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Experimental investigation on the performance of improving jet pump cavitation with air suction

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ABSTRACT

In order to improve the jet pump cavitation, a new method of inhaling air into the low-pressure region was proposed, and its performance was investigated experimentally under different air suction quantity and cavitation levels. Test results show that the cavitation number increases with the air suction quantity increasing in a linear approximation fashion. Increasing air suction quantity corresponds to a sharp decrease in acoustic noise, especially for the severe cavitation. As the air suction quantity increases, the pressure fluctuation range and fluctuation variance both decrease in the downstream, which relieve the cavitation vibration damage and enhance the jet pump stability. In addition, the pressure loss ratio reduces by 0.95%–3.46% and the pressure ratio increases by 5.7%–18% due to the water–air cushion layer formed in the wall boundary. The marked effect on preventing cavitation damage and improving the pressure transmission performance of the jet pump proves that the new air suction method proposed is practical and effective. Therefore, it is believed that this study would lay an important foundation for the widespread application of jet pump in the future.

1. Introduction

Jet pump is a kind of fluid machinery and mixing reaction equipment that transfers momentum from a high velocity primary jet flow to a secondary flow [1]. With advantages of simple structure, easy to machine, low capital cost, and convenience of operation and maintenance [2], it is widely used in hydraulic engineering, aerospace engineering and fire protection engineering and has delivered significant economic and social benefits [3]. However, the jet pump is easy to generate cavitation, causing a series of negative effects, such as a sharp drop-off in efficiency [4], acoustic noise, component vibration [5], mechanical erosion [6] and increase in hydrodynamic drag. Using it under cavitation condition for a long time will result in the jet pump fatigue rupture and then shorten the pump working life. These unfavorable drawbacks severely restrict the wider popularization and application of jet pump, which are also the bottlenecks of the jet pump design [7]. Hence, the investigation of new technical measures to prevent the jet pump cavitation has long been the focus of much research effort.

At present, relieving cavitation through naturally aspirated or aeration has obtained general consent and been applied widely around the world. Early in 1953, the experiments conducted by Peterka [8] had proved that air entrainment had effect on decreasing cavitation damage. The finding revealed that the cavitation damage of material was greatly decreased as the air was entrained into the water on the surface of material [9]. Now, this technology has been used in almost all the release works of high dams since the inception of air entrainment in the Grand Goulee Dam in America [10]. For stepped spillways with high heads, the flow energy can be dissipated significantly owing to the flow aeration, together with the vortexes on the steps [11,12]. As a result, the inception point prediction of the air entrainment for stepped spillway has become a research hotspot since it is closely related to the cavitation damage control, the energy dissipation ratio, and the designs of the training wall height and stilling basin [13,14]. Yu et al. [15] and Wang [16] believed that aerating air into the low-pressure region solved the problem of cavitation damages caused by high velocity flow and raised the abrasion resistance of boundary material. Long et al. [17,18] discussed the possible air supplying positions for improving the jet pump cavitation performance and concluded that supplying air into the throat can relieve flow choking effectively, along with reductions in the acoustic noise and vibration.

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There are some preliminary quantitative studies on the air suction against the jet pump cavitation. Hammitt [19] suggested that cavitation was severe at a small air suction quantity, while the cavitation erosion rate and cavitation damage degree decreased with the air suction quantity increasing. Through aerating air into the low-pressure region of venturi, Peterka [8] found the cavitation number increased with the air suction quantity increasing. Holl' study [20] showed that the change of cavitation number with air suction quantity was related to the cavitation level, and the cavitation number increased with raising the air content under traveling cavitation. Unfortunately, there is no further research on the pressure distribution and pressure fluctuation in the jet pump during the air suction process. Moreover, how the pressure transmission of the jet pump affected by the inhaled air has not ever been reported.

Therefore, improving the jet pump cavitation through inhaling air into the low-pressure region was investigated in the present paper. Its performance was measured and evaluated using a self-built experimental testing system for monitoring the real-time pressure at each position of the jet pump, acoustic noise, and pressure fluctuation. Then the pressure loss ratio and pressure ratio were calculated to analyze the pressure transmission performance of the jet pump. The image acquisition was conducted to observe the regime change of bubbles in the jet pump in the air suction process. Based on the above-mentioned contributions, the study is not only helpful for preventing cavitation damages, but also of great practical significance to improve the pressure transmission performance of jet pump, which would greatly promote its wide application in related engineering field.

