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A contribution to the understanding of cavitation effects on droplet formation through a quantitative observation on breakup of liquid jet

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ABSTRACT

Cavitation is an effective way to enhance fuel jet breakup and evaporation in order to improve the quality of fuel spray in the combustion chambers and hence mitigate engines exhausts emissions without compromising the performance and fuel economy. However, what happened inside the nozzle and how it affects the breakup and atomization characteristics of the emerged liquid jet is still unknown. This study was conducted to quantitatively investigate the macroscopic characteristics of the cavitation-driven atomization through a two dimensional transparent nozzle, which was designed to trigger more cavitation on one side than the other. The cavitation occurrence inside the nozzle and the spray near the nozzle exit were directly imaged and recorded by a high-speed visualization system. As a result, the following conclusions are obtained. (1) The liquid jet breakup characteristics are strongly affected by the cavitation extent inside nozzle and better atomization characteristics are obtained on the side where cavitation is more promoted. (2) Supercavitation regime, where bubbles are swept outside the nozzle exit, is an optimal point at which the nozzle internal flow structure and the atomization characteristics of resulting jet changes significantly. These results provide insightful information for understanding the breakup mechanism of a cavitation-driven liquid jet and modeling a supercavitation spray.

Introduction

Liquid jet atomization, which is the transformation of a liquid bulk into a spray of small droplets in a surrounding gaseous medium, is the basic requirement for combustion chambers of many propulsion-related applications such as aircraft propulsion systems, after-burners in jet engines, gas turbine combustors, ramjet engines, liquid rocket engines, diesel engines, spark ignition engines and industrial furnaces [1–3]. The rapid advancements in engine combustion technology have prompted the need for high-pressure atomization in order to inject the fuel into the combustion chamber with high momentum and to fulfill the rigorous exhaust gas laws, otherwise, partial combustion or misfire may occur, and soot emissions may become severe. Thus, to produce well-atomized fuel sprays, spray devices (known as atomizers or injectors) with small discharge orifice diameters

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(diameter ≈ 0.1 mm and length ≈ 1 mm) and very high injection pressures (up to 2000 bar) are used [4] as shown in Fig. 1. The nozzle flow under these conditions, where a quick and abrupt change in the flow direction, generates low static pressure of the liquid at the entrance of the hole till the local tension exceeds the tensile strength of the liquid, which is believed to induce cavitation in the form of bubbles [5]. These bubbles being convected by the flow will collapse in regions of high pressure. This process of smooth growth and violent collapse of bubbles in a flowing liquid is called cavitation or precisely hydrodynamic cavitation [6].

The formation of cavitation in atomizers is crucial to the breakup of liquid jets and has been a topic of research for quite some time. Early experiments of Bergwerk [7], using simplified large-scale and real-size single-hole acrylic nozzles, have showed that cavitation, resulting from an abrupt acceleration of the liquid flow as it enters the nozzle holes, had a dramatic influence on the appearance of the liquid jet. It was also demonstrated that the discharge coefficient of the nozzle is mainly dependent on the spread of cavitation within the nozzle. Bergwerk made an important hypothesis that cavitation bubbles, which are formed in the cavitation region and swept along with the flow, influence the disintegration process of the liquid jet. Nurick [8] has developed a phenomenological model to explain the behavior of the coefficient of discharge within a cavitating nozzle, it was concluded that besides the beneficial effect of cavitation on improving the atomization of the liquid jet, it came at the expense of hydraulic resistance, which is described by a reduction in the discharge coefficient. Reitz and Bracco [9] studied different atomization mechanisms with the incorporation of cavitation phenomena. They realized when cavitation occurs inside the nozzle, a wider spray cone angle is produced. Arai et al. [10] and later Hiroyasu et al. [11,12] using transparent large-scale nozzles to observe the formation of cavitation structures at low speed flow; they observed a very strong connection between the nozzle flow and the resulting spray. It was also found that as soon as the cavitation takes place in the nozzle, the spray cone angle increases considerably and the jet breakup length becomes short. Based on these measurements, an extended jet stability curve in the atomization regime was proposed as presented in Fig. 2.

