Performance analysis of a new type of space guide vane for T-type hydraulic turbine

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Abstract
At present, the flow passage of multistage T-type (designed according to the theory of hydraulic prime mover) hydraulic turbine directly adopts pump type interstage guide vane, which has poor matching degree and low performance. In order to improve the performance of T-type hydraulic turbine, this paper takes a two stage T-type hydraulic turbine as the research object, designs a new type of space guide vane as its interstage guide vane according to the theory of hydraulic prime mover, selects the thickness of the baffle, the diameter of outer edge of guide vane, the outlet angle of positive guide vane, and the number of guide vanes to formulate L\textsubscript{0} (3\textsuperscript{4}) orthogonal test, and applies CFD numerical calculation to 9 Through the range analysis method, the primary and secondary factors affecting the external characteristics of T-type hydraulic turbine are found out. The results show that the outer diameter of the guide vane has the greatest influence on the performance of the new type of space guide vane. In order to further study the influence of guide vane outer diameter on turbine performance, four different guide vane outer diameter of 700mm, 750mm, 800mm and 850mm are selected to analyze its influence on the outer characteristics and internal flow field of the whole T-type hydraulic turbine. It is found that with the increase of the outer diameter of the guide vane, the efficiency of the hydraulic turbine increases first and then decreases, the head decreases first and then increases, and there is an optimal value of the outer diameter of the guide vane. As the diameter of the outer edge increases, the flow path of the positive guide vane and the negative guide vane becomes longer, the flow velocity decreases, the flow control ability decreases, the turbulent kinetic energy increases, the area of the high pressure area of the negative guide vane decreases, and the flow pattern becomes worse.

Keywords: T-type hydraulic turbine; New space guide vane; Performance analysis; CFD;

Introduction: Hydraulic turbine is a kind of energy recovery device, which is commonly used in mining, power and industrial fields. At this stage, most of the hydraulic turbine units use the reverse pump as the flow channel. In recent years, some scholars have proposed a new type of T-type hydraulic turbine, in addition to the pump type hydraulic turbine. Its flow passage is designed according to the hydraulic prime mover theory, which can effectively solve the problems of low efficiency and narrow efficient area of the pump type flow passage. The research shows that the T-type hydraulic turbine has a good flow state and stable performance \cite{1-2}. In the study of T-type hydraulic turbine, Zhu Pengyan et al\textsuperscript{3} studied the hydraulic effect of different runner blades on each flow passage component. At the same time, in the process of optimizing multistage T-type hydraulic turbine, it is found that the loss of interstage guide vane accounts for 30% to 40% of the total loss, and the performance of interstage guide vane directly affects the performance of the whole flow passage, which cannot be ignored\cite{4}.

As the middle part of the device, the interstage guide vane receives the flow from the upper runner and changes the speed circulation to meet the circulation required by the next runner. Its structure mainly includes axial guide vane, radial guide vane, runner guide vane, space guide vane and new a new type of space guide vane. Among them, the axial guide vane does not have a positive guide vane, and its structure is incomplete; the radial guide vane is a combination of positive guide vane and negative
guide vane, with low efficiency; the positive guide vane, reverse guide vane and transition section of runner guide vane are all separate parts, with relatively high processing and manufacturing costs. The space guide vane is a twisted shape in space, and the positive and negative guide vanes are connected as a whole. The whole guide vane is divided into independent flow channels, with strong flow conductivity, but the structure is short in radial direction and long in axial direction, which is suitable for pump flow channels [5-7]. At present, there are few researches on the interstage guide vane at home and abroad, especially on the structure of interstage guide vane. Most multistage centrifugal pumps and multistage hydraulic turbines are directly composed of positive and negative guide vanes, with low efficiency [8-9].

