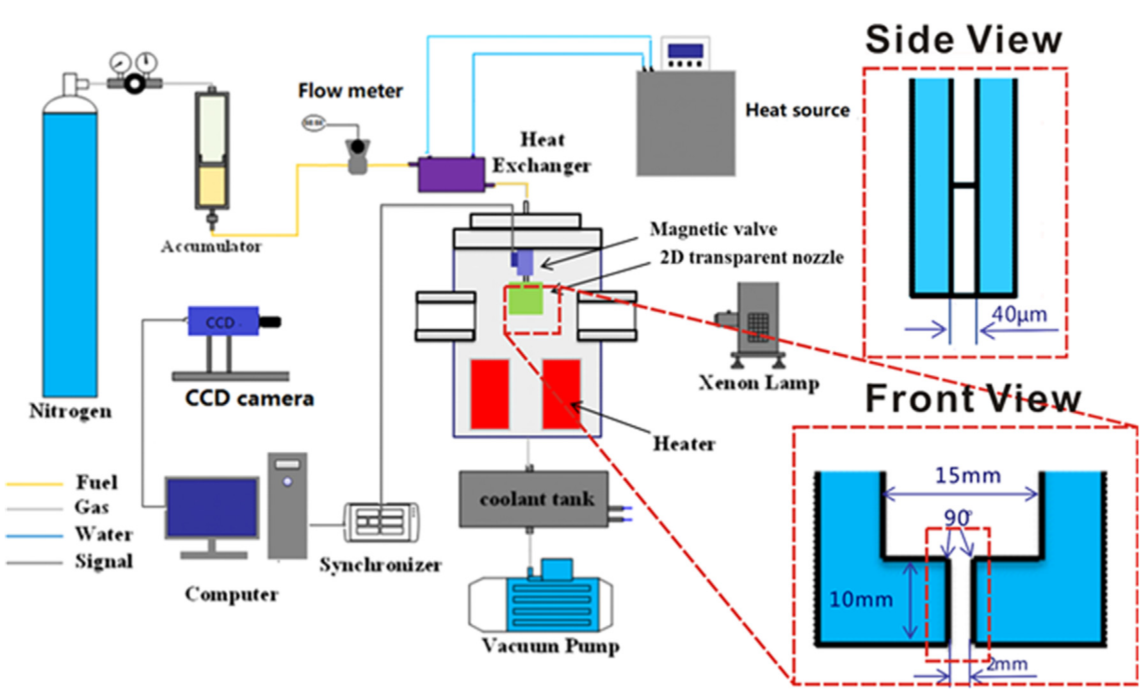

Fig. 1. Schematic of the two-dimensional transparent nozzle experimental setup.