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Morphology analysis on multi-jet flash-boiling sprays under wide ambient pressures

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ABSTRACT

The main objective of this study is to investigate the effect of ambient pressure (P_{amb}) on the morphology of multi-jet flash boiling sprays and to promote the understanding on the collapse mechanism. With the high-speed imaging technique, the n-hexane spray process in a constant volume vessel was captured under the ambient pressures from 2 kPa to 101.3 kPa and the fuel temperatures (T_{fuel}) from 20 °C to 120 °C. The spray width within the axial distances of 20 nozzle diameters (*do*) could be increased by increasing T_{fuel} and/or decreasing P_{amb}. Beyond 20*do*, the change in spray width against superheated degree (ΔT_{SD}) was fairly sensitive to P_{amb}. It decreased with the increase in ΔT_{SD} at P_{amb} larger than 50 kPa, and increased with ΔT_{SD} at P_{amb} less than 50 kPa. Based on the new understanding that the collapse in multi-jet flash-boiling sprays was induced by vapor condensation at the nozzle exit and the resultant local pressure drop (i.e. generation of low-pressure zone), the sensitivity of spray width on P_{amb} could be well explained as follows: relatively larger P_{amb} (> 50 kPa for the used injector) would be conducive to the vapor coagulation and cause stronger vapor condensation (i.e. larger pressure drop) while the vapor dispersion may become dominant at lower P_{amb} (< 50 kPa for the used injector), negatively influencing the intensity of vapor condensation.

1. Introduction

The automotive industry has been facing the challenges of fossil fuel resources and CO_2 reduction. Current researches [1,2] have pointed out that vehicles driven by internal combustion engines, including those with hybrid powertrain systems, will still take a large part of the global market even in 2040s. This means the research on energy saving in internal combustion engines, especially for gasoline engines, will still be a critical issue in R & D during the coming decades. Gasoline direct injection (GDI) engines have become the dominative engine type in passage cars due to the flexibility in control and advantages in fuel economy [3]. Comparing with traditional port fuel injection gasoline engines, in-cylinder fuel injection and mixture formation are more important in the design of combustion chamber, because the mixture formation not only determines the engine performance and efficiency, but also has great impacts on particle emissions controls [4,5], which is strictly limited by the recent emission regulations. Therefore, recent researches in GDI sprays highlight the concerns on fuel evaporation and mixing with intake charge.

Flash boiling is the rapid phase transition from liquid to vapor when the liquid is suddenly depressurized into the one below its saturation pressure. This sudden change forces the liquid into a superheated state and leads to a drastic vaporization and atomization. Superheated liquid can be obtained by increasing the liquid temperature and/or decreasing the ambient pressure. Also, there are two ways to express the superheated degree, the temperature difference (ΔT_{SD}) between liquid temperature and saturation temperature, and the ratio of saturation pressure over ambient pressure (P_{sat}/P_{amb}). In the automotive industry, flash boiling is regarded as a potential way to meet the future emissions legislations due to the enhanced atomization quality [6,7]. Furthermore, it has been reported that up to 99% of all injection process during the 'New European Driving Cycle' and 95% during the 'Real Driving Emissions' tests in mid-range cars are in thermodynamic non-equilibrium states below the vapor pressure of gasoline or its light components [8]. Therefore, in-depth understanding on flash boiling of GDI spray is necessary not only because of its potentiality to improve the mixture formation, but also due to its frequent appearance during engine working process. Zhang et al. [9,10]reported that the bubble

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number density was the driving force enhancing the breakup of superheated liquid jet using a transparent slit nozzle. Using a real-size transparent nozzle, Aleiferis et al. [11,12] found that the in-nozzle flow regime was highly sensitive to the fuel temperature, and the increase in superheated degree dramatically improved the primary breakup and atomization. A series of studies on the external spray process under flash boiling conditions have also been carried out with different optical diagnostic techniques [13–16].

One of the noticeable features of flash-boiling spray is the spray collapse when multi-hole GDI injectors are used [13,17–21] in certain conditions. The collapse would cause fuel impingement and the resultant oil dilution, which are believed to be one source for super-knock [22]. Additionally, fuel impingement could also negatively influence the emissions in GDI engines due to the fuel film formation [23]. Yang et al. [18] used the ratio of collapse (maximum spray width over penetration length) to describe the collapse intensity and found that the ratio of collapse increased dramatically with the superheated degree when the ambient pressure was larger than 0.4 bar. Zeng et al. [20] correlated the spray width at the axial distance of 30 mm from the nozzle with superheated degrees, and found that the spray width had an inverse trend with decreasing ratio of ambient pressure over saturation pressure during flash boiling conditions. Mojtabi et al. [19] reported that the increase in superheated degree would enhance the collapse, but further increase in superheated degree by decreasing the ambient pressure may widen the spray. Yang et al. [18] proposed that the spray collapse under flash boiling conditions was the joint effect of the low-pressure core and the jet overlap, and could be enhanced by increasing superheated degree. Aori et al. [24] also viewed the collapse as a result of the low pressure core due to the enclosure of the jets. However, by terming the above explanation as jet-induced spray collapse, Guo et al. [25] reported that the jet-induced low pressure zone could only be used to explain the collapse at elevated ambient pressures because the jet-to-jet interaction is much weaker at low ambient pressures, e.g. the ambient pressure in flash boiling conditions. Further, they attributed the collapse in multi-jet flash-boiling sprays to the vapor condensation and the resultant local pressure drop, termed condensation-induced spray collapse.

