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Effect of the flow in blade root-leakage on hydraulic characteristic in axial flow pump system

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Abstract. The clearance locate on blade root is almost 10~20 times than tip in adjustable axial flow pump, the flow in blade root clearance has obvious impact on the hydraulic characteristic in pump systems. In order to research the effect of blade root clearance on hydraulic characteristic in axial flow pump system, a vertical axial flow pump system is researched by numerical simulation and experiment. After considering the root clearance, the result has high precision under large and design flow condition. The simulation result shows with the effect of the blade root clearance, the velocity distribution from hub to shroud is trend bad, and the streamline near the blade root is changed greatly, under the same flow condition, the flow far away from the hub in the cascade is increasing, the work ability of blade is reducing, the head has a sharp fall. In this paper, only 0.5mm clearance exist, 2.9% blade surface area is loss, the head decrease 7.86%, shaft power decrease 6.35%, the efficiency from 76.04% down to 74.82%. The conversion formula between the pump station with and without gap clearance is gained by theoretical derivation.

1. Introduction

Impeller as the core components of pumping station, its performance directly determines the safe, stable and efficient operation of the pumping station. In the process of upgrading and remodeling of large pump stations, only the impeller is replaced, and the overall efficiency of the pump device can be greatly improved. For example, after Jiangdu first and second stations have replaced the impeller, the efficiency of the device increases by more than 9% and the flow rate increases by more than 3% [1]. The newly developed impeller at Zaohe Station increased the efficiency of the impeller by 4% compared with that of the previous pump unit, which has significant economic and social benefits. With the improvement of manufacturing level and the development of CFD, it is possible to further study the detailed structure of the blade to meet the requirements of the national economy for the engineering performance and stability of pumping station. On the basis of traditional blade design, some research departments have carried out researches on the detailed structure of the blade, such as blade swept joint forming [2-3], wheel hub leakage flow [4], adjustable blades [5], the fan in the tail of the leaves to imitate the goshawk wing tail structure [6] and other details of the blade structure optimization to enhance the overall performance.

Axial flow pump is characterized by large flow, low lift, high efficiency range of narrow, in the actual operation of the greater impact of changes in the water level, pumping station performance and stability after a sharp departure from the high efficiency area. In order to ensure the safety, stability and economy of the pump station, a variable angle approach is adopted to adapt to different operating conditions. In order to ensure the rotation of the blade in both directions of the rotation center of the blade and the rotation center of the impeller, the impeller chamber is processed into a spherical shape to ensure that the outer edge of the blade remains unchanged from the impeller chamber at all angles, And the root of the blade is greater than the vertical height of the hub spherical surface in the height direction. When the blade angle is adjusted, the root gap inevitably arises, and the gap enlarges further with the adjustable range of the angle. The blade root clearance usually reaches the tip clearance 10 ~ 20 times, have a certain impact on the hydraulic characteristics of the pumping station. In the study of the root clearance of leaves, the hydraulic model of Axial Flow Pumps No. 1 and No. 20 in the same test in Tianjin was tested for sealing wax and non-sealing wax at the root gap when the blade placement angle was zero. The maximum efficiency of the hydraulic model of the 8th hydraulic model exceeded 87% [7], which is the highest efficiency tested by the authoritative hydraulic model of the axial-flow pump at present. The domestic axial flow pump models all perform the performance test under the adjustable blade angle. By studying the root clearance, the hydraulic performance of the axial flow pump can be further improved. The spatial and surface irregularities confined to the root gap and the complexity of the internal flow mechanism has not been able to further investigate the related aspects.