In recent years, some scholars have designed a new type of space guide vane based on the characteristics of traditional space guide vane twisted blade and small axial dimension of radial guide vane. The axial dimension of the new type of space guide vane is small, and the flow channels is independent, which is conducive to reducing hydraulic loss, as shown in Figure 1. Yuan Danqing et al [10-11] used the new type of space guide vane in deep well centrifugal pump. Compared with the traditional space guide vane, the processing technology is good, the axial up and down draft is available, the injection molding is convenient, and it is conducive to standardized production. At the same time, it is found in the application of the multi-stage centrifugal pump that the space twisted guide vane formed by the smooth transition connection of the positive and negative guide vanes of the new type of space guide vane has the characteristics of the axial distance break of the radial guide vane and the smooth transition of the passage of the space guide vane, which is helpful for the energy saving of the multi-stage pump. The results show that the new spatial has better performance for pump runner, but it is difficult to find a specific research on the application of T-type hydraulic turbine.

Researching out a new type of space guide vane suitable for T-type hydraulic turbine can improve the performance of the entire T-type hydraulic turbine and increase the residual energy recovery rate.

![Fig. 1-1 New type space guide vane](image_url)

1. Determination of Research Model

This paper selects an ultra-low specific speed mixed flow turbine two-stage hydraulic turbine runner for research. The basic parameters of the two-stage runner are Q = 0.87m³ / s, the specific speed is 50m.kw, and the speed is 1500r / s. Runner inlet diameter D₁ = 500mm, runner outlet diameter D₂ = 250mm, runner inlet angle β₁ = 122 °. According to the basic data of the runner, the basic data of the new space guide vane is calculated as follows: the guide vane inlet diameter D₃ = 250mm, the guide vane outlet diameter D₄ = 502mm, the inlet width and outlet width b₃ = b₄ = 50mm. The water inlet chamber is a volute water inlet chamber with a water inlet section radius of 0.137m. The water outlet chamber adopts a circular water outlet chamber. As shown in Figure 1-2.
1.2. Determination of Water Inlet Angle and Circulation Required by Runner

The guide vane plays the role of changing the velocity loop, and the $C_1$ flow at the exit of the guide vane should meet the requirements of the inlet loop of the connected rotor. Except for the first stage runner, which is not affected by the interstage guide vane, the inflow conditions of the other stage runners are directly affected by the interstage guide vane. The degree of matching between the interstage guide vane and the connected runner has an important effect on the overall efficiency.

In this paper, the mixed flow runner with ultra-low specific speed is used in the two stages of T-type hydraulic turbine channel, and the inlet angle $\beta_1 = 122^\circ$. According to the basic equation (formula 2-1) and the velocity loop formula (formula 2-4), the inlet angle $\alpha_1$ of water flow required by the runner is $13.44^\circ$ (2-2, 2-3), and the required velocity loop is $64.94$.

Export of French exports: $v_{u2}=0$,

$$H\eta = \frac{1}{\rho} (u_1 v_{u1} - u_2 v_{u2})$$

(2-1)

$\eta = \frac{1}{\rho} u_1 v_{u1} = \frac{1}{\rho} u_1 v_{in1} \tan^{-1} \alpha_1 = \frac{1}{\rho} u_1 \frac{\vartheta}{\pi R_1} \tan^{-1} \alpha_1$

(2-2)

$$u_1 = \frac{\pi D_1 n}{60}$$

(2-3)

$$C_1 = 2\pi r_1 v_{u1} = 2\pi r_1 \frac{v_{u1}}{\tan \alpha_1} = 2\pi r_1 \frac{\vartheta}{\pi R_1} \alpha_1$$

(2-4)

2. Orthogonal Experimental Design

2.1 Determination of orthogonal test factors and test scheme

The main structural parameters affecting the performance of the new type of space guide vane are the thickness of the baffle, diameter of outer edge of guide vane, Positive guide vane exit angle, and the number of guide vanes. These four factors are selected to design a four-factor three-level L9 (3^4) test scheme. Considering the matching and rationality of the whole device, the diameter of the outer edge of the new type of space guide vane is usually $1.4D_1 - 1.7D_1$; the thickness of the baffle is $0.8b_3 - 1.4b_3$; it is calculated that the inlet angle of the liquid flow required by the runner is $13.44^\circ$; considering the speed slip at the inlet of the runner, the outlet angle of the positive guide vane is selected as $15^\circ, 17^\circ, 20^\circ$, and the number of guide vanes is selected as 8, 10, 12. Design scheme under different size parameters. The specific scheme is shown in Table 2-1, 2-2.