Further, the previous studies were mainly emphasizing on the effect of superheated degree on the spray morphology while ambient pressure was viewed as a way to control superheated degree. However, from the aspect of external sprays, the spray behaviors should be different for a given superheated degree, which can be realized with different combinations of liquid temperature and ambient pressure. The flash-boiling spray penetration in the case by decreasing ambient pressure should have a longer penetration rate than that in the case by increasing liquid temperature. In fact, the collapse of multi-jet flash-boiling sprays does not always occur: Under flash boiling conditions but with the ambient pressure of 0.1 bar, the spray expansion rather than collapse has been observed [18,26]. Therefore, it can be concluded that, in addition to the role of superheated degree controlling, ambient pressure should play an important role in determining the spray morphology, but how to affect the morphology has not been well understood.

Thus, the main objective of this work is to investigate the effect of ambient pressure on the morphology of multi-jet flash-boiling sprays and to explain why the flash-boiling jets collapse in some conditions and expand under low ambient pressures. This work could help unveil the collapse mechanism. Direct imaging has been widely used and demonstrated as an effective way to study the spray process [18,19,27–29]. In the present study, the same way was used and it can directly capture the spray morphology of the liquid part. Ambient pressures from 2 kPa to 101.3 kPa was used in order to observe both collapse and expansion under flash boiling conditions and the fuel temperatures from 20 °C to 120 °C.

2. Methodology

2.1. Experimental set-up

Fig. 1 shows the experiment set-up. The experiments were 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 inside the adaptor for the injector mounting, and monitored by the thermocouples inserted into the adaptor. The ambient pressure was achieved by a centrifugal pump (HS452, Agilent), and two pressure gauges (DPG409-025HG and DPG409-002BG, Omega) were used to monitor the ambient pressure. A high-speed camera (SA X2, Photron) was utilized to capture the spray morphology using backlit method. The camera speed was set as 25000 frame/s and the spatial resolution was 0.116 mm/pixel. A five-hole GDI injector was used. The spray footprint is shown in Fig. 2 and the hole diameter (*do*) is 0.18 mm.

2.2. Experiment conditions

n-hexane was used as the injected liquid due to its closer behavior to light components of gasoline [30]. The test conditions are shown in Fig. 3. The fuel temperature (T_{fuel}) ranged from 20 °C to 120 °C, and the absolute ambient pressure (P_{amb}) ranged from 2 kPa to 101.3 kPa. The injection pressure was fixed at 10.0 MPa, the injection duration was 1.5 ms and the ambient temperature was fixed at 20 °C. The data for the saturated pressure against liquid temperature was obtained from National Institute of Standards and Technology (NIST). Table 1 gives the corresponding superheated degrees (ΔT_{SD}), which is the difference between fuel temperature and the saturation temperature (T_{sat}) under the given ambient pressure, as shown in the following equation.

$$\Delta T_{SD} = T_{fuel} - T_{sat}(P_{amb})$$

2.3. Imaging processing

The spray widths were extracted from the captured images using in-house MATLAB codes. The procedure is displayed in Fig. 4. A typical spray image is shown in Fig. 4(a). In Fig. 4(b), the background was subtracted and the contrast of the image was enhanced by mapping the gray values of the raw image to a new image such that 1% of the gray values in the raw image were saturated at low and high intensities (0 and 255, respectively). In Fig. 4(c), the enhanced image was binarized with a fixed threshold value of 0.1. In Fig. 4(d), the edge of the spray was obtained from the binarized image using Sobel approximation to the derivative, where the gradient of the binarized image is maximum. Finally, the spray widths were obtained by counting the pixels of the two sides of the spray and the penetration length was defined as the distance between the injector tip and the furthest position where the spray contour can reach in the binarized image.

It should be noted that there are some uncertainties associated with this technique of spray development measurement. One is caused by the shot-to-shot variations of the fuel spray due to the inherent feature of transient fuel spray process. Another is in relation to capturing the spray edge. The turbulent and irregular edge is relatively diluted and this uncertainty may be 1–2 pixels, which correspond to physical length of 0.116–0.232 mm. However, it should be significantly reduced by the data averaging. To guarantee the accuracy of the results, six repeated tests were conducted under each experiment condition and the averaged spray widths are used.

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