Experimental and numerical study on the free surface vortex of a mixed flow pump device model

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Abstract. Because of the advantages of small installation space, good cavitation performance, low cost and easy maintenance, the open channel pump station is widely used in agricultural production, flood control and ecological construction. In the process of operation, large-scale vortices such as wall vortex, bottom vortex and surface vortex easily appear. Under special working conditions, the head and efficiency of the pump station will be reduced, cavitation will occur at the blades, shafting will move, and the unit will vibrate, which will reduce the service life and safety of the pump station. In this paper, the head, efficiency, flow characteristic and free surface vortex of a mixed flow pump device model in pumping station under different water level and flowrates are studied numerically and experimentally, providing experience and theoretical reference for the design of the pumping station.

1. Introduction

The primary function of the pumping station is to transform the mechanical energy into the kinetic and pressure energy of water so that the fluid can be transported to the place where people want. It is an essential hydraulic structure in agricultural and industrial production, flood control and drainage, regional ecology and other aspects, and is a crucial component of water conservancy projects [1-3].

Vortex is a kind of usual motion form of viscous fluid. Surface vortex, sidewall vortex and bottom wall vortex often appear in the inlet tank of the pump [4, 5]. When the vortex is sucked into the pump, the speed uniformity and direction uniformity of the fluid at the pump inlet are significantly reduced, resulting in the drop of head and efficiency, cavitation and destructive vibration [6].

Scholars have studied the effect of the vortex in the open inlet tank on the pump. Ansar et al. [7] used the Acoustic Doppler Velocimetry (ADV) technology to study the internal flow field of the vertical axis pump station model. Without cross flow, the pump-approach flow distributions were characterized by nearly uniform streamwise velocities in the pump bay and weak free surface vortices near the pump column. With cross flow, the three-dimensional mean velocity measurements revealed the existence of a large recirculation zone upstream of the pump column such that strong streamwise velocities were present at higher depths and near the left sidewall, while the reverse current concentrated at lower depths along the right sidewall. Rajendran [8] used particle image velocimetry (PIV) to study the number, position, shape, size and strength of surface vortex, wall vortex and bottom vortex in the intake pool of pumping station. It was found that the wall vortex and bottom vortex were affected mainly by the distance between the suction pipe and the wall and the base. Xiao et al. [9] eliminated the surface vortex...
and improved the performance of the pump at low water level by setting a cross water guide plate on the pump inlet. Yang et al. [10] concluded that the bottom vortex is greatly affected by the installation height of the pump inlet pipe. The pump inlet pipe of the open pumping station is always very short, which misguides the flow. Under low water level, the axial force and radial force of the blades are abnormally large and unstable, because of uneven flow at pump inlet [11].

Through the above research, it can be found that the flow characteristic in the pump inlet tank has a great impact on pump performance. Under different structure and water level, the flow in the inlet tank is quite different. In this paper, a mixed flow pump device model used in a pumping station is taken as the research object. The results of the head, efficiency, flow characteristic and free surface vortex of mixed flow pump in a pumping station under different water levels and flow rates are explored numerically and experimentally.

2. Research object and test system

2.1. The pump device model

The vertical mixed flow pump device model was used in the experiment. The design parameters of the model pump are as follows: design flow rate $Q_d = 518 \text{ m}^3/\text{h}$, head $H = 3 \text{ m}$, efficiency $\eta = 60 \%$, rotation speed $n = 1875 \text{ r/min}$, and specific speed $n_s = 698.5$. The main geometric parameters of the pump device model are shown in Table 1.

| Name                              | Symbol | Value |
|-----------------------------------|--------|-------|
| Impeller inlet diameter / mm      | $D_1$  | 180   |
| Impeller outlet diameter / mm     | $D_2$  | 216   |
| Impeller outlet width / mm        | $b_2$  | 66    |
| Impeller blade thickness / mm     | $\delta_1$ | 5   |
| Distance between impeller inlet and pool bottom / mm | $H_1$ | 178 |
| Number of impeller blades         | $z_2$  | 3     |
| Axial length of diffuser blade / mm | $L_1$ | 145  |
| Diffuser inlet width / mm         | $b_3$  | 63    |
| Diffuser outlet width / mm        | $b_4$  | 74    |
| Diffuser blade thickness / mm     | $\delta_2$ | 3   |
| Number of diffuser blades         | $z_2$  | 5     |

2.2. Experimental test system

![Figure 1. Test system](image)

The schematics of the measuring station are shown in Figure 1. The measuring station consists of the following parts: 1. Pump inlet tank, 2. Rectifier grille, 3. Diverting cone, 4. Pump case, 5. Siphon,
6. Downstream water tank, 7. Torque transducer, 8. Frequency converter, 9. Impeller, 10. Diffuser, 11. Upstream water tank, 12. Electromagnetic flowmeter.

2.3. Preparations before the experiment
The following preparations need to be done before the experiment: 1. Close the valve at the outlet of the downstream water tank, open the exhaust valve at the top of the downstream water tank and siphon, and run the pump; 2. After the exhaust is completed, close the exhaust valve at the top of the downstream water tank and siphon, and open the valve at the outlet of the downstream water tank; 3. Test under different water level and flow rate.

3. Numerical model

3.1. Fluid domain and mesh
The calculation model could be simplified appropriately for improving efficiency. By setting the inlet as the flow velocity with the vector evenly distributed, the rectifier grille is omitted. Pump shutdown does not exist in the numerical calculation, so it is unnecessary to consider the backflow from the downstream water tank to pump inlet tank, the siphon part, therefore, is omitted, and the straight pipe is used instead.