| Thickness of the baffle ($b_7$) | Diameter of outer edge of guide vane ($D_4$) | Positive guide vane exit angle ($\alpha_1$) | the number of guide vanes ($Z$) |
|--------------------------------|---------------------------------------------|---------------------------------------------|--------------------------------|
| Level 1                        | 50                                          | 700                                         | 8                              |
| Level 2                        | 60                                          | 750                                         | 10                             |
| Level 3                        | 70                                          | 800                                         | 12                             |
2.2 Results and Analysis of Orthogonal Simulation Test

2.2.1 Analysis of efficiency and head test results

Table 2-3 Efficiency of each design scheme under design flow

| Scheme number | \( \eta \) (%) | Scheme number | \( \eta \) (%) | Scheme number | \( \eta \) (%) |
|---------------|----------------|---------------|----------------|---------------|----------------|
| (1)           | 73.44          | (4)           | 70.26          | (7)           | 68.28          |
| (2)           | 72.61          | (5)           | 73.58          | (8)           | 72.85          |
| (3)           | 71.03          | (6)           | 60.88          | (9)           | 65.87          |

Table 2-4 Head of each design scheme under design flow

| Scheme number | \( H \) (m) | Scheme number | \( H \) (m) | Scheme number | \( H \) (m) |
|---------------|-------------|---------------|-------------|---------------|-------------|
| (1)           | 491.47      | (4)           | 483.11      | (7)           | 469.21      |
| (2)           | 468.69      | (5)           | 476.60      | (8)           | 484.08      |
| (3)           | 470.91      | (6)           | 450.22      | (9)           | 463.24      |

2.2.2 Range analysis of experimental results

After post-processing the data in table 2-3 and 2-4, the range analysis of efficiency and head after orthogonal processing is obtained as shown in table 2-5 and table 2-6, respectively, and the figure 2-1 and figure 2-2 are obtained.

Table 2-5 Analysis of efficiency range

| Level ① | Thickness of the baffle | Diameter of outer edge of guide vane | Positive guide vane exit angle | The number of guide vanes |
|---------|-------------------------|--------------------------------------|-------------------------------|---------------------------|
| Level ② | 72.36                   | 70.66                                | 69.06                         | 70.96                     |
| Level ③ | 67.24                   | 73.01                                | 69.43                         | 67.26                     |
| R       | 5.12                    | 7.08                                 | 1.1                           | 4.12                      |

Table 2-6 Analysis of head range

| Level ① | Thickness of the baffle | Diameter of outer edge of guide vane | Positive guide vane exit angle | The number of guide vanes |
|---------|-------------------------|--------------------------------------|-------------------------------|---------------------------|
| Level ② | 477.02                  | 481.26                               | 469.21                        | 477.10                     |
| Level ③ | 469.98                  | 476.46                               | 471.68                        | 462.7                      |
| R       | 472.18                  | 461.46                               | 472.24                        | 479.37                     |
| R       | 7.04                    | 19.8                                 | 6.58                          | 16.67                      |
The structural parameters of the new type of space guide vane have the same trends for the T-type hydraulic turbine efficiency and head influencing factors. The outer diameter of the guide vane is greater than the thickness of the baffle, the number of guide vanes, and the exit angle of the positive guide vanes. In terms of efficiency, the diameter of the outer edge increases, and the efficiency increases first and then decreases. The efficiency is highest when the diameter is 750 mm. When the thickness of the baffle increases, the efficiency decreases first and then rises. The efficiency is the highest at 50 mm. The reason may be that the increase of the thickness of the baffle increases the area of the transition section, reduces the control ability, and reduces the pressure. The positive guide vane exit angle has little effect on the overall performance, and the efficiency of the exit angle change is not obvious. When the number of guide vanes increases, the efficiency decreases first and then rises. The maximum is when the number of guide vanes is 12. In terms of head, the diameter of the outer edge increases, the head shows a downward trend, the thickness of the baffle increases, the head decreases first and then increases, and the head has the largest head when the thickness of the baffle is 50 mm. The positive guide vane exit angle has no significant effect on the overall lift of the hydraulic turbine, and the increase in the number of guide vanes decreases first and then increases.