Relevant scholars focus on the study of radial clearance in the tip clearance, literature [8-11] describes the turbine roof clearance on the outer characteristics of the internal flow field and the impact of the structure. Yang Changming [12] carried out a simulation calculation of the axial flow pump with tip clearance, and compared with the test, confirmed the gap on the axial flow pump flow field. Shi Weidong and Zhang Desheng of Jiangsu University [13-14] focused on the research of cavitation of vane clearance and leakage vortex. Li Yaojun [15-16] of China Agricultural University analyzed the pressure pulsation caused by gap. Wang Jueing [17] analyzed the excitation force under the non-uniform tip clearance, and the paper [18-21] also discussed respectively the influence of the end-clearance of the axial flow pump on the performance. The relevant scholars at home and abroad have verified the effect of tip clearance on the efficiency, lift, cavitation performance and pressure pulsation of axial-flow pump, but the research on blade root clearance is much less than the research on tip clearance. The research results are less, and the effect of root clearance on hydraulic performance of axial-flow pump needs to be further explored.

Based on the model test data of a pumping station, the numerical simulation is used to analyze the influence of the axial root pump clearance on the hydraulic performance of the model pump device. The pressure distribution on the blade surface, As well as the impact on the overall performance of the pump device. Based on the basic equations of the blade, the flow phenomenon caused by the root clearance and the influence formula on the axial-flow pump device are discussed, which provides the theoretical basis for the influence of blade root clearance on the axial-flow pump hydraulic

2. Computational model and meshing

2.1. Computational model

Select a vertical model pump device for the study, the impeller diameter of 300 mm, the number of blades 4, the hub ratio of 0.5, the number of guide vanes 7, the model pump speed of 1200 rpm. When the blade is placed at a zero angle, the clearance between the blade root and the hub is measured as 5 mm. As shown in figure 2-f, the tip clearance is 0.3 mm with a feeler gauge. Reference [22] pump device calculation method, the entire calculation domain is divided into bell-shaped inflow and its extension, the impeller chamber, the guide vane chamber, the outlet channel and its extension, the assembly of the various components shown in figure 1.

Inlet flow channel structure for the bell-type, the back wall for the "ω" type, the water outlet is a vertical shaft extension structure [23] form, the overall line is optimized to ensure that the flow of water in the steering flow smoothly. Impeller and guide vane part of the data file into Turbogrid generated.

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2.2. Model meshing

The inflow channel uses an unstructured grid to adapt to the "omega" changing surface and is locally encrypted at the corners. Impeller, guide vane Turbogrid inside the block structure can be easily divided into structured grid. The outlet runner block processing, generating a high-quality structured grid. The surface grids of each part are shown in figure 2, in which the influence of the root clearance on the overall performance of the pump unit is compared and the grids with or without the root clearance of the blades are respectively adopted. The size of the root gap is simulated according to the field test result of 5.0 mm. As shown in figure 2-f, there is no root clearance in the hub portion embedded in the middle of the petiole, and there is a gap at the root water guiding edge and the trailing edge. The root gap is generated using ICEM's grid "engraving" technique. The number of components and the total number of grids are shown in table 1.

