Influence of suction chamber profile on flow field of annular jet pump

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Abstract. Jet pump is a kind of fluid machinery, which uses jet shear and turbulent diffusion to transfer mass and energy. It is widely used in water project, civil engineering and other fields. In order to investigate the influence of suction chamber profile on flow field of annular jet pump, the conical suction chamber and the streamlined suction chamber were compared by applying turbulence numerical simulation method. The performance, pressure characteristics, velocity and turbulent energy distributions of annular jet pumps with two suction chambers are analysed. The calculation shows that compared with the traditional conical suction chamber, the efficiency of annular jet pump with streamlined suction chamber is improved at low flow ratio, and the change is not obvious at high flow ratio. In the same section, the cross sectional area of streamlined suction chamber is slightly larger than that of conical suction chamber, so the primary flow velocity near the wall is slightly lower, which can reduce the friction loss caused by high speed wall-attached flow. In addition, the smooth turning of the primary flow in streamlined suction chamber can weaken the extrusion on the entrained flow field. Different from the conical suction chamber, the streamlined suction chamber is smoothly connected with throat without sudden corner change, which can eliminate the low pressure near the inlet wall of throat, improve the wall pressure distribution and reduce the possible cavitation. The research results of suction chamber profile of annular jet pump can provide scientific basis for the popularization and application of jet pump.

1. Introduction

Jet pump is a kind of fluid machinery which uses high speed primary flow as a power to suck, mix and transport low velocity fluid. The absence of moving parts in a jet pump results in many advantages, such as simple structure, high safety and conveniences of operation and maintenance. It is widely used in water conservancy, civil engineering, geology and other fields. Kayukov [1] proposed that the use of jet pump in the technical water supply system of hydropower station is safer and more efficient than traditional water supply methods, and has achieved good economic benefits. Jin [2] recommended the construction technology of jet pump in foundation construction of water conservancy project can solve the problems of large amount of engineering, difficult construction, long working hours and high cost caused by common manual drilling method and large excavation scheme of cofferdam diversion foundation pit. Xiao [3] studied and analysed the application of jet pump in aquatic industry and pointed out that the application of jet pump to transport fish has less damage to fish than traditional centrifugal pump and pneumatic fish pump, and can realize live fish transportation.
According to the shape of nozzle, jet pump can be divided into central jet pump and annular jet pump (CJP and AJP for short). The primary flow of AJP surrounds the suction pipeline, forming an annular jet, as shown in figure 1(a). The suction pipe of AJP is located in the axis, so the suction passage can form a larger passage path than that of CJP. The increase of the cross-section area is very conducive to the transportation of larger solid media [4]. At present, there are many studies on the influence of AJP structure on its performance and internal flow details, such as area ratio, suction chamber contraction angle, throat length and diffuser diffusion angle. Long [5] numerically simulated the internal flow field of AJP with different throat lengths. It was considered that the expansion mixing of AJP exists in both throat and diffuser. The longer the throat, the better the mixing degree of jet expansion. However, the longer the throat, the greater friction loss will be caused. When the length of the throat is 2.69 times the diameter of the throat, the efficiency is the highest. Zeng [6] considering the flow ratio, the contraction angle of the suction chamber, the relative throat length and the diffuser diffusion angle, using the design of experiment method and numerical simulation analysis, the optimum combination of AJP performance is obtained as follows: the flow ratio is 0.6, the contraction angle of the suction chamber is 15°, the relative throat length is 2.45, and the diffuser diffusion angle is 4°.

However, the research on the suction chamber of annular jet pump mostly focuses on the influence of its contraction angle on pump performance and internal flow field. Shimizu [7] conducted a series of experimentations on twenty-five AJPs with different structures. The results show that the optimum contraction angle of the suction chamber was between 18°and 30°. Kwon [8] studied the influence of the contraction angle of the suction chamber on the pump performance at different flow ratios by numerical simulation. It was found that the AJP had the highest efficiency when the angle is 12°. Xiao [9] found that the flow separates at the throat inlet and leads to a relatively low local pressure when using the conical suction chamber, which would induce cavitation. High speed primary flow in AJP flows along the wall of suction chamber and throat, and the difference of suction chamber structure has a great influence on the internal flow field. In order to optimize the internal flow field of jet pump, a streamlined suction chamber is proposed, as shown in figure 1(b). The high speed primary flow can flow smoothly at the junction of the suction chamber and the throat and reduce the energy loss and avoid the formation of local low pressure, thus improving the working performance of the jet pump.

