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Visual experiment of transient cavitating flow characteristics in the real-size diesel injector nozzle☆

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ABSTRACT

Cavitating flow inside diesel injector nozzles affects subsequent atomization behaviors and then spray characteristics which is decisive for diesel engine performance and pollutant formation. In this paper, particular attention was focused on the transient flow characteristics in the real-size diesel nozzle. An experimental study under different pressures was conducted to analyze the evolution of cavitation inside diesel nozzle, and it was found that higher injection pressure leads to earlier cavitation inception. The bubble "suction" from orifice exit at the end of injection and the bubble "discharge" at the initial stage of the next injection were observed as well. Moreover two types of "string cavitation" were observed and the "string cavitation" as a special cavitation phenomenon which considerably boost the spray angle was investigated in details. It was found that the occurrence of "string cavitation" has a strong relationship with the location of needle, the injection pressure, and the shape of sac. Furthermore the effects of these three factors on the occurrence regularity of the "string cavitation" were also investigated.

1. Introduction

The requirements on the diesel fuel injection system have been higher and higher with the proposing of new combustion modes, such as homogeneous charge compression ignition (HCCI) and low temperature combustion (LTC) to satisfy both the customer demands and the legislation requirements concerning pollutant emissions. The technology development trend of higher injection pressure and smaller nozzle hole diameter makes the researches on the two-phase cavitating flow characteristics in the orifice and its influence on spray process increasingly important. Especially the high speed cavitating flow in the real-size injector nozzle, which occurs with a fraction of a millimeter in diameter and only a few milliseconds of in duration, is strongly transient and highly turbulent, making the cavitating flow difficult for the experimental study. As a result, the complicated cavitating flow remains not clear enough, impeding better understanding of the spray atomization process and hole-to-hole spray variations under high injection pressure, which is important for the design of the next generation engines.

To visually explore the cavitation distribution inside the nozzle and reveal the mechanism of the cavitation inception, development and collapse, Ganippa et al. (2001), Sou (2007), Suh et al. (2008), Lee et al. (2008) and Raditya Hendra Pratama1 et al. (2014) [1–6] simplified the nozzle structure based on the real diesel one, where the two-dimensional and the simplified pressure chamber structure nozzles were widely used. The characteristics of cavitation in the orifice and its effects on the spray were deeply and systematically studied, but the limitations of the simplified nozzle make the measurement results incapable of well being used for the real situations, especially transient characteristics considering of needle movement and sometimes even contradictory. Soteriou C (1995), Arcoumanis (2000), Gavaises (2002), Andrew (2008), Andriotis A (2008), et al. [7–11] used the scaled-up model of the real injector nozzle to experimentally study the effects of the needle motion on the transient characteristics of the nozzle two-phase cavitating flow, while the relevance of cavitating flow in the scaled-up nozzle and real-size nozzle and scale effects have not been well revealed. Thus, direct experiment of cavitating flow in real-size nozzles has attracted much more attention in recent years. Chaves (1995), Badock (1999), Arcoumanis (2000), Lockett (2013), G. J. Jiang (2015) et al. [12–16] made some attempts on the visualization of cavitating flow in real-size transparent nozzles, but the experimental data are very limited. The flow velocity of fuel will be very high under the high injection pressure with common rail injection system, and the Reynolds number (Re) can reach to the magnitude of 50,000. Then the opening and closing of the needle rapid in milliseconds will have great influence on the transient characteristics of the cavitating flow,

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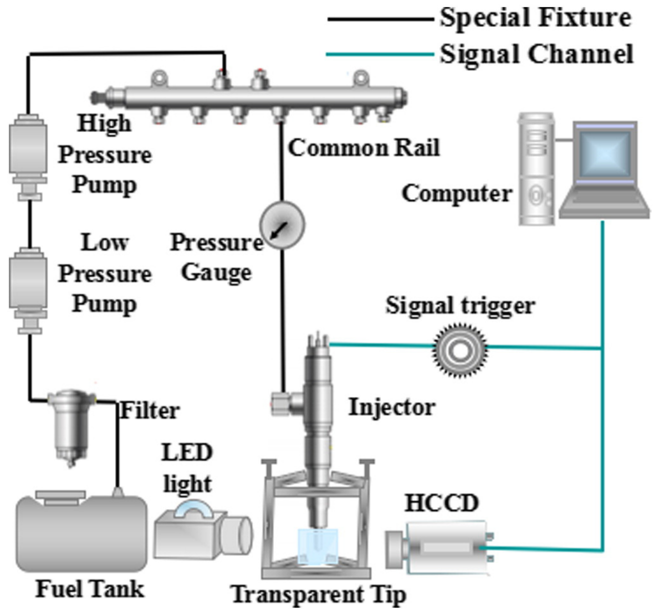

Fig. 1. Schematic of the experimental visualization system for internal nozzle flow and spray.

especially occurrence of string cavitation during this period may largely vary the nozzle flow characteristics and then affect the subsequent spray. Actually, till now the geometry-induced cavitation in nozzles has been studied quite profoundly and can be effectively controlled and even be avoided, such as the nozzle with round corner of the orifice and K-factor of the nozzle can be over 1 meaning convergent orifice. However the string cavitation induced by vortex flow in multi-hole nozzles cannot be avoided and then acquirement of its occurrence regularity during the period of needle moving will be important for understanding the hole-to-hole spray variation.