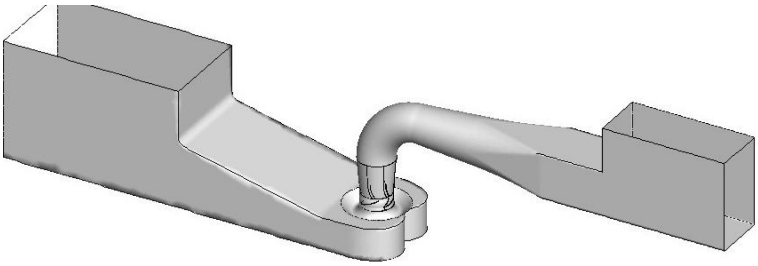
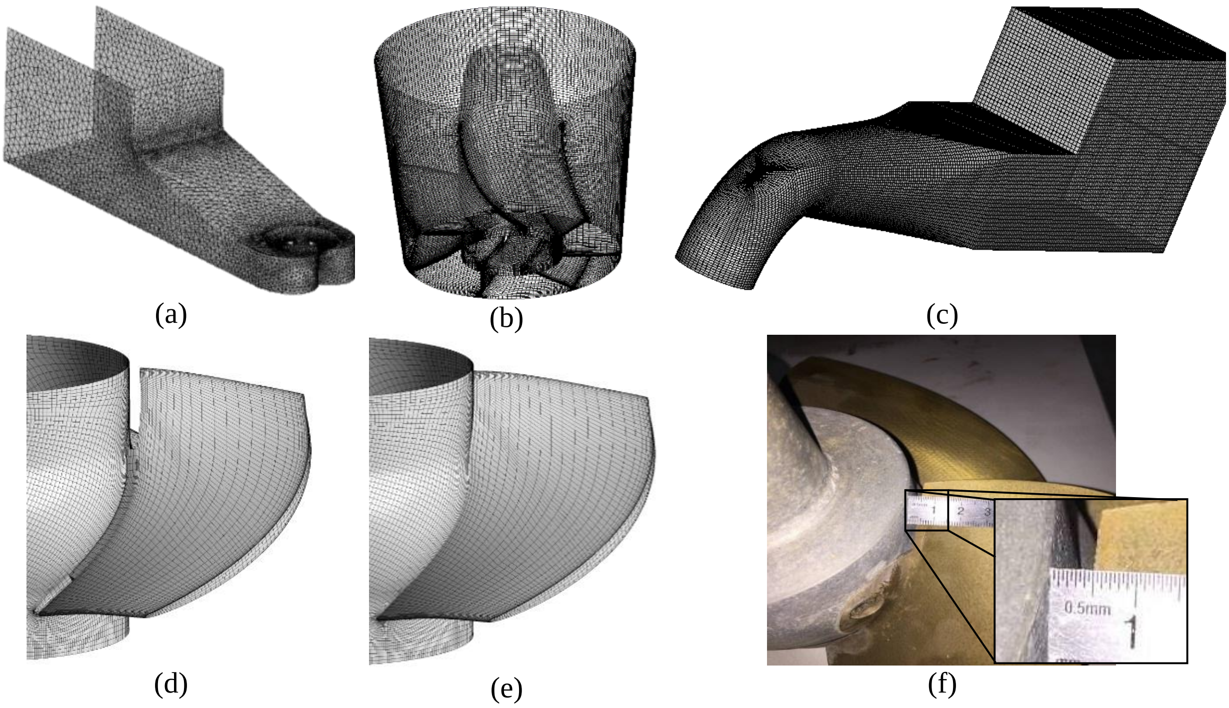


Figure 1. Assembly diagram of vertical axial flow pump system



(a) Inlet runner grid (b) Guide vane grid (c) Outlet runner grid (d) Blade ① (e) Blade ② (f) Root clearance Physical photographing

Figure 2. Surface mesh of parts and picture of blade root clearance

Note: ① contains the blade root gap, ② does not include the blade root gap, the same below

Due to the existence of the root gap, equivalent to the expansion of the fluid computational domain, based on the original grid number has increased. In addition, the existence of the gap also has a certain influence on the structure of the flow field, requiring a more dense grid, so the number of grids is relatively large.

Table 1. Nodes and elements

Calculated domain	Nodes	Grids
Inlet conduits and its extension	102513	468794
impller①	938260	887720
implle②	665760	624544
Guide vane	599214	555513
Outlet conduits and its extension	492704	473373
Summary①	2132691	2385400
Summary②	1860191	2122224

