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Quantitative analysis of the minor deviations in nozzle internal geometry effect on the cavitating flow

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ABSTRACT

Cavitation is an important phenomenon occurred inside the nozzle hole and has a significant influence on the internal and jet flow. The quality of atomization for the liquid engines is depended on the status of liquid flow, so that the complicated cavitating flow inside discharge nozzles has long been concentrated on. Cavitation is sensitive to geometric structure, operation condition and liquid properties. At present, achieving high precision in mass manufacturing and measurement of nozzle orifices on micrometer scales is still very difficult, and minor deviations in nozzle internal geometry caused by manufacturing errors or abrasion are inevitable. These deviations will cause an irregular and more complicated internal morphology of the nozzle structure, so that the circumstances of cavitation and flow field are also diversiform, and thus affect the quality of fuel atomization and engine performance. In this paper, the diameter error, conicality and incline that embody common deviations in nozzle geometry are experimentally investigated using transparent nozzles. The geometry dimensions of tested nozzles were ultra-precise measured by self-developed microhole-measuring system based on a twin FBG (fiber Bragg grating) probe. The internal flows of nozzles were visualized and their hydraulic characterization analyzed. The results indicate that very small differences in geometric structure still have consequences for the obviously different characteristics of cavitating flow.

1. Introduction

The performance and efficiency of liquid engines are strongly depended on fuel atomization quality, which, in turn, is strongly related to injector characteristics. The discharge orifice of atomizer plays an extremely important role in spray process. With the rapid development of high-precision manufacturing and measurement technologies, the diameter of orifice in liquid engines has been engineered to a few hundreds, and even dozens, of micrometers to improve atomization efficiency. Recently, many sophisticated technologies have been developed to achieve high-accuracy measurement of micro-holes with a high ratio of depth to diameter [1–4]. The objective of nozzle measurement is to acquire highly accurate data on orifice internal geometry to improve processing and manufacturing technology; these data also facilitate a comprehensive analysis of the performance of fuel spray as influenced by nozzle geometry. The accuracy of the latest measurement technology can reach the nanoscale level [3], so it is feasible to measure nozzles and obtain comprehensive information on nozzle internal geometry in order to facilitate the detection of minor deviations.

Current manufacturing technology makes it difficult to produce ideal smooth and uniform nozzles in production quantities. Usually there are dozens, and even hundreds, of orifices in one injector (such as impinging jets atomizer in liquid propulsion systems), and many of these nozzle holes are inconsistent and diverse in terms of the specific nature of their deviations. From an ultraprecise measurement of an aero-engine nozzle sample, it can be found that the internal geometric morphology of a nozzle hole is extremely complicated. In a single hole, it is difficult to guarantee the geometric consistency and equal size of the diameter and position of the inlet, outlet, and middle area. The forms of errors are diverse, e.g., errors of diameter and radius of curvature of the nozzle entrance; conical, inclined, and bended shape; internal wall roughness, etc. However, in practice, deviation of more than one type might exist in a single nozzle orifice, and it is prudent to investigate the influence of each type of minor deviation individually and independently in order to comprehensively research the effect of nozzle internal geometry on the spray process. Furthermore, the investigation results of the influence rule of minor deviations on the characteristic of cavitating flow will provide the standards and references for the high-precision manufacture of nozzle orifice, the sensitivity of each deviation and the results of quantitative analysis can be used in nozzle design to control the extent and condition of the cavitation.

Cavitation describes the process of the growth and collapse of the

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vapor phase in continuous flow when the local pressure drops below the saturated vapor pressure at constant temperature; this phenomenon occurs around the nozzle orifice and has a profound impact on the internal flow, and therefore has a great effect on spray characteristics [5–12]. Cavitation phenomena will induce a large disturbance in the fluid at the outlet of the orifice that may accelerate the spray breakup, and could also increase spray angle, shorten fuel jet breakup length, and decrease the magnitude of droplets, resulting in better spray characteristics [13–16,20]. Though cavitation is expected to be beneficial for spray breakup, it may have undesirable effects on fuel-injection performance. For example, experiments have revealed that, under certain conditions, cavitation can result in the formation of hydraulic flip flow, which is not beneficial for atomization. Moreover, undesirable effects of cavitation are associated with flow instabilities, excessive noise generation, and erosion, which cause damage to nozzle [17–19].

Cavitation is extremely sensitive to nozzle geometric morphology, fluid properties, and operating conditions, all of which have been widely investigated by many scholars for a long time using numerical and experimental methods. Payri et al. [20–22] employed experimental measurements and numerical calculations to characterize the internal flow in cylindrical and converged conical nozzles. They found that the converged conical nozzle did not present cavitation effects, while under the same conditions in a cylindrical nozzle cavitation was detected. Suh et al. [14] and He et al. [23] investigated internal flow under the influence of different length-to-diameter (L/D) ratios. The results indicate that, with a larger L/D ratio, the internal flow requires higher injection pressure to induce cavitation. Li et al. [24] and Echouchene et al. [25] studied the effects of nozzle wall roughness on cavitating flow and concluded that, for low injection pressure, increasing the roughness height will promote cavitating flow, but for large injection pressure the effect was relatively small. The radius of curvature of the nozzle entrance was researched by Som et al. [26] and He et al. [27], who concluded that with decreasing curvature radius, the pressure at the nozzle entrance decreases and dramatically accelerates the flow to start cavitating. De Giorgi [28] conducted experiments to investigate the influence of temperature on the flow regime transition and found that temperature influenced both the cavitation intensity and the cavitation number. Vijayakumar et al. [29] investigated the effect of the properties of the fluid on cavitating flow by numerical simulations of nozzle flow characteristics for diethyl and dimethyl ether and diesel fuel. Wang et al. [30] have particularly analyzed the pressure fluctuations, cavitation content of nozzle hole and the mean dynamic behavior of local bubbles through a combination of experimental measurements and numerical modeling with a two fluid approach. Asnaghi et al. [31] has improved the cavitation mass transfer source term modeling for transport equation based models by considering local flow properties. In brief, many aspects of factors that may have impact on cavitation have been fully investigated by experimental and numerical methods.

