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Microscopic study on diesel spray under cavitating conditions by injecting fuel into water

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HIGHLIGHTS

- Bubbles due to cavitation are very small after exiting nozzle.
- Bubbles in nozzle are prolonged into thread before collapse.
- Increasing fuel temperature deteriorates the spray breakup for end stage.

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ABSTRACT

Cavitation is a phenomenon which can significantly enhance spray breakup and affect the mixture preparation by introducing air or vapour bubbles. Attempts were made to capture the bubbles due to cavitation by injecting fuel into water based on the difference of density and refraction between water and vapour bubbles apart from the attempts to directly visualize vapour bubbles in an enlarged transparent nozzle. Tests were carried out with the employment of highly resolved microscope and ultra-high speed camera. The spray morphology and primary breakup characteristics in the near field were also investigated. It was found that irregularly shaped bubbles due to cavitation under low pressure can be observed in the nozzle. The increase of injection pressure (thereby increase of velocity) could significantly prolong the bubbles. At the nozzle outlet, the significant variation of pressure prolonged air bubbles into "thread" before collapsing. Vapour bubbles after exiting the injector nozzle were very small and the resolution of 3 μm/pixel was insufficient to capture the bubbles through direct visualization. A tree-shaped spray tip with significant radial propagation was observed. The sucking-in of water when the needle started to lift, the flow regime and the strong water resistance were closely related to the formation of tree-shaped spray tip. In addition, although the increase of fuel temperature generally enhanced the atomization of spray, the primary breakup of spray during the initial stage and end stage when the spray velocity was low surprisingly deteriorated for hot fuel.

1. Introduction

Transport of goods and people is mainly powered by internal combustion (IC) engine, consuming up to 20% of primary energy and producing 23% CO_2 emission [1,2]. Up to 380 million commercial vehicles and more than 1.2 billion passenger cars driven by the by internal combustion engine consumes around 60% liquid fuel from petroleum [2]. Decrease of fuel consumption and emissions therefore becomes increasingly important either through new technologies or application of new fuels [3,4]. However, the alternatives would not make up approximately 10% of the energy required for IC engine by 2040 due to growth constraint [2]. Fuel injection and spray breakup characteristics which dictate the fuel mixture preparation, fuel mass distribution and heat release rate significantly are seen as important factors that can improve diesel engine performance and emissions [4,5]. Both fuel injection and spray breakup processes are influenced by various factors and the well-known cavitation is one of them [6,7]. The study on the behaviour of bubbles due to cavitation is, therefore, a key point for the study on mass flow rate control, the mechanism of spray primary breakup and its corresponding modelling [5,8,9]. Investigation of the cavitation characteristics and the corresponding impact on spray primary breakup is a hot topic.

Cavitation is featured by the formation of cavities or bubbles when the liquid fuel experiences an abrupt pressure change, and this

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generally leads to the existence of multi-phase flow and strong interaction between different phases [10,11]. The formation and collapse of air bubbles because of cavitation lead to local pressure shock and significant local temperature increase, exerting profound effects on the periphery liquid behaviour and breakup [12,13]. Although the finish of the injector nozzle wall may be corroded due to the explosion of the cavitation bubbles, the atomization and spray breakup are favourably enhanced by the appearance of bubbles. The bubbles produced due to cavitation can be visualized by injecting fuel into liquid [14]. The differences of refractive index and density between ambient liquid and the vapour phase of fuel enable the visualization of bubbles [14]. In [14], it was reported that the bubbles were observed before the effect of cavitation on the mass flow rate was detected. The results in [14] 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 gave limited information because the development of spray cannot be captured in high temporal resolution. In [15,16], the effects of cavitation on the primary breakup were studied and it was found that cavitation leads to large cone angle and well-dispersed spray. The improved spray dispersion significantly decreases the potential impingement [17–19]. The corresponding emissions can also be reduced, especially the soot [20,21]. In [22,23], a transparent nozzle was employed to visualize the vapour bubbles for diesel sprays. Cavitation was classified into string cavitation, film cavitation, cloud cavitation and super cavitation and bubbles with a wide range of sizes were observed in the nozzle. In [24], a similar technique was employed and it was reported that the throttling effect generated a large number of cavitation bubbles between needle and needle seat. Vapour bubbles due to cavitation appear quickly during the initial injection stage are very dynamic due to the continuous opening of the needle.