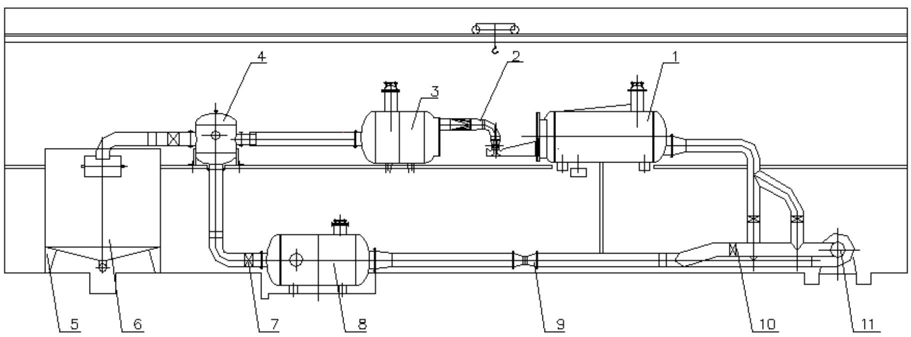
2.3. Boundary conditions settings

Based on the Reynolds-averaged N-S equation, a standard k-ε turbulence model is used to solve the computational domain [24]. Imported with the total pressure import boundary conditions, the export mass flow outlet boundary conditions, followed by the calculation of descending from 7 kinds of different flow conditions, the wall with no-slip wall, the import and export of free surface set to a symmetrical surface, rotating impeller Components and the fixed guide vane and the inlet runner between frozen rotor transfer method of static and dynamic components of the data [25], the remaining interface is set to normal connection. Impeller room calculation domain speed 1200 rpm, because the outer wall of the impeller chamber does not rotate in the rotating field set to reverse rotation, equivalent to stand still in absolute coordinates. The maximum number of iterations is 2000 and the residual value is set to 10^-4. Express the expression of head and torque values in the preprocessor and set the monitoring points to monitor the stability of the points as the secondary convergence criterion.

3. Results and analysis

3.1. Comparison of calculation and test results

Our team finished the on the high precision test bench of Key Laboratory of Hydraulic Power Engineering of Jiangsu Province. The comprehensive accuracy of the test bench is ±0.39%, of which the flow rate uncertainty is 0.16%, the head uncertainty is 0.1%, and the shaft power uncertainty is 0.2%. The rest of the relevant parameters are introduced in reference [26]. The model test procedure is carried out according to "SL140-2006". Figure 3 is a photograph of a high-precision hydro-mechanical test bench and pump unit. The test results and numerical simulation results compared to the chart shown in figure 4.



(a) High-precision hydraulic machinery test stand

(b) Pump Unit Field Test Photograph (c) Impeller room assembly photograph

Figure 3. Picture of high-precise hydraulic machinery test stand and pump system

Note: 1. Inlet tank; 2. Pump unit under test and drive motor; 3. Pressure water tank; 4. Bifurcated water tank; 5-6. Flow in situ calibration device; 7. Condition regulating valve; 8. Regulated rectifier tube; 9. Electromagnetic flowmeter; 10. Positive and negative valve control system run; 11. Auxiliary pump unit

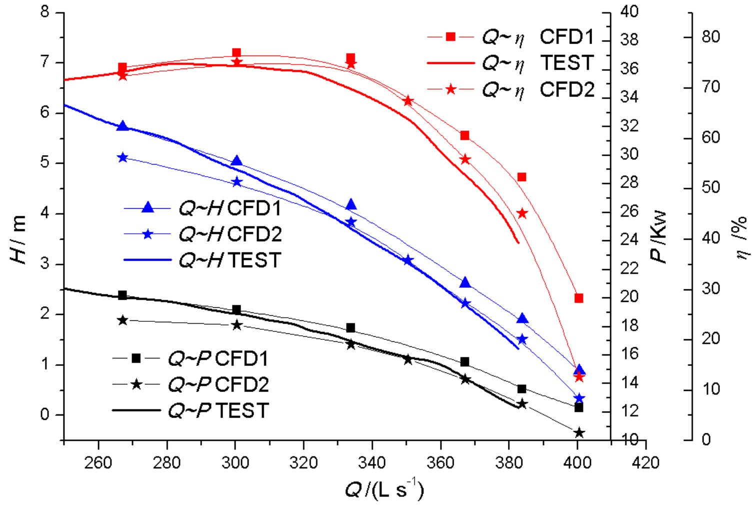


Figure 4. Comparison of experimental data and numerical data

Without considering the root clearance of the blade, the numerical results of the hydraulic performance of the numerical simulation are generally higher than the hydraulic performance of the model test. After taking into account the root clearance, the blade surface area decreases and the actual work capacity decreases, and the root clearance leakage on the blade backside to form a part of the off-flow will affect the reduction of the lift, shaft power and efficiency, which agrees with the model test. With the effect of the root clearance, the simulation result shows that the head decrease 7.86%, shaft power decrease 6.35%, the efficiency from 76.04% down to 74.82% under design conditions. Simulation results that take root clearance into account give better accuracy at design flows and high flow rates.

