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Breakup of fuel sprays under cavitating and flash boiling conditions

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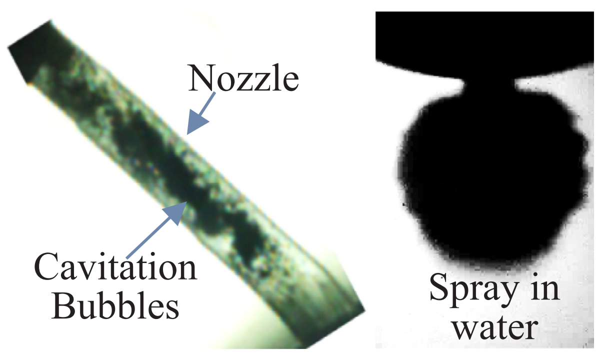
HIGHLIGHTS

- Bubbles are very small with diameter less than 9 µm after exiting nozzle.
- Hot fuel temperature boosts atomization for steady stage but not for end stage.
- Strong disturbance causes significant radial expansion of cold diesel spray.
- Strong cavitation causes considerable radial propagation of hot gasoline spray.

GRAPHICAL ABSTRACT

A large number of cavitation bubbles are generated in the nozzle and breakup into very small ones with diameter of less than 9 µm after exiting the nozzle.



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ABSTRACT

Cavitation and flash boiling are important phenomena for fuel sprays of IC engines and can significantly boost spray breakup by introducing vapour bubbles, enhancing combustion, energy conversion efficiency and reducing emissions. In this study, attempts were made to capture the bubbles either due to cavitation or flash boiling under cavitating and flash boiling conditions by injecting fuels into liquid. The differences in density and refraction between water and vapour bubbles enable the bubbles to be visualized. The evolution of vapour bubbles in transparent nozzle was investigated. The direct visualization of vapour bubbles was carried out with the employment of highly resolved microscope and ultrahigh-speed camera. The spray morphology and primary breakup characteristics in the near field and macroscopic characteristics in the far field were also investigated. It was found that vapour bubbles due to cavitation or flash boiling were very small with the diameter of less than 9 µm after the primary breakup at the nozzle outlet. A tree-shaped spray tip with significant radial propagation was observed for diesel and isooctane fuels but not for dieseline (75% gasoline and 25% diesel) under liquid ambient condition. The increase of fuel temperature generally enhanced the spray atomization for the steady stage but surprisingly suppressed the primary breakup during the initial stage and end stage when the spray velocity is low. In addition, the strong disturbance of flow led to considerable radial propagation for cold diesel spray (20 °C) while the strong cavitation or flipping flow resulted in the significant radial expansion for hot gasoline spray (140 °C).

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1. Introduction

Spray breakup process is of great importance for fuel mixture preparation, mass distribution, combustion process and heat release, significantly affecting the engine performance and emissions [1–3]. Both fuel injection and spray breakup processes are influenced by various factors [2–6]. The well-known cavitation is one important factor, and the occurrence of flash boiling is another one when recently gasoline-like fuels, for instance, dieseline (the mixture of gasoline and diesel) are likely to be used. Sound understanding of the fundamental principles of the two phenomena and their effects on spray behaviour and fuel mixture preparation is beneficial to spray modelling and combustion control. How to capture the spray characteristics caused by the two factors and studying the corresponding impact on spray breakup therefore become hot topics.

Cavitation is featured by the formation of cavities or bubbles when the liquid fuel experiences an abrupt pressure reduction [7]. The formation of the bubbles can lead to the detachment of fuel from the wall surface when going through the nozzle hole [8,9]. The atomization and spray breakup are favourably enhanced by the appearance of bubbles however the fuel flow rate and fuel mass delivered are adversely affected by these bubbles [2,9–12]. The effects of cavitation on fuel flow rate can be studied by identifying the choke point through the variation of injection pressure with the employment of long tube measuring instrument or other measuring techniques [6,10]. The bubbles produced due to cavitation can be visualized by injecting fuel into liquid [6,10]. The differences of refractive index and density between ambient liquid and the vapour phase of fuel enable the visualization of bubbles. In [10], it was reported that the bubbles are detected before the effect of cavitation on mass flow rate becomes detectable. The results in [10] also showed that the cone angle increases quickly when cavitation initiates, and there is a hysteresis for the appearance of cavitation between increasing and decreasing back pressure. However, the low frame rate of the employed camera and laser only gave limited information because the development of spray cannot be captured in high temporal resolution. Recently, In [13], microscopic imaging technique was employed to investigate the cavitation behaviour and reported that some vapour bubbles due to cavitation existed in the nozzle during the initial stage. In [14,15] similar technique was employed and it was reported that large number of vapour bubbles appeared during the initial stage and end stage. However, the breakup process of these vapour bubbles was not studied in either of these studies. In [16,17], the effects of cavitation on the spray breakup are studied, and it is found that cavitation leads to large cone angle and well-dispersed spray.

