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Quantitative observation on characteristics and breakup of single superheated droplet

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ABSTRACT

Flash-boiling atomization is an effective way to enhance fuel jet breakup by introducing explosion of vapor bubbles and thus improve the evaporation of fuel spray, compared with the conventional high pressure injection. However, the break-up mechanism of a superheated jet, especially, that associated with the explosion of vapor bubbles inside the droplets, is still unknown. In this study, a superheated droplet generator was developed for observing the droplet morphology variation and the breakup process resulting from the vapor bubbles inside a superheated droplet by microscopic imaging. It was found that the droplet morphology is mainly influenced by droplet temperature, but micro bubbles formation and the breakup of the superheated droplet are dominated by superheat degree, and the superheat degree of 25 °C is an important critical point at which the droplet breakup occurs resulted from the ever-increasing void fraction exceeding a value of approximately 50% and the breakup mode shifts from aerodynamic mode to thermodynamic mode. The surface tension of superheated droplet was also evaluated by the droplet morphology, and the results show that the maximum reduction in surface tension reaches 70% as superheat degree increases to approximately 25 °C, and this explains the sharp decrease in SMD for a flash boiling spray when the superheat degree approaches this level. These results provide insightful information for understanding the breakup mechanism of superheated droplets and liquid jet and its modeling.

1. Introduction

Atomization quality of fuel spray is of great significance for the overall design of fuel injection system of internal combustion engines. Compared with the conventional fuel spray atomization which adopt ever-increasing high injection pressure, atomization technology based on flash boiling is more effective and it could avoid most of negative effects of conventional atomization, e.g. over-penetrating, low cost-performance ratio, and low stability [1]. Flash boiling spray can be easily achieved by slightly elevating the fuel temperature for spark ignition engines, as the thermal state of fuel will change to superheated immediately once it is injected into the ambient pressure which is lower than its saturation pressure [2,3]. Inside the superheated liquid jet the bubbles forms and subsequently bursts, which causes liquid jet breakup to fine droplets. According to droplet size distributions measurements [4,5], dropsize (Sauter mean diameter, SMD) decreases significantly as superheat degree (SD) increases, and the dropsize reduction effect is more significant at lower injection pressure conditions compared with non-flash-boiling spray [6]. It is recognized that the influence of aerodynamic force is significant for spray atomization under non-flash boiling conditions, however, for flash boiling spray the breakup is dominated not only by the aerodynamic force but also the thermodynamic shattering over a certain range of superheat degree [7,8].

Many researchers have an in-depth investigation of flash-boiling spray in the last few decades and they have divided different modes of flashing atomization based on superheat degree, ranging from non-flashing, transitional flashing and finally flare flashing [9,10]. The atomization and evaporation characteristics of liquid jet in different flashing regimes have also been experimentally and numerically observed and correlated with non-dimensional parameters mentioned above as well as dimensionless superheat degree (*Pa/Ps*) [10]. Among these parameters *We* number and dimensionless superheat degree (*Pa/Ps*) plays an important role especially on SMD.

Several authors have reported that at the beginning of flashing stage, little difference was observed between jet breakup under low degrees of superheat conditions compared with traditional

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aerodynamic breakup [11–13], and they concluded that the effect of nucleation appears to be negligible, therefore, the aerodynamic breakup still dominates the breakup process. At slightly higher degrees of superheat, it is assumed that the aerodynamic breakup process no longer dominates. Based on experiment results, the vapor quantity increases slowly and SMD decreases dramatically at this stage [14]. With further increase of superheat degree to beyond a critical value, the bubbles burst immediately in the vicinity of nozzle exit and therefore it is capable of producing very fine sprays soon after injection [11], and the vapor quantity increases dramatically compared with transitional regime.

Although the above-listed conclusions and assumptions are widely accepted in this area, however, the mechanisms that govern the atomization and evaporation of flash boiling spray have yet to be revealed, and therefore no accurate models were established. In our previous studies [10,13], the flash-boiling mechanism was first revealed quantitatively by correlating the superheated liquid jet breakup in the vicinity of nozzle exit to the bubble number density inside the transparent slit nozzle. However, the occurrence and mechanism of bubble burst outside the nozzle was not addressed yet, and without bubble burst observation, it becomes difficult to identify the dominant breakup mechanism at the transitional stage from the aerodynamic breakup to the thermodynamic breakup. Therefore, further observation on bubble behaviors in a single droplet is strongly required for addressing the breakup characteristics of superheated liquid jet under the transitional conditions.