2. Theory

2.1. Theoretical analysis of air suction in jet pump

Fig. 1 illustrates the structural view of the jet pump. Negative pressure is formed in the nozzle cavity and throat cavity when the jet flows out at a high speed. It is true that water is hard to be vaporized for its strong strength of extension. However, a very rapid partial transition from liquid to gas occurs and cavitation is generated when the negative pressure is lower than the liquid vapor pressure [21]. In spite of the small value of the saturated water quality, the volume of producing vapor bubbles is very large [22]. Masses of vapor bubbles move to the downstream of throat [23] along the streamline, and then they are caught up by the flowing liquid and collapse in the jet pump when they reach the high pressure region. This process accompanies with a violent collapse or implosion of bubbles and a tremendous increase in pressure, which is similar to water hammer blow [24].

The outside air is automatically introduced into the low-pressure region of the jet pump via the air intake hole and mixed with the working flow by the combined effects of energy and mass transfer. As the air suction quantity increases, the air content rises in the water. The gas diffusion towards vapor bubbles enhances [25] and sound velocity in the water reduces significantly [26,27], causing a sharp decline in the bubble collapse pressure. The wall load forced by the bubble collapse decreases and the cavitation damage reduces [28]. In addition, air entrainment converts the fluid composition in the boundary layer from a pure water layer to a water–air cushion layer, which decreases the mass density, viscosity and current gradient in the boundary layer [29], creating a good condition for reducing flow resistance of jet pump.

There is a close relationship between the working flow rate and air suction quantity. According to jet theory [3], the vacuum degree (negative pressure) increases with the raising of jet velocity. That is to say, the maximum air suction quantity increases as the working flow rate increases when all the structure parameters of jet pump are determined.

2.2. Cavitation number

Cavitation number σ shows the tendency for cavitation to occur in the flowing stream of liquid and is defined by the following equation [30]:

$$\sigma = \frac{P_d - P_v}{\frac{\rho v^2}{2}} \tag{1}$$

where P_d is the outlet pressure of the jet pump; P_v is the water vapor saturation pressure at the corresponding temperature, which is very small (e.g. 3.169 kPa at 25 °C) [31]; v is the nozzle exit velocity.

Substituting the jet nozzle exit velocity $v = Q/A$ into Eq. (1), we can get:

$$\sigma = 2A^2 \frac{P_d - P_v}{\rho Q^2} \tag{2}$$

where A is the sectional area of jet nozzle, $A = \frac{\pi d_2^2}{4}$; Q is the volume flow rate.

It has reached a consensus that the more serious the jet pump cavitation is, the smaller the cavitation number is. Thus, increasing the cavitation number has become a key evaluation criterion for the jet pump cavitation improvement. It can be seen from Eq. (2) that the cavitation number σ is related to the downstream pressure P_d and volume flow rate Q when the sectional area of jet nozzle A is determined. Therefore, different cavitation levels are obtained through regulating the working flow rate, and the improve performance for the jet pump cavitation is evaluated at different cavitation levels during the air suction process.

3. Experimental setup

3.1. Testing system

Fig. 2 illustrates the self-built experimental testing system. The clean water is used as the water source, which is powered by the plunger pump with the flow range of 0–4.0 m^3/h and rated

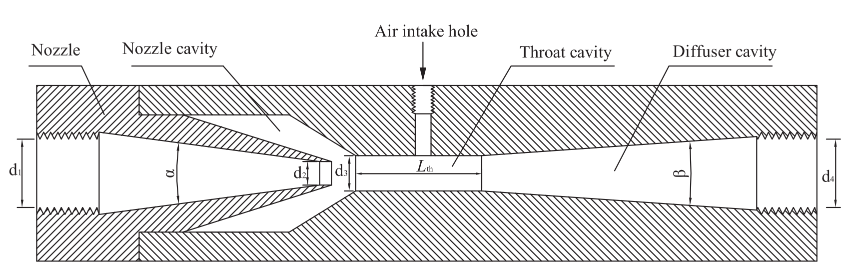

Fig. 1. The structural view of jet pump.