Effect of Inlet Section of Circular Section Spiral Case on Performance of Ultra-Low Specific Speed Diagonal Flow Turbine

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Abstract: Variation of section area at volute inlet is a key factor affecting turbine performance. By changing the inlet section of the turbine volute, the inlet angle of the guide vane is changed, so the guide vane parameters will also be changed, which will affect the turbine performance. In order to study the influence of different volute inlet section areas on the overall hydraulic performance of ultra-low specific speed diagonal flow turbine, this paper redesigns the volute inlet section area of an ultra-low specific speed diagonal flow turbine. On the premise of applying the same runner, seven different volute inlet circular sections are designed. The numerical simulation of the full flow channel is carried out for each scheme, and the influence of inlet circular section area of different volutes on hydraulic performance of the ultra-low specific speed diagonal flow turbine is analyzed and compared. The results show that with the increase of flow rate, the calculated head and runner loss of the turbine increase, and the hydraulic efficiency of the turbine first increases and then decreases. When the turbine runs under small flow conditions (less than rated flow), the hydraulic efficiency of the turbine increases with the decrease of the diameter of the inlet circular section of the volute. When the turbine operates under high flow condition (greater than rated flow), the hydraulic efficiency of the turbine decreases with the decrease of the diameter of the inlet circular section of the volute. Through comparative analysis of seven schemes, the optimum radius of the inlet circular section of volute for the ultra-low specific speed diagonal flow turbine is 127mm and the corresponding inlet angle of guide vane is 32°. At this time, the efficiency of the turbine is 81.59% and the calculated head is 4.821m. The flow pattern inside the turbine is more uniform without whirlpools. It provides a reference for future design of similar type turbines and selection of suitable volute inlet circular section area.

Key word: Ultra-low specific speed diagonal flow turbine, turbine volute, CFD, numerical simulation, hydraulic performance

0 Introduction

Utilizing the surplus head of circulating water pump in cooling tower and gravitational potential energy of water in circulating cooling water system, the fan is driven by ultra-low specific speed turbine instead of electric motor[1], thus achieving the purpose of energy saving and consumption reduction. According to the requirement of specific speed of turbine for cooling tower, the specific speed of Francis turbine is the lowest in reaction turbine. Therefore, since 2008, Professor Dexin Chen[2] and Professor Yuan Zheng[3] have designed ultra-low specific speed mixed flow turbines specially for industrial cooling towers. Although the specific speed of axial-flow turbines and diagonal-flow turbines is higher than that of Francis turbines, axial-flow turbines can overcome the problems of oversize dimensions and difficulty in welding runners when using Francis turbines. In 2011, Professor Yanpin Li[4] applied the axial-flow turbine to the fan driven by the hydraulic cooling tower. The
application of diagonal flow turbine is between Francis turbine and axial flow turbine. At the same time, the diagonal flow turbine has the advantages of both and is easier to achieve super specific speed. Yingxin Wu\cite{5} has designed the ultra-low specific speed diagonal flow turbine based on the ultra-low specific speed mixed flow turbine as the template.

At present, in the field of ultra-low specific speed turbine, scholars have studied the guide vane number, impeller geometry parameters, volute section shape and geometry parameters of Francis turbine and axial flow turbine\textsuperscript{[6-11]}. However, there are few studies on the ultra-low specific speed diagonal flow turbine. As the inlet of the ultra-low specific speed diagonal flow turbine, the size and geometry of the volute have a great influence on the hydraulic performance of the turbine. In turbines, the change of volute section area will change the inlet angle of the guide vane, so the type of guide vane will also change, which can change the inlet circulation of the runner, so that the ultra-low specific speed diagonal flow turbine will have the better hydraulic performance.

This paper takes an ultra-low specific speed diagonal flow turbine as the research object, carries out retrofit design based on different dimensions of volute inlet circular section, and puts forward seven schemes. Under five flow conditions, each scheme is numerically simulated by ANSYS to accurately predict and analyze the performance of the turbines.