3.2. Root clearance on the external characteristics of the pump

The differences are summarized in figure 5 based on the simulation results of the external characteristics with the root clearance of the blades minus the external characteristics of the pump without the root clearance.

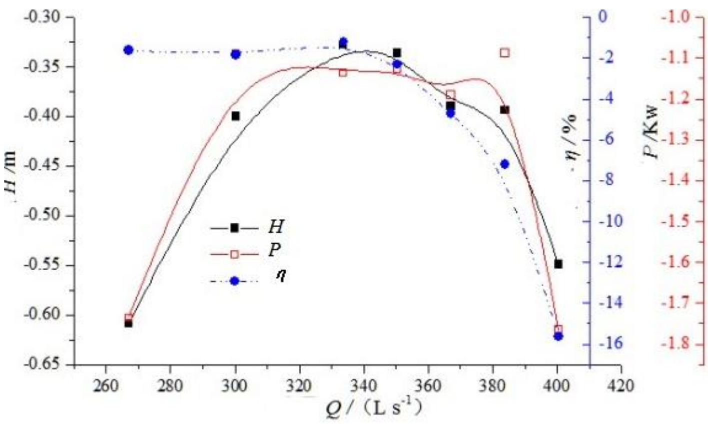
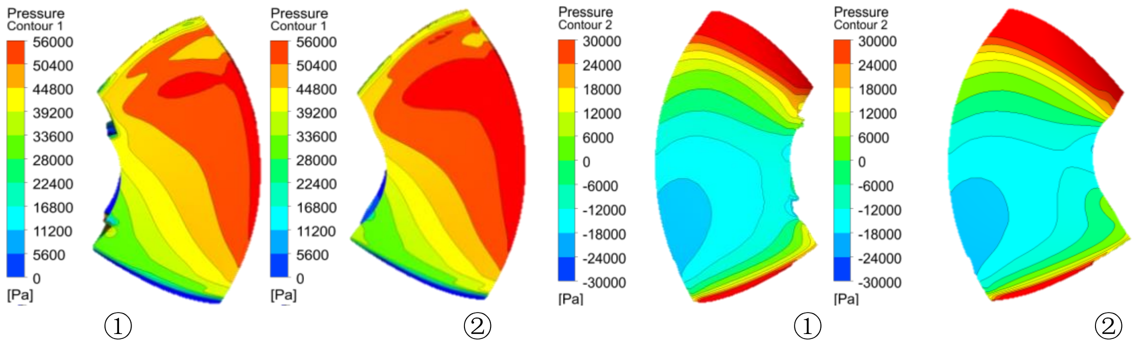


Figure 5. The characteristic variation with the effect of root clearance

In this paper, the blade surface area decreased by 2.9% due to the influence of the root clearance. In the design flow condition, the lift is reduced by 0.328 m, a relative decrease of 7.86%, the shaft power is reduced by 1.137 Kw, a relative decrease of 6.35%, The change of head and shaft power are larger than the area decrease, the efficiency decreases from 76.04% to 74.82%, a decrease of 1.22%. As shown in figure. 5, under the influence of the root clearance, the axial power and lift are more obvious under the condition of design, and the effect is almost constant when the flow rate is less than the design condition.

3.3. Root clearance on the pump device characteristics

3.3.1. Blade surface pressure distribution. The pressure distribution on the blade surface under design conditions is plotted, and the effect of root clearance on the pressure distribution is compared and analyzed as shown in figure 6.



(a) Pressure surface (b) Suction surface

Figure 6. Picture of blade surface pressure distribution

The blade root gap is divided into two sections by the central part of the blade connected with the hub. One section is located close to the flow side and the leading edge of the root gap, and the other section is close to the outlet section side and trailing edge root gap. The pressure distribution on the pressure surface of the blade is less affected by the root clearance of the leading edge, but obviously affected by the root clearance of the trailing edge. The high pressure area decreases as a whole. The pressure distribution on the suction side of the blade surface is less affected by the root clearance, which increases only near the root clearance, leaving the rest almost unaffected. The variation of pressure distribution on the blade surface is also the reason for the decrease of shaft power and lift more than the decrease of area.