Flash boiling is another phenomenon that can introduce a large number of vapour bubbles. Superheating liquid fuel leads to the intense nucleation and growth of bubbles. The expansion and subsequent explosion of vapour bubbles occur when the pressurized bubbly liquid is going through a quick pressure reduction, resulting in the instant disintegration of spray [9,18]. Flash boiling shows some similarities to the micro-explosion since both relate to the generation and growth of vapour bubbles in the liquid due to heat transfer. However, the micro-explosion is mainly caused by the large differences of vaporization and heat transfer between different components, especially for emulsified fuels [19–21]. For gasoline, flash boiling is more frequently reported and micro- explosion.

Recently, dieseline (the mixture of ultra-low sulphur diesel and commercial gasoline) shows great potential to reduce the soot significantly with no penalty of NOx emission [22,23]. This is because the strong evaporation and high auto-ignition temperature of gasoline allow more time for mixture preparation before the initiation of combustion, resulting in less concentrated fuel area. It was reported in [22] that a blending of 75% gasoline in diesel could decrease soot by 90%. The existence of gasoline in diesel can cause the occurrence of flash boiling when the engine is hot due to the high vapour pressure of some highly evaporative composition in gasoline. The primary breakup of dieseline spray in the near field is expected to be different from that of gasoline or diesel. In [9,24], the primary breakup of gasoline-like fuel spray under flash boiling in ambient air condition was studied. It was observed that flash boiling significantly boosted the atomization and radial expansion of plume. In [25], it was pointed out flash boiling greatly boosts the dispersion for the injection end-stage when the effective injection pressure is low. The spray collapse of multiple-spray was studied in [26] by using high-speed imaging and microscopic imaging techniques and reported that flash boiling boosted the spray collapse at the inside through jet-air interaction.

Although some studies on visualization of spray under cavitating or flash boiling conditions in ambient air condition have been done, the studies on spray primary breakup in the near field by injecting fuels into liquid condition under cavitating or flash boiling conditions are very limited. The understanding of the fundamental regimes for the initiation of the vapour bubbles in real sprays due to the two phenomena is still insufficient. In addition, how the vapour bubbles affect the spray dispersion and propagation in the dense spray is unknown. In this study, attempts are made to investigate the breakup of bubbles produced either due to cavitation or flash boiling by injecting fuel into liquid water under different fuel temperature conditions. The vapour bubbles are to be visualized by injecting fuel into water due to the difference of density and refractive index. The effects of very dense ambient substance on spray behaviour can also be investigated by employing water ambient condition. The evolution of vapour bubbles in the nozzle is probed by employing a transparent nozzle. The primary breakup characteristics are also investigated with the employment of ultrahigh speed and ultrahigh resolution imaging technique. This research method can give useful information for the effects of vapour bubbles on the primary breakup process from a very different perspective.

2. Experimental setup

The test system includes a light source, a lens, a water container, oil bath system, a long distance microscope and an ultra-high speed camera (Fig. 1). The light source is a 500-Watt xenon lamp, and the lens is used to focus the light to the injector tip so that the plume can be sufficiently illuminated for ultra-high speed imaging tests. Fuel is injected into water to try to capture the air bubbles and vapour bubbles either due to cavitation or flash boiling. The oil bath method is employed to heat the injector and the liquid fuel inside. A heating system (not shown in the figure) is used to heat the oil and maintain the oil temperature. The injector tip is protruded into the water only for 2 mm to minimize the cooling effect of water. A thermocouple is fixed at the fuel returning outlet to monitor the fuel temperature during the injection process and another thermocouple is employed to monitor the temperature of heating oil. The comparison of the two measured temperature shows a small variation within the range of 6 deg C when the

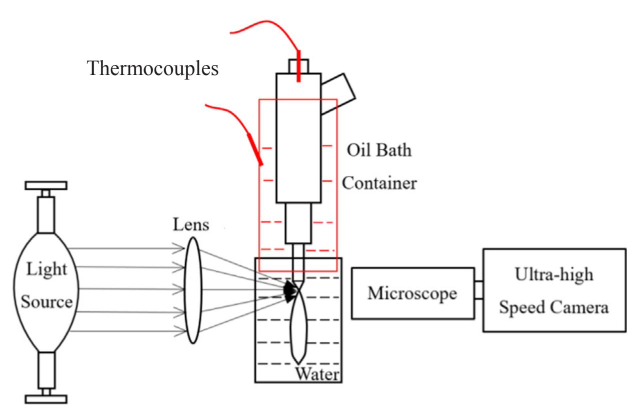

Fig. 1. Experimental setup.