The fluid domain of the mixed flow pump device model is divided into seven sections: 1. Upstream water tank, 2. Pump inlet tank, 3. Outlet pipe, 4. Diffuser, 5. Impeller, 6. Diverting cone and Diverting contractile tube. UG 10.0 software is used to build the physical model, and ICEM18.0 software is used to generate the mesh. As shown in Figure 2.

3.2. Calculation model and boundary settings
CFX 18.0 software is used for unsteady calculation. The time step is set as the time when the impeller rotates 2 degrees: 0.0001777778 s, and the total time is set as 12 rotation cycles of the impeller: 0.384 s. RNG $k-\varepsilon$ Turbulence Model and Homogeneous Multiphase Flow Model is used. The surface tension of the air-water interface is set to 0.072 N/m. The Continuous Surface Force Model is adopted. The water is the primary phase, and the air is the secondary phase. The surface in contact with the atmosphere is set as Opening Pressure and Direction, and the reference pressure is 0 atm. The exit is set to Mass Flow Rate. The static-static interface is set to General Connection, and the dynamic-static interface is set to Transient Rotor Station. All walls are set to No Sliding.

3.3. Mesh independence analysis
In order to eliminate the influence of the number of meshes on the numerical results, the mesh independence analysis is carried out. Figure 3 shows the head under different mesh numbers at flowrate 518 m$^3$/h. It can be seen that when the number of meshes is more than 11 million, the predicted value of pump head is unchanged. Therefore, the scheme of 12.135 million grids is selected for numerical calculation, which not only meets the accuracy of the numerical calculation but also keeps the efficiency of the numerical calculation.
4. Result analysis

4.1. Pump head and efficiency

Pump head refers to the increase of energy per unit mass of liquid from the inlet to the outlet. Pump efficiency refers to the effective degree that the pump converts mechanical energy into kinetic and pressure energy of the liquid. The pump head $H$ and efficiency $\eta$ are calculated as follows:

$$H = \frac{P_3}{\rho g} + \frac{v_3^2 - v_1^2}{2g} + H_0 - Z_3$$  \hspace{1cm} (1)

$$\eta = \rho g Q H / P$$  \hspace{1cm} (2)

Where, $P_3$ - average pressure at the outlet of the outlet pipe, Pa; $v_3$ - average velocity at the outlet of the outlet pipe, m/s; $v_1$ - velocity at 2 m upstream of diverting cone, m/s; $\rho$ - density of water, kg/m$^3$; $g$ - acceleration of gravity, m/s$^2$; $z_3$ - Height of outlet pipe from pump inlet tank, m; $H_0$ - the height of water level, m; $Q$ - flowrate, m$^3$/s; $H$ - pump head, m; $P$ - shaft power, W.

Figure 4 shows the pump head and efficiency curve under different water level and flow rate. It can be seen that the deviations of both the pump head and efficiency obtained by experiment and calculation are within 5%. The head decreases and the efficiency increases first and then decreases with the increase of flow, and the efficiency reaches the highest point when flow $Q = 518$ m$^3$/h. The head and efficiency all increase with the rise in water level and the effect of water level on the head and efficiency increases with the increase of flow rate.
4.2. Free surface vortex
The lower the water level means a smaller wetted area and more significant flow velocity in the pump inlet tank, which makes the free surface vortex stronger, as shown in Figure 5. It can be seen that under a low water level, the flow at the free surface is very uneven, the flow vector changes dramatically, part vortex in one side is sucked into the other side, the flow vector is asymmetric, and the influenced area of the free surface vortex is large. With the increase of water level, the flow vector changes smoothly and stably, the flow vector is symmetric, and the influenced area of the free surface vortex is less.

![Figure 5](image)

4.3. Free surface vortex
When air is entrained in the free surface vortex of the pump inlet tank and sucked into the pump, it will cause a sharp decline in performance and severe vibration and noise and other negative effects. The experimental and numerical results of free surface air-entraining vortex under the water level of 0.6m are shown in Figure 6. It can be seen that the free surface air-entraining vortex is funnel-shaped, and the liquid surface drops to form a cave. In the process of downward extension, the diameter of the airband decreases, and finally, a long and thin gas belt is formed. With the decrease of flow rate, the volume of cave decreases, and the length of the airband decreases until it disappears. The shape of the free surface air-entraining vortex of experiment and simulation are the same, which proves the accuracy of the calculating model and method.

![Figure 6](image)
5. Conclusion
The pump head, efficiency, internal flow and free surface vortex of a mixed flow pump device model under different water level and flowrate are studied experimentally and numerically.

The head decreases and the efficiency increases first and then decreases with the increase of flow, and the efficiency reaches the highest point when flow $Q = 518$ m$^3$/h. The head and efficiency all increase with the rise in water level and the effect of water level on the head and efficiency increases with the increase of flow rate. Under low water level, the flow at the free surface is very uneven, the flow vector changes dramatically, part vortex in one side is sucked into the other side, the flow vector is asymmetric, and the influenced area of the free surface vortex is large. The free surface air-entraining vortex is funnel-shaped, and the liquid surface drops to form a cave. In the process of downward extension, the diameter of the airband decreases, and finally, a long and thin gas belt is formed. With the decrease of flow rate, the volume of the cave decreases, and the length of the airband decreases until it disappears.

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