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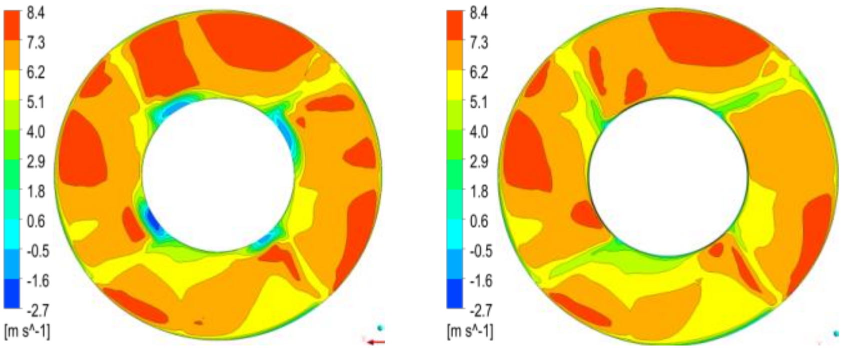
3.3.2. *Axial velocity distribution at the impeller outlet section*. Due to the existence of the root clearance, the velocity distribution at the impeller outlet section will form a local flow near the hub. To compare and analyze the influence of flow on the flow field at the impeller outlet section, the axial velocity distribution at the outlet section of the impeller at design conditions is taken out, shown as figure 7

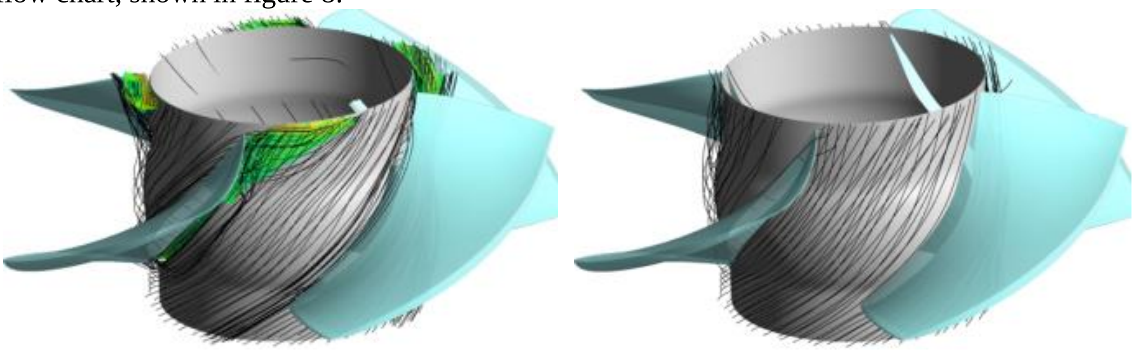


section ① section ②

Figure 7. The velocity contour of axial velocity in the impeller outlet section

It can be seen from the figure 7 that under the influence of the root clearance, the axial velocity distribution at the outlet of the impeller expands along the radial direction, and due to the impact of the leak gap reflux.

3.3.3..Streamline distribution near the hub side. The influence of root gap leakage flow line near the hub side of the leakage vortex mixed, inevitably lead to redistribution of the flow field, here is a near-hub flow chart, shown in figure 8.



impeller① impeller ②

Figure 8. The streamline near the impeller hub

Comparing the streamline near the impeller hub that can be found that under the influence of the root clearance the vortex appeared. The vortex structure on the outlet section side of the blade forms a vortex structure when the flow of the front of the blade through the gap to the back of the blade is mixed with the flow of the back of the blade.

3.3.4. Total pressure distribution at impeller outlet section. The total pressure distribution at the outlet section of the impeller is taken out,and averaged in the circumferential, as shown in figure 9.