3. Influence of Different Outer Edge Diameters of New Type Space Guide Vanes on Overall Performance

The results of orthogonal experiment show that the variation of the outer diameter of guide vane has the most significant influence on the performance of the whole T-type hydraulic turbine. In order to further study the influence of the variation of the outer diameter of guide vane on the performance of T-type hydraulic turbine, four kinds of new space guide vanes, i.e. the number of guide vanes is 12, the thickness of the baffle is 50 mm, the diameter of outer edge is 700 mm, 750 mm, 800 mm and 850 mm, are selected to study and analyze their influence on the performance of the whole T-type hydraulic turbine. The external characteristics and internal flow field of the model turbine are studied.

3.1 Flow-Efficiency, Flow-Head Out-of-Head Characteristics Analysis
(a) External characteristics of head and efficiency under rated conditions
(b) External characteristics of head efficiency under different flow conditions

Fig. 3-1 External characteristic curves for different outer diameters of guide vanes

When the diameter of the outer edge of the guide vane increases, the efficiency first increases and then decreases, reaching the highest value at 750mm. Under different working conditions, the efficiency presents the same trend, reaching the highest value near the rated working condition. The head decreases gradually, and the lowest value at 800mm, and then has an upward trend. The larger the flow is, the greater the head is. Because the diameter is too small, the flow buffer channel of the negative guide vane is short, the flow velocity of the transition section changes abruptly, the impact force and impact loss are large, the head efficiency is low, but the diameter of the outer edge of the guide vane is too large, the flow channel of the negative guide vane is long, the flow velocity is reduced, the pressure is reduced, and the flow in the negative guide vane channel produces eddy current, the loss is large, and the efficiency is reduced. Through the model test, when the diameter is 750 mm, the loss of liquid flow is small and the comprehensive value of head and efficiency is the best.

3.2 Internal Flow Field Analysis
3.2.1 Internal turbulent kinetic energy distribution

When the diameter of the outer edge of the guide vane is the smallest, the local area of the turbulence intensity of the negative vane is partially caused by the short passage of the negative vane, the large curvature of the negative vane, and the large impact of the liquid flow on the positive guide vane. In the area of high turbulence intensity, when the diameter increases to 750mm, the area of high turbulence disappears and the intensity of turbulence decreases, but when the outer diameter continues to increase, the side of the flow path of the negative vane becomes longer, and the hydraulic force generates vortices in the flow path, and the loss increases. The turbulence intensity increases, and the turbulence energy increases proportionally.

![Turbulent kinetic energy characteristic curve inside different guide vane outer diameter](image)

Fig. 3-3 Turbulent kinetic energy characteristic curve inside different guide vane outer diameter

(a) Diameter 700mm (b) Diameter 750mm (c) Diameter 800mm (d) Diameter 850mm

Fig. 3-4 Turbulent kinetic energy distribution inside different guide vane outer diameter

3.2.2 Analysis of internal pressure characteristics
The diameter of the outer edge of the guide vane increases from 700mm to 850mm, and the pressure distribution of the whole new space guide vane decreases gradiently from the inlet of the negative guide vane to the outlet of the positive guide vane. When the outer diameter is 700mm, the negative guide vane pressure has a sudden change area, and the positive guide vane has a gradient reduction. When the outer diameter is 850mm, the negative guide vane has a long flow passage, and the flow pattern in the negative guide vane flow passage becomes poor after the liquid passes through the segment speed reduction, and the pressure distribution appears disorder, and the gradient is not obvious. At the same time, with the increase of diameter, the area of the high pressure area of the guide vane decreases, the reason is the increase of diameter, the decrease of flow velocity and pressure.

