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Experimental investigation of the propagation characteristics of an interface wave in a jet pump under cavitation condition

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ABSTRACT

There is a dynamic equilibrium interface wave between the bubble region and the liquid region when a jet pump produces cavitation. The interface wave has an unstable boundary that moves backward and forward, and it is a pressure propagation front that causes the pressure change. The reason why the jet pump upstream pressures remain unchanged is because the interface wave has not arrived there. The interface wave moves upstream with the increase in outlet pressure. The region that it passes through experiences obvious pressure fluctuation and pressure rise. The nozzle cavity pressure rises slower than the throat cavity pressure, and the nozzle cavity has a lower pressure fluctuation frequency and smaller fluctuation range. Therefore, it is a good design for the jet pump to set the suction inlet near the nozzle cavity. In addition, the bubble region length, bubble region volume and bubble diameter decrease as the cavitation number increases in the jet pump. The bubbles completely vanish when the cavitation number reaches 1.53–1.59. Based on the above contributions, it is believed that this study will lay an important foundation for further research on the jet pump cavitation mechanism and cavitation prevention.

1. Introduction

With the advantages of simple structure, convenience of operation and maintenance, and low capital cost, the jet pump is widely used in agricultural irrigation, the rocket propulsion system, and fire protection engineering and has delivered significant economic and social benefits [1]. However, the jet pump produces cavitation easily, causing a sharp drop-off in efficiency, acoustic noise, component vibration and mechanical erosion [2]. These unfavorable drawbacks severely restrict the normal working range of the jet pump and also create bottlenecks in the jet pump design. This problem has attracted many researchers' concerns. To find an easier way to evaluate the cavitation erosion properties of materials, Sun [3] used a high-pressure water jet and a horn nozzle to produce cavitation. Okada et al. [4] investigated the relation between impact loads by collapsing cavitation bubbles and erosion damage using a pressure detector, and Hattori et al. [5] proposed a prediction method for cavitation erosion based on the measurement of bubble collapse impact loads. At present, a consensus has been reached in that there is rapid bubble formation and coalescence when cavitation occurs in the jet pump [6], along with multiphase flow, phase transition and turbulence flow. Therefore, the jet pump cavitation has obvious thermodynamic instability even though the operation conditions are determined [7], which makes further study on the cavitation mechanism and cavitation prevention become difficult.

Cunningham et al. [8] considered that incipient cavitation first occurs in the jet boundary, which has no effect on the jet pump's efficiency, while it spreads to the walls under severe conditions. The cavitation degree is described by the cavitation number in the range of 0.8–1.67. Through theoretical derivation, Abdulaziz [9] simplified the cavitation number into the pressure ratio of downstream pressure and upstream pressure, which is used to analyze the cavitation process. Bonnington [10] and Kudirka et al. [11] suggested that the cavitation bubbles occupy a large space until they reach the throat pipe wall, causing a choke flow and an unchanged mass flow rate. Winoto et al. [12] believed that the lowest pressure point moves from upstream to downstream with a decrease in outlet pressure, and bubbles expand from upstream to the throat end. Witte [13] thought that there is a sudden change of the flow structure in gas–liquid flows. It can be described as a transition from 'jet flow' to 'froth flow' accompanied by energy dissipation and pressure build-up. A mixing shock is formed between the upstream and downstream, which shows

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some similarity and also some differences with the plane shock wave in gas dynamics. Zhao [14] conducted an experiment on sound velocity in liquid–gas flows with the gas fraction in the range of 5–80%. It was found that the sound velocity decreases sharply as the gas fraction increases, declining to only 25 m/s at a high gas fraction. Long et al. [15] investigated the critical cavitation flow in the jet pump and observed a liquid–vapor mixing shockwave. The wave front moves back and forth around the lowest pressure point at a low frequency, while the pressure fluctuation and propagation rule of the wave are not mentioned in further study.

Therefore, the present paper adopted a new experimental method to investigate the cavitation bubble movement in the jet pump. A dynamic equilibrium interface wave was observed and its pressure fluctuation characteristic was analyzed. By monitoring the real-time changes of pressures at the nozzle cavity, throat cavity, diffuser cavity and jet pump outlet, the pressure propagation rule of the interface wave was obtained. Furthermore, the bubble region was measured and calculated under different cavitation conditions, and a critical cavitation number was proposed. The study is important to supplement not only the fundamental theory of the cavitation mechanism but also the jet pump cavitation prevention, which is helpful for promoting the widespread application of the jet pump.

