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Cavitating flow in annular jet pumps

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ABSTRACT

Based on the experimental and numerical methods, the pump performance and inner flow details of annular jet pumps under three area ratios (cross sectional area ratio of throat and nozzle) were studied in the present paper. The cavity clouds forming at the shearing layer, recirculation center and throat inlet were captured via high speed video. The realizable k–ε turbulence model combined with mixture cavitation model was well validated by experimental results on the pump performance (pressure ratio and pump efficiency) and the static wall pressure distribution. When the annular jet pump works under the critical working condition, the pressure ratio and the pump efficiency experience a sudden drop. Simultaneously, the flow rate ratio and cavitation number keep constant regardless of the decreasing outlet pressure, since the main flow is filled with cavity clouds. Moreover, the inception and development of cavity cloud induced at the throat inlet were particularly studied in this paper. The cavitation in the throat experiences three stages (incipient, stable and unstable stage) before extending into the diffuser, in which the unstable stage signals the approaching of the critical working condition. The cavity cloud there fluctuates slowly and faintly, while it may suddenly expand over the whole throat and vanish immediately. When the cavity cloud extends into the diffuser with the closure place $x/D_t < 2.8$ (D_t is the diameter of throat length), there is a low frequency cavity cloud surge. However, the surge disappears as the cavity cloud increases to the intermediate part of the diffuser. Additionally, based on imaging analysis method, the frequency characteristic of the cavity shedding in the diffuser was also studied. The shedding of cavity cloud in the diffuser experiences multiple periodicities when $L_{cav} = 3.25D_t$ (cavity length in diffuser), while there are two fundamental frequencies (58 Hz and 6 Hz) for $L_{cav} = 1.1D_t$ with the higher one corresponding to the shedding frequency. In the case of $L_{cav} = 3.25D_t$, the detached cavity cloud in the diffuser is pushed downstream only by the re-entrant jet. However, the main flow plays an important role on accelerating the detached part downstream in the case of $L_{cav} = 1.1D_t$.

Introduction

Jet pump is a sort of pump working by transferring momentum from the high velocity primary flow to the secondary flow. It has been widely used in various special situations for simple structure (no rotating part and excellent sealing ability) and superior cavitation performance. A typical jet pump mainly composes of a nozzle, a suction chamber, a throat pipe and a diffuser. According to the shape of the nozzle, jet pump can be classified into two categories: central type jet pump and annular type jet pump (CJP and AJP for short). As for CJP, the nozzle is circular and the working flow with high velocity is surrounded by the secondary flow. However, the nozzle of AJP is annular and the secondary flow is encircled by the primary flow. It is because the suction pipe is surrounded by the nozzle on the axis that AJP is suitable to convey the liquid with solid particles, such as potato, onion and capsule, even the living fish.

Being different from the cavitation in traditional centrifugal pump, the cavitation in a jet pump is shear cavitation (Franc and Michel, 2006) that the bubbles always occur at the shearing layer due to the great velocity gradient there. With the decreasing outlet pressure, cavitation area keeps on developing in the throat and even extends into the diffuser. As the outlet pressure drops to a critical value and the cavity cloud congests the throat, the pump efficiency declines abruptly and the accompanied vibration threatens the stability of the whole pumping system. Hence, more studies on the cavitation of jet pump are of great importance.

There are a series of theoretical studies about the pump performance and structural optimization of CJP (Elger et al., 1991;

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Winoto et al., 2000; Long et al., 2008), especially the cavitation performance (Cunningham et al., 1970; Lu and Shang, 1987; Long et al., 2010a, 2010b). A systematical theory is built on evaluating the pump performance and the cavitation performance in CJP, which can be referred to as well on investigating AJP. Besides, many researches, including experiments and simulations, have conducted to understand the mechanisms of cavitation flow in CJP. Kudirka and Decoster (1979) found that the vapor bubble firstly occurred inside the jet boundary in CJP. Then, Ran and Katz (1994) validated that the cavitation inception appeared at the vortex center of the jet, which was related to the fluctuation of the shearing layer, and it will also form in the vortex center of the co-flow with the cavitation nuclei growing. Hence the inception of cavitation in CJP can be due to high shear and vortex in jet boundary (namely shearing layer). However, Long et al. (2009) pointed out that adverse pressure gradient caused by the convergent suction chamber was another reason for cavitation occurrence. According to high speed camera, he sorted the flow pattern in CJP into four stages, namely cavitation inception, cavitation development, intensive cavitation and intensive two-phase cavitation, and captured the liquid–vapor mixing shock wave under the limited operation condition. Even though the annular jet in AJP can also cause high shear in jet boundary as that in CJP and the adverse pressure gradient still exists in suction chamber, the flow separation caused by the high speed primary flow running adhering to the inner wall is the most significant reason for cavitation occurrence. The cavitation flow pattern in AJP, consequently, is different from that in CJP and this is particularly concerned in this study.