![Fig. 3-5 Internal pressure distribution inside different guide vane outer diameter](image)

3.2.3 Analysis of internal streamline characteristics

With the increase of the outer diameter of the guide vane, there is no obvious effect on the flow line of the positive guide vane. With the increase of the outer diameter of the guide vane, the flow speed decreases, and the flow line of the negative guide vane gradually presents vortex. The larger the diameter is, the larger the vortex area is, and the internal loss of the whole new space guide vane increases, which is consistent with the decrease of the efficiency and the increase of the head.

![Fig. 3-6 Internal streamline distribution inside different guide vane outer diameter](image)

3.2.4 Analysis of internal velocity loop characteristics

The guide vane plays the role of changing the speed loop, and at the same time, the C₁ flow at the exit loop of the guide
vane needs to meet the inlet loop of the connected runner. When the liquid flows out of the guide vanes, there is a certain amount of ring. If this part of the ring is too small, there will not be enough ring to enter the connected runner, and the internal flow state of the secondary runner will be disordered. Conversely, if this part of the loop is too large, it will increase internal losses. Making the liquid flowing out of the guide vane enter the lower runner with an optimal amount of loop is helpful for the optimization design of the flow path and is more beneficial to improving the performance of the T-type hydraulic turbine device.

Increasing the outer diameter of the new type of space guide vane, the velocity loop volume will increase first and then decrease, and the maximum value is 750 mm. The velocity loop volume at the exit of the guide vane from 800mm to 850mm will hardly change, and both are less than 700mm and 750mm. The longer the side, the lower the flow rate, and the lower the loop volume. At the same time, the speed loops of the guide vane outlets at the four outer edge diameters did not meet the speed loops required for the second-stage runners. The reason is that the guide vane shape is poor, the water conductivity is weak, and the ability to change the flow loop is weak.

![Fig. 3-7 Velocity loops of different outer diameters of guide vanes](image)

4 Conclusion

1. The axial dimension of the new type of space guide vane is smaller than that of the traditional type of space guide vane, which can effectively reduce the axial dimension of the whole T-type hydraulic turbine. The whole channel are divided into several flow channels, and each channel is independent. For T-type hydraulic turbine, considering the matching and rationality of the whole device, the diameter of the outer edge of the new type of space guide vane is usually 1.4D, and the thickness of the baffle is 0.8b3. Considering the speed sliding of the runner inlet, the outlet of the new type of space guide vane is β 1 + 2 ° ~ 5 °, and the number of guide vanes should be about 10.

2. The L9 (3^4) test schedule is made by selecting the thickness of the baffle, the diameter of the outer edge of the guide vane, the outlet angle of the positive guide vane and the number of the guide vanes. The results show that the order from large to small of influencing the external characteristics of T-type turbine efficiency is: the diameter of the outer edge, the thickness of the baffle, the number of guide vanes and the outlet angle of the positive guide vane; the order from large to small of influencing the external characteristics of the head is: the diameter of the outer edge, the number of guide vanes, the thickness of the baffle and the outlet angle of the positive guide vane.

3. With the increase of the outer diameter of the new type of space guide vane, the efficiency of the T-type turbine increases first and then decreases; the head decreases first and then increases, and the outer diameter has the optimal value. At the same time, the negative of the guide vane and the positive guide vane is longer, the flow velocity is reduced, the flow control ability is weakened, the turbulent kinetic energy is increased, the area of the high pressure area of the guide vane is reduced, the pressure distribution edge of the positive guide vane is disordered, the streamline becomes poor, and the velocity...
circulation first increases and then decreases.

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