1 Parameters and geometric structure of turbine

The research object of this paper is an ultra-low specific speed diagonal flow turbine, whose basic design parameters are shown in Table 1.

| Flow (m\(^3\)/h) | Head (m) | Specific speed (m\(^3\)/kW) | Average diameter of runner inlet (mm) | Number of blades | Speed (r/min) | Guide vane outflow angle (°) | Number of guide vane |
|-----------------|----------|-----------------------------|--------------------------------------|-----------------|---------------|-------------------------------|---------------------|
| 500             | 7.5      | 55                          | 420                                  | 22              | 240           | 13                           | 19                  |

The guide vane inlet angle of the ultra-low specific speed diagonal flow turbine changes with the size of the volute inlet circular section. The geometrical structure of the volute in this study is shown in Figure 1.

\textbf{Figure 1.} The geometrical structure of the volute
The volute inlet section of the turbine model selected in this paper is circular. On the basis of the research object, this research changes the size of the inlet circular section of the volute by increasing or decreasing the average flow velocity of the volute. This will cause a change in the inlet angle of the guide vane and the type of guide vane will change accordingly. Based on this, this paper mainly studies the influence of different volute inlet circular section sizes on hydraulic performance and efficiency of ultra-low specific speed diagonal flow turbine. Main scheme parameters are shown in Table 2.

Table 2 Seven specific scheme parameters

| Scheme number | Inlet circle section radius \(D_0\) (mm) | Section average velocity \(V_0\) (m/s) | Guide vane inlet angle \(\theta\) |
|---------------|------------------------------------------|--------------------------------------|--------------------------------|
| Scheme one    | 144                                      | 4.024                                | 41                             |
| Scheme two    | 140                                      | 4.343                                | 39                             |
| Scheme three  | 136                                      | 4.679                                | 37                             |
| Scheme four   | 131                                      | 5.138                                | 35                             |
| Scheme five   | 127                                      | 5.798                                | 32                             |
| Scheme six    | 122                                      | 6.365                                | 30                             |
| Scheme seven  | 118                                      | 6.987                                | 28                             |

2 Numerical calculation of geometric models

The full-channel 3D geometric model of the ultra-low specific speed diagonal flow turbine which from the volute inlet to the draft tube outlet is established on the basis of Creo as shown in Figure 2.

![Figure 2. The full-channel 3D geometric model of ultra-low specific speed diagonal flow turbine](image_url)

The full flow path of the turbine consists of four parts: volute, fixed guide vane, diagonal flow runner and draft tube. For the seven schemes listed in Table 2, this study will establish 3D models and unstructured grid partition of 3D models for each scheme is carried out by ICEM. ANSYS-FLUENT is used as a pressure-based solver, which mainly uses pressure correction algorithm and is good at solving incompressible flow and steady-state solution. Because of the strong rotation of internal flow and strong 3D random fluctuation, the turbine has the features of high reverse pressure gradient and high streamline curvature, the standard k-\(\omega\) model is used for turbulence model. The inlet boundary of volute is set as speed inlet condition and outlet condition of draft tube is set as pressure outlet condition. In the model of ultra-low specific speed inclined flow turbine, the interface between volute and fixed guide vane is static-static interface, the interface between fixed guide vane and runner is dynamic-static interface, and the interface between runner and draft tube is dynamic-static interface.
All interface parts are set as interface connection.

3 Analysis of calculation results

3.1 Fixed guide vane and runner line distribution

The flow line distribution of fixed guide vanes and runners is affected by the different dimensions of the inlet circular section of the volute. As shown in Figure 3, the longitudinal conclusion of this study is: (a) Under the same flow condition and different volute inlet circular section sizes, the water flow velocity increases from guide vane inlet to outlet along the direction of fixed guide vane. Because the inner streamline of the runner has a certain angle with the inner streamline of the guide vane, there is a local impact at the outlet of the guide vane, which causes the increase of velocity. (b) As the dimension of the inlet circular section of the volute decreases, due to the impact of the water flow entering the runner, the outflow at the inlet and outlet of the runner blades becomes worse. (c) As the size of the inlet circular section of the volute decreases, the loss of the runner increases, and secondly, the flow rate from the guide vane to the runner increases, which will cause partial flow instability. Therefore, the runner flow line becomes more and more uneven when the dimension of the inlet circular section of the volute is reduced.