In this paper, the turbulence numerical simulation method is used to calculate the internal flow field of conical suction chamber and streamlined suction chamber for the AJP with an area ratio of 1.75. Comparing and studying the performance, pressure characteristics, velocity and turbulent energy distributions of AJP can provide scientific basis and technical support for the performance optimization of AJP.

2. Numerical method

2.1. CFD model

The internal flow of AJP belongs to axisymmetric flow in finite space. The two-dimensional axisymmetric plane in the calculation area can meet the research requirements [8-10]. Realizable k-ε model combined with standard wall function can effectively predict the performance of jet pump and obtain the details of internal flow field. The accuracy of this combination has been verified by experiments [11-12]. In this paper, FLUENT is used as a computational tool.

Based on the structural size of the AJP in the Shimizu [7] experiment, the simulation study was carried out, and the reliability of the numerical simulation method was verified by the experimental data. The specific sizes of the annular jet pump are as follows: the diameter of diffuser $D_e=55\text{mm}$, the diameter of suction pipe $D_s=43\text{mm}$, the diameter of throat $D_t=38\text{mm}$, the conical suction chamber contraction angle $\alpha=18^\circ$, the conical suction chamber length $L_c=54.37\text{mm}$, the relative throat length $L_t/D_t=2.69$, the diffuser diffusion angle $\beta=5.8^\circ$, area ratio $m=1.75$. The profile equation of streamlined suction chamber is as follows:
\[ R_c = L_c \times \cot\left(\frac{\alpha}{4}\right) + \frac{D_t}{2} - \left[ L_c^2 \times \cot^2\left(\frac{\alpha}{4}\right) - (x - L_c)^2 \right]^{\frac{1}{2}} \tag{1} \]

where \( R_c \) is the radius of the streamlined suction chamber and \( x \) is the axis coordinate. According to equation (1), the streamlined suction chamber profile could be obtained, as shown in figure 1(c). It can be seen that the diameter of streamlined suction chamber is slightly larger than that of conical suction chamber on the same cross section. Therefore, the cross sectional area of streamlined suction chamber is larger than that of conical suction chamber, especially at the inlet of throat.

2.2. Grid and boundary conditions

The calculation domain is shown in figure 2, including: suction pipe, nozzle, suction chamber, throat, diffuser and outlet pipe. The axis coordinate \( x \) is positive with the flow direction of the water flow and \( r \) is the radial coordinate. The origin is set at the centre of the inlet of throat.

The primary flow flows out of the nozzle and enters the suction chamber to absorb the entrained flow. The two flows exchange their energy, momentum and mass in the throat. The mixed flow then gains more pressure energy when passing through the diffuser and finally discharges out. Considering the severe turbulent shear motion in the nozzle exit and the suction chamber in the flow field, the grid in these areas should be relatively dense, as shown in figure 3. With the development of the flow, the velocity in the flow field is gradually uniform, and the corresponding grid layout should also be uniformly transited.
Boundary conditions: primary flow inlet and entrained flow inlet are both set as velocity inlet, mixed flow outlet is set as pressure outlet, and the standard wall function is adopted to resolve the near-wall region. The velocity at the entrained flow inlet varied to obtain different flow ratios with the velocity at the primary flow inlet constant.