Vapour bubbles collapse instantly just at the outlet of the nozzle and considerably boost the spray primary breakup, combustion and emission reduction. Yu et al. [25] studied the effect of cavitation (by varying injection pressure) and operation modes on the spray characteristics, combustion characteristics and emissions by using various fuels. It was reported that stronger cavitation led to lower soot emission when gasoline was used. In [26], it was also pointed out that cavitation can enhance plume breakup and evaporation, improving the subsequent combustion and soot emissions. Yao et al. [27] investigated the influence of nozzle geometry on combustion and emissions. It was reported that stronger cavitation and smaller nozzle caused smaller droplets, significantly reducing the soot emission and considerably improving the release rate of heat and chemical energy conversion.

Although the existence of cavitation can significantly boost the spray atomization, the formation of the bubbles can lead to the undesirable detachment of fuel from the wall surface when going through the nozzle hole [14,28,29]. The fuel flow rate and fuel mass delivered are correspondingly adversely affected by these bubbles [14]. Strong cavitation can reduce the fuel mass and make fuel injection and spray breakup somewhat unpredictable. The effects of cavitation on fuel flow rate can be studied by identifying the choke point with the employment of long tube measuring instrument [14]. Before the appearance of the choking point, the mass flow rate increases linearly with the rise of the root square of the injection pressure difference and the mass flow rate shows a decrease after the choke point appears [28,29]. Consequently, the effects of cavitation on fuel mass delivered to the cylinder for practical application should be considered when controlling the engine work output [30]. The application of nozzle hole convergence is a good way to suppress the inception of cavitation and to control the fuel mass flow rate [15,31,32].

The aforementioned studies mainly focused on the spray characteristics under cavitating conditions by injecting fuel into ambient air condition, however, the studies on spray primary breakup in the near field by injecting fuel into liquid ambient condition under cavitating conditions are very limited. The spray with cavitation bubbles is expected to present different behaviour compared with the non-cavitating ones under liquid ambient conditions. The large vapour bubbles are expected to collapse after exiting the nozzle due to the lack of wall constraint and pressure variation. To what extent can the vapour bubbles collapse is still unknown. During the explosion process, multiple phases, namely liquid fuel, diesel vapour and ambient air exist simultaneously. Strong interaction among these phases is expected and can significantly change the spray behaviour. The understanding of how the collapse of bubbles and the interaction among phases boost the primary breakup at the very outlet of the nozzle is still very limited. In addition, the injection process is highly dynamic and the microscopic characteristics and properties of the spray are consistently changing. The states, shapes, sizes and characteristics of the vapour bubbles during and after exiting the nozzle have not been investigated.

In this study, to answer these questions, attempts were made to visualize the bubbles produced due to cavitation by injecting fuel into liquid water under different fuel temperature conditions. This cutting-edge research method enables the spray primary breakup to be investigated from a quite different perspective. The primary breakup characteristics are also investigated through the employment of imaging technique with ultrahigh speed and ultrahigh resolution. To the best knowledge of the authors, this is the first time to study the microscopic characteristics of vapour bubbles under liquid ambient condition by employing ultrahigh speed imaging technique which can capture the very dynamics of spray. Then, the behaviour and characteristics of bubbles in the transparent nozzle is investigated on the microscopic level to provide more insights for the effects of cavitation on the spray primary breakup process. The deforming process of these bubbles in the transparent nozzle is finally studied to probe the velocity field and pressure field which are closely related to the appearance of cavitation. This investigation gives innovative insights into the flow regimes in the nozzle, the primary breakup characteristics of sprays, modelling for spray and combustion, emission control and design of the injection system.

2. Experimental setup

The test system includes a light source, a lens, a water container, an oil bath system, a long distance microscope and an ultra-high speed camera (Fig. 1(a)). 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 bubbles due to cavitation. 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. The temperature of the heating oil is treated as the fuel temperature although a small difference between real fuel temperature and oil temperature may be expected. During the test, the injection rate is set to one injection per minute so that the fuel temperature can be maintained at the desired one.

Two injectors, namely a real sized modern diesel injector and a transparent enlarged in-house made injector (Fig. 1(b)) are employed in this study. The real sized injector is a single hole cylindrical diesel injector with the diameter of 0.16 mm. It is used to study the primary breakup of spray after exiting the nozzle under air ambient condition and water ambient condition. However, the transparent injector with the hole diameter of 2 mm and length of 6 mm is made from plexiglass and mainly used to study the morphology of bubbles due to cavitation inside of nozzle hole rather than the outside. The needle seals the single hole and the mini-sac by gravity. The energization of this injector is controlled by an electric-magnetic valve and the lift of needle is regulated through a lift adjusting bolt. The lift control accuracy of the adjusting bolt is 4 μm per degree which gives great freedom to study the effects of throttling effect on the injection characteristics. This