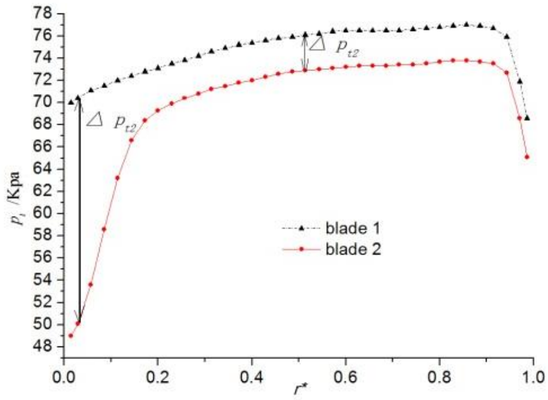


Figure 9. The total pressure at the impeller outlet section along with radial direction.

Note：*r**,radial dimensionless factor,*r**=(*r*- *r*1)/(*r*2- *r*1),r, radius position; r1, hub radius; r2, rim radius.

After the blade comprising a root gap, the value of total pressure at the impeller outlet section turns smaller. The influence of clearance leakage on the hub side is obvious. The affected area r * is 0-0.2, which is larger than the area where the gap is located. However, when r * is 0.2 ~ 0.8, the shaft power is reduced as a whole, although it is far away from the leakage of clearance. However, due to the increase of the flow velocity near the blade surface at the time of r *, the axial power decreases as a whole. The existence of the gap not only causes hydraulic loss at the gap leakage, but also produces a pressure drop Δp_{t2} near the hub side in the figure. More importantly, the velocity distribution at the outlet of the vane changes the distribution of the flow field, So that the operating conditions relative to the blade root clearance to the large flow direction offset, resulting in the graph away from the hub Δp_{t1} pressure drop.

This also explains exactly the phenomenon that the efficiency of the axial flow pump device with the root gap is greatly decreased under the condition of large flow rate, as shown in figure 5. Because the efficiency curve is high efficiency near the design condition and decreasing on both sides of the curve, when the blade root clearance makes the efficiency curve of the axial flow pump device offset to the left, and the overall decline, this creates a significant reduction in efficiency at high flow rates.

3.3.5. Velocity distribution changes along the radial direction on the impeller outlet section. The axial, tangential and radial velocity distributions of the impeller outlet section in the absolute coordinate system are respectively taken out and averaged in the circumferential direction, as shown in figure 10.

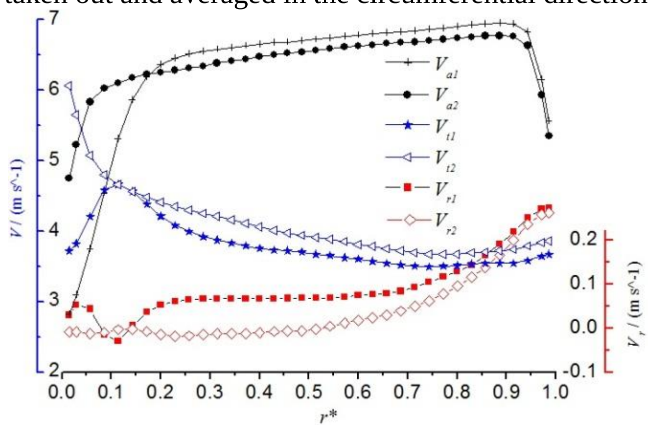


Figure 10. The velocity in the impeller outlet section along with radial direction.

The axial velocity changes most obviously. It decreases most in the range of 0-0.2 in the region, and decreases by about 2 m / s. Because of the same inlet flow rate, the conservation of flow rate is maintained at r * of 0.2-1.0. The tangential velocity directly reflects the work done by the blade on the water body. As can be seen from the figure, the decrease of the near hub side is the most obvious, and the rest is also reduced. The radial velocity increases as a whole, with some fluctuations at the r * of 0.1.