Compared with CJP, studies on AJP are relatively fewer. Shimizu and Kuzuhara (1983) and Shimizu et al. (1987) firstly conducted a series of experimentations on twenty-five AJPs with different area ratio, throat length and inclined angle of the suction chamber. In his experimental results, the AJP with area ratio 1.75 gave the highest pump efficiency and the recommended angle of suction chamber was between 18° and 30°. In our previous investigations, these results are also validated by numerical method (Long et al., 2010a, 2010b; Long et al., 2012). Hence the structure of AJP in this study is mainly referred to that in Shimizu' studies, except that the nozzle is specially designed to reduce head loss by structural mutation. Besides pump efficiency of AJP, Elger et al. (1994) investigated the size and position of recirculation in gas AJP under different area ratio and confirmed the onset and disappearance of the recirculation through a dimensionless number J (the momentum ratio of the primary flow and secondary flow). This kind of flow also exists in liquid AJP. Combining the method suggested by Elger et al. (1991) and the approximate theory of confined jets (Craya and Curtet, 1955), Xiao et al. (2013) suggested the design space of recirculation and no-recirculation which can be used for determining area ratio in AJP designing. Recirculation is an interesting flow characteristic in AJP, while it is relatively independent and only happens under a low flow rate ratio which is generally far from the optimum working condition. Since this study mainly focuses on the cavitation flow which occurs when flow rate ratio is larger than that under the optimum working condition, recirculation and the accompanied cavitation will not be studied in this study.

In fact, the flow in AJP is a sort of confined annular jet running adhering to the inner wall. The high velocity working flow in AJP can cause cavitation at the intersection of the suction chamber and the throat, which is not obvious in CJP. The cavitation flow in AJP and CJP is considerably different. Unfortunately, there are few relevant investigations, especially on the cavitation inception, the cavitation development and the critical working condition. The present conclusions on the mechanism of the cavitation inception in AJP are inconsistent and the development of the cavity cloud is not clear.

Hence this work mainly concentrates on the inner flow details under different cavitation stage and the development of the cavity cloud in AJP through experimental and numerical method. Additionally the unsteady cavitation behavior in the throat and diffuser is analyzed based on experimental observations.

Experimental setup

Experiment device

Being similar to the traditional CJP, AJP also comprises of a suction duct, an annular nozzle, a suction chamber, a throat and a diffuser as shown in Fig. 1. The high pressure working flow accelerates through the annular nozzle and exerts an entrainment effect to the secondary flow in the suction duct. Two flows mix intensively in the suction chamber and the throat, and then flow out through the diffuser with the outlet pressure rising. Tested AJPs were designed on the ground of our previous studies (Long et al., 2012; Xiao et al., 2013) about structural optimization. The main structural parameters in Fig. 1 were set as follows: $L_c = 63$ mm (the length from the nozzle tip to the throat), $L_t = 120$ mm (the length of the throat), $D_s = 50$ mm (the diameter of the suction duct) $D_t = 40$ mm (the diameter of the throat), $D_d = 80$ mm (the diameter of the diffuser outlet), $\alpha = 20°$ (the inclined angle of the suction chamber) and $\beta = 6°$ (the inclined angle of the diffuser). Besides the stainless steel suction duct and nozzle, the suction chamber, the throat and the diffuser were made of transparent Perspex material for observing the cavity cloud during the mixing process. Moreover, pressure taps in Fig. 1 represent the mounting position of pressure transducers. Since the pressure gradient is great in the suction chamber and the throat, seven pressure transducers were assigned there and the other four pressure transducers were along the diffuser.

For the purpose of altering the area ratio (m), three different nozzles were produced. The configuration of those nozzles is shown in Fig. 2. By adjusting the inner and peripheral diameter of the annular nozzle instead of changing the structure of the suction chamber, three different area ratios, $m = 1.72$, 2.26 and 3.33, were obtained. The following experiments were all concentrated on these three AJPs.

Test rig and scheme

Fig. 3 illustrates a sketch of the experimental rig. Pumped by a centrifugal pump, the high pressure primary flow entrains the secondary flow from a water tank. And then the mixed flow is discharged to a reservoir. The primary flow rate (Q_j) and the mixed flow rate (Q_c) are controlled by valves (1 and 13 in Fig. 3) and measured by magnetic flow meters (2 and 12 in Fig. 3).

The water tank, with the length 2.0 m, the width 1.0 m and the height 0.70 m, mainly functions as a container of suction water. Another centrifugal pump keeps on conveying water into the water tank via the water supply pipe. A baffle plate acting as a spillway separates the water tank into two parts and keeps the water level of suction water constant. Then the spilled water, which can be adjusted by a valve (11 in Fig. 3), flows into a reservoir. Note that the reservoir storing the circulation water is sufficiently huge and consequently the variation of temperature is negligible during the experiment.

Monitoring the pressure during the AJP working process is essential for investigating the internal flow details. A pressure gauge (4 in Fig. 3) was installed at the primary flow inlet to monitor the driving pressure. Besides the aforementioned 11 pressure transducers installed along the AJP, two other pressure transducers were employed to measure the pressure of the secondary flow (p_s)