Over the last few years, studies have shown that the geometric-induced cavitation phenomenon, which occurs when the pressure reduction is caused by an abrupt change in

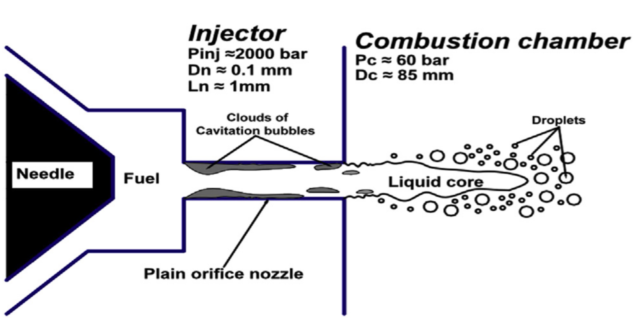

Fig. 1 – Sketch of the atomization processes of liquid fuel from a Diesel injector.

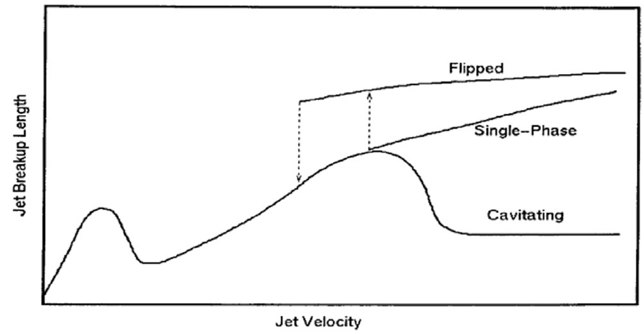

Fig. 2 – Breakup length stability curve [21].

the geometry of the flow passage behind the sharp corners, will modify the internal flow structure of the nozzle hole and greatly affects the spray characteristics [13–19]. As a consequence, cavitation can lead to changes in engine performance, pollutant emissions and combustion efficiency [20].

Despite its significance, the details of cavitation and bubbles formation inside internal nozzle flow and the downstream behavior of these cavitation structures still remain a major challenge in understanding and studying the mechanisms of atomizing a liquid jet. In the present study, efforts have been placed on developing a two-dimensional optically transparent nozzle to simultaneously and quantitatively observe the internal flow inside nozzle and the spray characteristics near the nozzle exit using high-speed flow visualization system.

Experimental setup

Experimental apparatus

Fig. 3 shows the schematics of the experimental apparatus. Filtered tap water at room temperature (T = 293 K) is pressurized in a buffer tank by a plunger pump to be discharged through a two dimensional nozzle into the ambient air, then gravitate into a collection tank from whence it is returned to the buffer tank to ensure continuous injection with a constant pressure supply throughout the injection process. Liquid flow rate is measured using a flow meter. The rectangular nozzle illustrated in Fig. 4 was made by the transparent acrylic resin to simplify the optical observation. The width Wn, length Ln and thickness of the nozzle are about 5, 10 and 2 mm, respectively. The left wall of the nozzle is slightly positioned at low level compared to the right wall (about 1 mm) in order to create non-symmetric cavitation levels along the walls of the nozzle. It is assumed that flow separation occurs at the sharp-edged inlet of the nozzle, so combining a mass continuity balance and a Bernoulli analysis between separation point 1 and 2 (Fig. 4 (c)), it can be demonstrated that the local pressure at the separation point 2 is predicted to be lower than at point 1. Therefore, by increasing the injection pressure, the cavitation is predicted to appear along the left wall at low injection pressures compared to the right wall.

The pre-nozzle width was selected to be sufficiently large to minimize the liquid velocity and flow disturbances, whilst