In this paper, visualization experiments on cavitating flow of the real-size injector nozzle under different injection pressure (30, 40, 50, 70, 90, and 110 MPa) with different injection duration were carried out. The effects of the needle motion on cavitation development and occurrence of string cavitation were analyzed.

2. Experimental equipment and methodology

The visualization experimental research on the cavitating flow in real-size optical nozzles under high fuel injection pressure is still in its infancy, and this paper has carried out the beneficial exploration in this aspect. The visualization injection system developed for the current work consists of two parts: the fuel injection system and the imaging acquisition system, as shown in Fig. 1. The fuel injection system is composed of a control system and a common rail injection system (CR-9000). The imaging acquisition system mainly includes a CCD Camera (FASTCAM SA-Z) mounted with a long distance microscope (QM-1, QUESTAR) and a high-power LED light as a lighting source. During the experiment, the capturing speed was set to 100,000 frames per second and the obtained images have a resolution of 640 × 280 pixels.

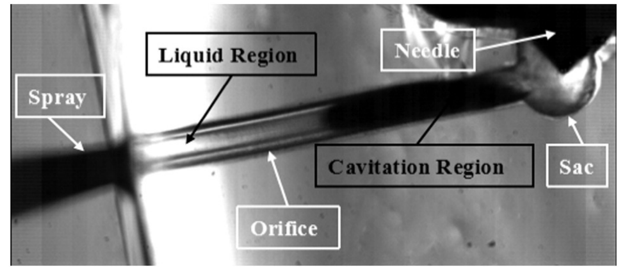

Fig. 3. The typical image of cavitating flow inside the tested nozzle.

The optical nozzle is the critical component in this experiment for achieving high quality images of cavitating flow inside the nozzle. The ADL-3 Solenoid valve injector nozzle tip was cut away and then replaced by an optical tip made by Polycarbonate. The shock resistances of polycarbonate are 250 times higher than that of traditional glass, and 30 times higher than that of acrylic plastic glazing. Moreover, the optical nozzles made up of polycarbonate can be operated under the injection pressure as high as 120 MPa. The optical performance of the polycarbonate can reach as high as the same level of the glass (86%), which is much higher than that of acrylic plastic glazing. Two different optical nozzle tips are used in this experiment.

The red dash line in Fig. 2 (a) depicts the position of the interface of the metal nozzle and the optical tip where is below the seat line [17]. Fig. 2(b), (c), (d), (e) (f), and (g) shows the original injector nozzle, cut nozzle without nozzle tip, optical nozzle tip with one orifice and sac, optical nozzle tip with two orifices and mini sac, optical nozzle tip with two orifices and sac, and the assembled injector nozzle, respectively. The original nozzle and the optical tip are connected by a fixture which ensures that the interface between the metal nozzle and the optical tip has no fuel leakage. In terms of the main geometric parameters of the tested optical nozzle, the diameter D of the orifice is 0.35 mm, the inclination angle φ of the orifice is 70°, and the length–diameter ratio L/D is 10.

3. Results and discussion

The typical images of the two-phase cavitating flow inside nozzles obtained from the experiments are shown in Fig. 3. The liquid phase

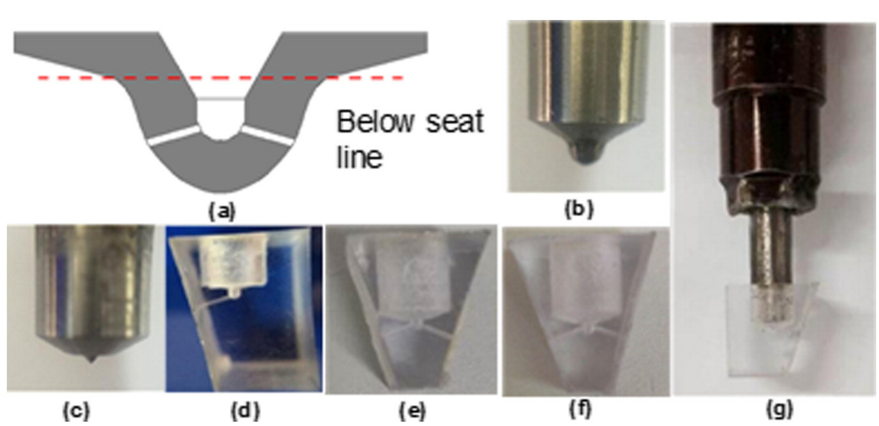

Fig. 2. Common-rail injector nozzle and real-size optical nozzle tip: (a) the incised position, (b) original injector nozzle, (c) cut injector nozzle without nozzle tip, (d) & (e) & (f) transparent nozzle tip and (g) the assembled injector nozzle.