From this brief review, it is found that cavitation phenomena occurring inside the injector nozzle has been considered an important factor in fuel atomization. Injection pressure, liquid properties, and geometric features that may impact cavitation have been fully investigated by experimental and numerical methods. However, due to the complexity of fluid dynamics, extreme miniaturization of the nozzle size, and lack of high-precision measuring and manufacturing technology, analysis of the effect of manufacturing errors on internal flow is still in a preliminary stage. Most of the previous simulations and experiments usually assumed that the internal wall of the nozzle orifice is smooth, and thus the minor deviations in geometrical morphology inside the nozzle hole caused by manufacturing errors or abrasion during operation have been completely ignored. In fact, these deviations are usually unavoidable and are hard to detect during the quantity production, and these deviations are bound to have a significant impact on fuel atomization in the process of practical application of engine injector nozzles. Diameter errors, conicality and incline are the most common minor deviations in nozzle geometry, and thus they have been the focus of this paper.

The main objective of this paper is to investigate the influence regularity and sensitivity of minor deviations on the hydraulic parameter and cavitation characteristic. The common minor deviation which is subdivided into diameter error, conicality and incline in nozzle geometry are quantified through the ultra-precision measurement by self-developed micro-hole-measuring machine. The critical pressure of cavitation and the volume flow rate of different flow state for each nozzle are also measured by high precision sensor. With these data, the effect of deviations on the cavitating flow can be quantitatively analyzed and the sensitivity of each deviation can be compared. In this paper, transparent nozzles have been fabricated for internal-flow visualization, and the emphasis is on the critical conditions of cavitation inception and hydraulic flip flow in different nozzle structures. This paper is structured as follows: In Section 2, the concepts used in the definition and calculation of cavitation and internal flow are reviewed to introduce several important parameters that will be used in the rest of the study. The experimental methodology is described in Section 3. In Section 4, the experimental results from hydraulic characterization and internal-flow visualization are presented and analyzed in order to explore the relationship between flow parameters and cavitation development. In Section 5, conclusions are summarized.

2. Theoretical background

Hydrodynamic cavitation describes the process of vaporization, bubble generation, and bubble implosion that occurs in a flowing liquid as a result of a decrease in local pressure. Cavitation will only occur if the local pressure decreases to some point below the saturated vapor pressure of the liquid. In an injector nozzle, due to the abrupt change in the geometry of the inlet section and flow direction at the orifice inlet, the flow tends to separate the boundary layer from the wall at the inlet section. This causes a flow contraction that allows the static pressure to fall under the vapor pressure of the fluid, leading to a local change of state from liquid to vapor. This phenomenon is called cavitation [32–36].

With the increase of injection pressure, the internal flow can be classified into five regimes: turbulent flow, cavitation inception flow, cavitation growth flow, super-cavitation flow, and hydraulic flip flow. Fig. 1 is a schematic of the status of cavitating flow. When increasing pressure reaches the critical pressure, cavitation occurs into the orifice and bubbles at the entrance of the nozzle, as shown in Fig. 1(a). The region of cavitation then grows and extends to the outlet to form super-cavitation [see Fig. 1(b) and (c)]. The surface of jet flow becomes more and more turbulent due to the growth of the cavitation region, and the spray angle also becomes larger. With the continuous increase of injection pressure, the air surrounding the nozzle outlet is sucked into the nozzle orifice to fill the cavitation area, which makes the cavitation disappear immediately and be replaced by a thin layer of gas attached to the wall. This phenomenon is hydraulic flip [see Fig. 1(d)]. At the same time, the flow inside the nozzle orifice becomes stable and a sharp decrease of the spray cone angle is presented. However, if the internal structure of the nozzle is not smooth and completely symmetrical, maintaining the hydraulic flip in a stable axisymmetric form is difficult, so the phenomenon of local reattachment will emerge [see Fig. 1(e)].

The cavitation number K is one of the criteria often used to determine the appearance of the cavitation proposed by Nurick [27]; it is defined as:

$$K = \frac{P_{in} - P_v}{P_{in} - P_{back}} \quad (1)$$

K increases as the injection pressure P_{in} decreases or when the discharge pressure downstream from the orifice, P_{back}, increases. P_v is the vapor pressure of the fuel. As the cavitation number K becomes smaller, the tendency for cavitation phenomena to appear grows larger. The critical cavitation parameter is defined as K_{crit}, which represents cavitation