3. Validation of CFD simulation

3.1. Basic parameters of AJP
The basic parameters of AJP are a set of dimensionless parameters (area ratio, flow ratio and pressure ratio), which are defined as follows [7]:

Area ratio $m$:

$$m = \frac{A_t}{A_j} \quad (2)$$

Flow ratio $q$:

$$q = \frac{Q_s}{Q_j} \quad (3)$$

Pressure ratio $h$:

$$h = \left( \frac{H_c - H_s}{H_j - H_c} \right) \quad (4)$$

Efficiency $\eta$:

$$\eta = qh \quad (5)$$

where $A_t$ and $A_j$ are the throat area and the nozzle area; $Q$ is flow rate; $H$ is pressure; subscripts $j$, $s$ and $c$ are primary flow, entrained flow and mixed flow respectively.

3.2. Comparisons between simulation and experiment
According to the equation (2)-(5), the numerical results are collated and compared with the experimental data of Shimizu [7]. The performance curve of AJP is obtained as shown in figure 4. It can be seen that the numerical results are basically consistent with the experimental data, which indicates that it is accurate and reliable to use the CFD model to calculate and analyse the internal flow field of AJP and predict its performance. In the subsequent calculation, 50,000 grid nodes are selected for calculation.
Figure 4. The performance curve of AJP

4. Numerical results and discussions

In order to analyse the influence of suction chamber profile on the performance and flow field of AJP, the AJP in the Shimizu [7] experiment was used to calculate. When calculating, the velocity at the entrained flow inlet varied to obtain different flow ratios ($q=0.2$–$0.6$) with the velocity at the primary flow inlet constant.

4.1. Characteristic curves

The $h$-$q$ and $\eta$-$q$ curves of AJP under different suction chamber profiles were shown in figure 5. It can be seen from figure 5, when $q<0.45$, there is a slight difference between the $h$ of conical suction chamber and streamlined suction chamber. The $h$ of the latter is slightly higher than that of the former, and the maximum difference of $h$ is about 3.12%. When $q>0.45$, the $h$ of the two chambers has little difference, as shown in figure 5(a). Correspondingly, when $q<0.45$, the efficiency of AJP is improved by streamlined suction chamber, the maximum efficiency increase is about 1%, but the increase is not obvious when $q>0.45$, as shown in figure 5(b). Since the mixing process of primary flow and entrained flow will be extended to diffuser at high flow ratio, so the effect of the suction chamber profile on the efficiency of AJP is relatively small.

Figure 5. $h$-$q$ and $\eta$-$q$ curves at different suction chambers

4.2. Pressure distribution

Figure 6(a) and 6(b) show the wall pressure distribution of suction chamber, throat and diffuser at different flow ratios when AJP adopts different suction chamber profiles. Pressure distribution is expressed by pressure coefficient $C_p$

\[
C_p = \left( \frac{p - p_j}{0.5 \rho u_j^2} \right)
\]  

(6)

Where $p$ is the wall pressure, $p_j$ is the nozzle outlet wall pressure, $u_j$ is the nozzle outlet primary flow static velocity, $\rho$ is the water density.

From figure 6, it can be seen that different suction chamber profiles have a great impact on wall pressure, especially at the inlet wall of the throat. When the conical suction chamber is used, the abrupt change of the pump structure will lead to the diversion of the primary flow and the obvious pressure drop in the area, while the streamlined suction chamber can make the primary flow smoothly...
flow into the throat along the wall of the suction chamber, so the low pressure at the throat inlet will not appear.

![Figure 6. Wall pressure distributions for different suction chambers](image)

![Figure 7. Pressure fields for different suction chambers](image)

Figure 7 shows the pressure fields at the junction of suction chamber and throat at different flow ratios. When conical suction chamber is used, there is a local low pressure on the wall of throat inlet, as shown in figure 7(a) and 7(c), while when streamlined suction chamber is used, there is no such local low pressure, as shown in figure 7(b) and 7(d). Thus, when AJP adopts streamlined suction chamber, it can obviously improve the wall pressure distribution at each flow ratio, eliminate the local low pressure at throat inlet, and reduce the possible cavitation.