2. Cavitation theory of the jet pump

2.1. Theoretical calculation of bubble region in the jet pump

Fig. 1 illustrates the structure profile of the jet pump. Negative pressure is formed in the nozzle cavity and throat cavity when the liquid flows out of the nozzle at a high speed [16]. Once the negative pressure declines to the water vapor pressure, a very rapid partial transition from the liquid to gas phase occurs and a liquid–gas two-phase flow forms. In spite of the small value for the saturated water quantity, the volume of producing bubbles is very large [17]. However, the bubbles coalesce and break up gradually when they move downstream where the pressure increases. As shown in Fig. 2, a wave surface is formed between the bubble region and liquid region, which is referred to as the interface wave in the paper.

The bubble quantity in the jet pump is largely dependent on the cavitation intensity. According to related studies [5], the cavitation number σ shows the tendency for cavitation to occur in the flowing stream and is defined by Eq. (1).

$$\sigma = \frac{P_d - P_v}{P_1 - P_d} \tag{1}$$

where P_1 is the upstream pressure and P_d is the downstream pressure; P_v is the vapor pressure of saturated water, which is considerably less than P_1 and P_d [18]. It can be deduced from Eq. (1) that the cavitation number σ decreases as the upstream pressure P_1 increases when the downstream pressure P_d is determined. Moreover, increasing the downstream pressure P_d is helpful for raising the cavitation number σ at a certain upstream pressure P_1.

To describe the bubble region, two dimensionless parameters are adopted as follows. One parameter is the bubble length ratio L^*, and the other parameter is the volume ratio V^*. To simplify the calculation, we use bubbles in the throat cavity and diffuser cavity as the bubble region, not considering bubbles in the nozzle cavity. The length ratio L^* can be written as Eq. (2) according to Fig. 2.

$$L^* = \frac{L_x}{L} \tag{2}$$

where L_x is the distance between the throat inlet and the interface wave; L is the distance between the throat inlet and the jet pump outlet.

There are two cases for the calculation of bubble volume ratio V^*. When the bubbles are in the throat cavity, L_x is less than the throat length L_{th}, so the bubble volume ratio V^* can be written as:

$$V^* = \frac{V_{th}}{V} \tag{3}$$

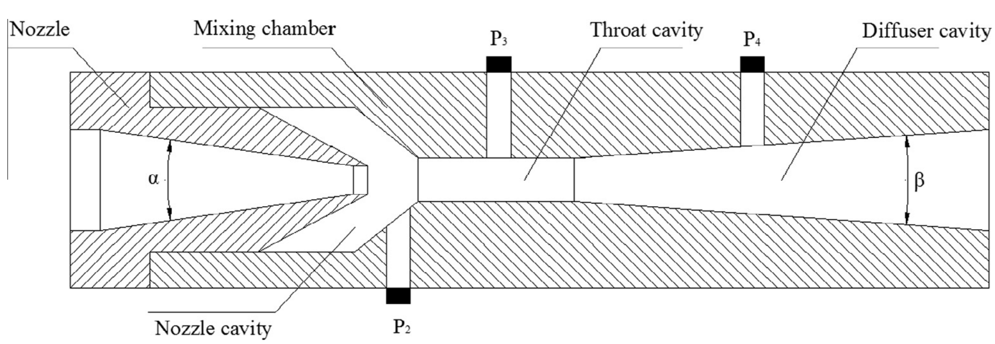

Fig. 1. Structure profile of jet pump.

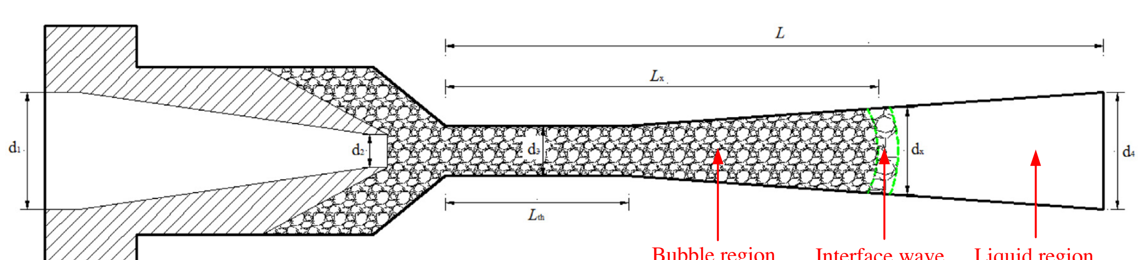

Fig. 2. Schematic diagram of interface wave in the jet pump.