In the present study, a single superheated droplet generator was developed to observe the morphologies and the breakup processes of superheated droplet at various conditions using microscopic photography. The new droplet generator facilitates to isolate the single superheated droplet as an objective, avoiding such influences as the collision and coalescence of droplets, and to separately vary the drop temperature, the liquid pressure inside the nozzle, the ambient gas pressure, and the ambient gas temperature. Through examining effects of the superheat degree on the morphologies and breakup characteristics of single superheated droplet, the atomization mechanism of flash-boiling sprays and its dominant breakup mode are expected to understand more easily, and it provides new clues for revealing the evaporation mechanism of flash boiling spray. These results will also provide insightful information for modeling a flash boiling spray.

2. Experimental apparatus and technique

In order to have a better understanding of breakup mechanism of superheated liquid jet, a fundamental research of a single droplet with same thermal properties is preferred, therefore, a droplet generator was developed to implement a micro-observation on morphology and breakup of single superheated droplet. As illustrated in Fig. 1, the droplet of around 2 mm, supplied by a capillary with inner/outer diameter of 0.51 mm/0.80 mm mounted under the fuel chamber. In order to generate a superheated droplet, a sudden pressure change must happen when fuel is issued from the nozzle exit. The cross-section of the capillary was blocked by inserting a precision metal rod with a diameter of 0.44 mm to form a throttle effect near the exit of the capillary, where the Re number is less than 20. The temperature of the droplet was controlled by water recirculation around the fuel chamber and has been calibrated by thermocouple.

Fig. 2 shows the schematic of experimental apparatus, including a constant volume chamber, an ambient pressure control system, a fuel supply system, a microscopic imaging system and an acquisition system. The constant volume chamber can be operated at pressure between 10 kPa and 8 MPa, and possesses five optical accessible windows. The upstream pressure of liquid fuel was controlled manually to keep a constant pressure difference under different ambient conditions. A liquid jacket surrounding the fuel chamber was connected to a heat exchanger, to cool or heat the fuel inside the nozzle to a fixed temperature between 0 °C and 200 °C. LED lamp was employed to illuminate the region near the tip of capillary homogeneously from the opposed direction of the camera. The morphology and breakup process of droplet can be observed and characterized through a micro-imaging system which consisted of a long distance microscope and a CCD camera. The raw image with resolution of 3.7 μm/pixel was recorded by image acquisition system.

3. Experiment conditions

The experiment conditions are listed in Table 1. Ethanol was used to investigate the flash-boiling droplet, because: (1) ethanol is one of the well-known alternative and renewable fuels, (2) its boiling point is low, thus easy to realize flash boiling at atmospheric pressure under temperature of 100 °C, (3) the results of ethanol fuel can be partially applied to gasoline fuel as the physical properties are close to those of the light components of gasoline. According to the previous studies [1,10,13], the spray characteristics are dominated by superheat degree (SD) for the flash boiling sprays, therefore, SD was used as the main parameter to analyze the characteristics and breakup mechanism of superheated droplet. SD was varied from 0 to 35 °C through different combination of droplet temperature from 40 °C to 75 °C and the ambient pressure from 0.18 bar to 0.87 bar.

4. Imaging and data processing method

In order to reveal the characteristics of superheated droplet, the following factors have been considered: (1) a high quality of the raw data is necessary, and the boundary of both droplets and bubbles are easy to identify; (2) by combining advanced image processing methods, the processed image must be of sufficient quality for precise determination of droplet morphology and bubbles inside the droplet; (3) the needle must be absolutely vertical (i.e. direct to the earth center), so as to keep the droplet axisymmetric, and the following image processing and stalagmometric methods [15] are effective; (4) the selected droplets for analysis at each condition are the last images before droplets detach from the needle; (5) At least three images are selected for analysis at each condition if the droplet is unbroken; (6) the evaporation of droplet can be neglected during very short pendent period at room temperature. Fig. 3 demonstrates the image and data processing in this study and some key parameters are introduced as below:

4.1. Morphological analysis of superheated droplet

The morphology of droplet can be characterized by the radius of curvature at the drop apex (R_0) and drop volume (V_d) as shown in Fig. 3, the drop volume V_d is calculated in cylindrical coordinates r and z, together with the tangent angle φ and arc length s measured from the drop apex as show in Eq. (1).

$$V_d = \pi \int r^2 \sin \varphi ds \tag{1}$$

4.2. Void fraction (ε) analysis

Since plenty of bubbles are found inside the droplet at superheated conditions, the outline of the bubbles was first distinguished and marked, and then the equivalent radius and the volume of each bubble were calculated. Note that the overlapped