4.3. Velocity distribution

Figure 8 shows the velocity distribution of each cross section under different suction chamber profiles at \( q=0.30 \). The calculations show that the cross section velocity distribution of AJP with conical suction chamber is different from that of streamlined suction chamber. Since the cross sectional area of the latter is larger than that of the former at the same axial position, the primary flow velocity near the wall of the latter is lower than that of the former, as shown in figure 8(a) and 8(b). Near the inlet of throat, the abrupt change of the pump structure of the former has more severe compression effect on
the entrained flow field, so the width of the suction flow field is smaller than that of the latter, as shown in figure 8(c) and 8(d).

![Velocity distributions on the cross section for different suction chambers (q=0.30)](image)

Figure 8. Velocity distributions on the cross section for different suction chambers (q=0.30)

Figure 9 shows the velocity contour of AJPs with different suction chamber profiles at different flow ratios. At low flow ratio, compared conical suction chamber with streamlined suction chamber, the primary flow core length of the two types of suction chamber are basically the same, but the primary flow velocity near the wall of the latter is lower than that of the former, so the friction loss caused by the wall-attached flow of the primary flow of the former is greater. The shape of the entrained flow field is slightly different. The length of the entrained flow field of the former is slightly longer than that of the latter, this is due to the abrupt change of pump structure at the throat inlet of the former and the tendency of primary flow moving towards the pump axis under inertia is more obvious. Therefore, the entrained flow field is compressed and its length is increased, as shown in figure 9(a). However, when the streamlined suction chamber is used, the primary flow can flow smoothly into throat along the wall at the inlet of throat, so the compression effect on the entrained flow field is not obvious. The entrained flow field is basically conical, as shown in figure 9(b). At high flow ratio, the distribution of primary flow core and flow velocity is consistent with that at low flow ratio, but the difference with that at low flow ratio is the mixing process of primary flow and entrained flow will extend to the diffuser at high flow ratio. At this time, the suction chamber profile has little influence on the entrained flow field, and the length and shape of entrained flow field are basically the same, as shown in figure 9(c) and 9(d). Therefore, the primary flow velocity near the wall is slightly lower than that of the conical suction chamber due to the cross sectional area of the streamlined suction chamber is slightly larger than that of the conical suction chamber, which can reduce the friction loss caused by the wall-attached flow of the high speed primary flow.

4.4. Turbulent energy distribution

Figure 10 shows the turbulent energy distributions in AJPs with different suction chamber profiles at q=0.20. The results show that the peak of turbulent energy near the throat inlet of conical suction chamber is larger than that of streamlined suction chamber. This is because the structure of AJP with conical suction chamber changes abruptly at throat inlet, and the tendency of primary flow moving
toward the axis and extruding the entrained flow under inertia is more obvious, resulting in more intense turbulence.

![Velocity contours for different suction chambers](image1)

![Turbulent energy distributions for different suction chambers (q=0.20)](image2)

5. Conclusion
The high speed primary flow of AJP flows along the wall of suction chamber and throat. The difference of suction chamber structure has great influence on the internal flow field of AJP. Based on the AJP with area ratio of 1.75, the performance characteristics and flow field differences of streamlined suction chamber and conical suction chamber are compared and analysed by turbulence numerical simulation method. We can conclude as follows:

1. When \( q < 0.45 \), the \( h \) and efficiency of AJP is improved by using streamlined suction chamber, but when \( q > 0.45 \), the effect of streamlined suction chamber on the \( h \) and efficiency of AJP is relatively small.

2. Smooth connection between the streamlined suction chamber and the throat can eliminate the local low pressure near the wall of the throat inlet, significantly improve the wall pressure distribution, and reduce the possible cavitation.

3. At the same section, the diameter of streamlined suction chamber is slightly larger than that of conical suction chamber, so the primary flow velocity near the wall is also lower, which can reduce the friction loss caused by the wall-attached flow of high speed primary flow.

4. The streamlined suction chamber can make the primary flow flows smoothly into throat, and weaken the extrusion of the primary flow to the flow field of the entrained flow and the turbulence between the primary flow and the entrained flow at a low flow ratio.
In addition, this research mainly analyses the influence of suction chamber profile on the performance and flow field of AJP. The influence on cavitation performance of AJP needs to be further studied in the future.

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