4. The approximate calculation of the effect of blade root clearance on axial-flow pump device

To analyze the effect of root clearance on pump performance, start with the pump's basic equations:

$$H = \frac{u_2 V_{u2}}{g} \tag{1}$$

Expanded along the radius can be expressed as:

$$H = \int_{r1}^{r2} \frac{\omega r v_{u2}}{gA} 2\pi r dr \tag{2}$$

In the same flow conditions, the total import flow rate unchanged, the additional leakage flow is set to ΔQ, the unit of time the actual flow of impeller work on the fluid is:

$$Q' = Q + \Delta Q \tag{3}$$

The amount of leakage is related to the area occupied by the lift and clearance of the vanes. The leakage flow at the inlet and outlet tails of the vanes is connected to form a closed area. The amount of leakage can be calculated using the formula of orifice flow:

$$\Delta Q = A' Cr\sqrt{2gH} = \xi\sqrt{H} \tag{4}$$

Among them, $\xi = A' Cr\sqrt{2g}$

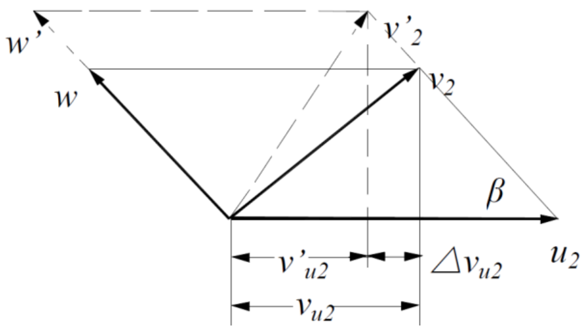


Figure 11. The picture of the meridional velocity change

After the flow rate increases, the total velocity v'u2 in the tangential direction decreases, which is the reason for the head reduction. Corresponding to $\Delta pt1$ in figure 8, the other part Δp_{t2} is caused by the reduction of the blade area and the hydraulic loss in the gap. Which Δp_{t1} can be seen as the deviation caused by the conditions can be calculated by the following formula:

$$\Delta H = k * \Delta Q \tag{5}$$

K, the slope of the flow head curve, in this paper 46.6 m^2 /s

Taking into account the root clearance, the original from the hub to the rim of r1 into r0, assuming that the hydraulic leakage caused by leakage and petiole part of the lift head is roughly the same, and then the head expression can be written as

$$H' = \frac{H - \Delta H}{H} \int_{r0}^{r2} \frac{\omega r v_{u2}}{gA} 2\pi r dr = (1 - \frac{k * \Delta Q}{H}) \frac{(r2^3 - r0^3)}{(r2^3 - r1^3)} H \tag{6}$$

$$N' = \rho g Q' H' = \frac{(Q + \Delta Q)(H - \Delta H)}{QH} \frac{(r2^3 - r0^3)}{(r2^3 - r1^3)} N \tag{7}$$

*r*2, 150 mm； *r*1,67.5 mm； *r*0, blade root outlet side radius,72.5 mm； *A'*,Root gap leakage area,4.74E-4 m^2； *Cr*,Clearance leakage hydraulic loss coefficient, take 0.82。

With Q=0.338 m^3/s, H=4.175 m available H'=0.938 H, N'=0.947 N, very close to the numerical simulation results H'=0.921 H,N'=0.938 N

5. Conclusions

In this paper, the influence of blade root clearance on the performance of axial-flow pump is analysed through numerical simulation, model test and theoretical analysis. The main conclusions are as follows。

- The existence of root clearance has obvious influence on the hydraulic performance of axial flow pump. On the one hand, root clearance leakage forms vortex belt on the outlet section side of impeller, which worsens the flow field distribution at the outlet of impeller, On the other hand, the increase of the flow rate away from the hub side reduces the overall workability of the pump device.
- Due to the existence of the root gap, the surface area of the blade decreased by 2.9%. Under the Q_d condition, the lift of the blade decreased by 7.86%, the shaft power decreased by 6.35% and the efficiency decreased from 76.04% to 74.82%, a decrease of 1.22%. Head and shaft power changes are greater than the area reduction rate, the blade root of the most obvious impact on the head, followed by shaft power, the minimum efficiency.
- Through the theoretical derivation, the formula of the head and shaft power of the pump device after the root clearance leakage was obtained, and the comparison with the numerical simulation results proved its feasibility.

Acknowledgments

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