In the operation of the turbine, the flow will change with the change of operating conditions. Here, three operating conditions (0.8Qo, 0.9Qo, 1.0Qo) are selected for lateral comparison and analysis: With the increase of flow rate, the velocity at guide vane outlet shows an increasing trend. High-speed water flow exists at the guide vane outlet under different flow conditions and the same volute inlet circular section size. With the increase of inlet flow velocity of volute, the speed of water flow entering the runner will increase and the hydraulic loss of the runner will increase accordingly. Unstable flow will also occur in the runner, but in general, the runner flow of each scheme is better, the streamline is smooth without vortices, and the streamline is evenly distributed along the blades.

Scheme one (41°)

Scheme two (39°)
Figure 3. Flow Line Distribution of Fixed Guide Vanes and Runners under Variable Flow Conditions

3.2 Pressure distribution of runner blades
Pressure distribution of turbine runner blades under design conditions is shown in Figure 4. The pressure distribution on the working surface and back of the runner blades in each scheme is uniform, and the pressure at the inlet of the working surface of the blades is higher than that at the inlet of the back side, which makes use of energy conversion. Moreover, the pressure transition at the inlet side of the blade working surface is relatively uniform and the pressure distribution at the back side of the blade is basically symmetrical. In contrast, with the reduction of the size of the circular section at the large volute inlet, the pressure at the blade inlet increases gradually in a small range. This is because, under design conditions, with the reduction of the inlet circular section size of the volute, the flow velocity entering the runner will increase, and some unstable flow conditions will occur in the runner, so that some uneven pressure distribution in the blades will also occur.
3.3 External characteristics

Different inlet circular section sizes of volute have different effects on hydraulic performance of turbine. The flow ratio-calculated head curve and flow ratio-efficiency curve of the ultra-low specific speed diagonal flow turbine with the seven schemes calculated in the range of five flow conditions (0.8Q₀, 0.9Q₀, 1.0Q₀, 1.1Q₀, 1.2Q₀) are shown in Figs. Among them, the performance parameters of the turbines under the design conditions are shown in Table 3. It can be seen from the analysis that the head increases with the increase of flow rate under the same volute inlet circular section size. At different flow rates, the head of the turbine increases with the decrease of the inlet circular section size of the volute. Under the design conditions, the head difference of scheme 5 and 6 is the smallest, about 0.002m. From the flow ratio-efficiency curve of the transverse analysis, it can be seen that the hydraulic efficiency of each scheme increases first and then decreases with the gradual increase of the inlet flow rate of the volute. And most of the highest efficiency points occur at small flow points (less than rated flow). Compared with the seven schemes, under the rated operating conditions, Scheme 1 has the highest efficiency but the lowest head. With the increase of average flow velocity in the volute, the head of scheme 4 and 5 is 1.3m higher than that of scheme 1. The output of the turbine increases with the increase of the size of the inlet circular section of the volute. Comprehensive analysis of Table 3 and Figure 5 shows that the efficiency and head of Scheme 5 (with inlet angle of guide vane 32°) are the best.

Table 3 Turbine performance parameters for each scheme under rated conditions

| Scheme number | Inlet circle section radius D₀ (mm) | Guide vane inlet angle (°) | Calculating head (m) | Hydraulic turbine output (kW) | Turbine efficiency (%) |
|---------------|-------------------------------------|-----------------------------|----------------------|-----------------------------|------------------------|
| Scheme one    | 144                                 | 41                          | 3.524                | 3.94                        | 82.07                  |
| Scheme two    | 140                                 | 39                          | 4.516                | 5.00                        | 81.26                  |
| Scheme three  | 136                                 | 37                          | 4.084                | 4.443                       | 79.86                  |
| Scheme four   | 131                                 | 35                          | 3.908                | 4.313                       | 80.996                 |
| Scheme five   | 127                                 | 32                          | 4.821                | 5.360                       | 81.59                  |
| Scheme six    | 122                                 | 30                          | 4.823                | 5.320                       | 80.96                  |
| Scheme seven  | 118                                 | 28                          | 6.095                | 6.413                       | 77.22                  |
Figure 5. Variations in the calculated head of the turbine under different conditions of each scheme

Figure 6. Turbine efficiency changes under different working conditions for each scheme

Figure 7. Hydraulic loss of the turbine runner under different working conditions of each scheme

From the analysis of figures 6 and 7, it can be seen that in hydraulic turbines, the hydraulic loss of runner increases with the increase of flow rate, and the hydraulic loss of runner of scheme seven (with inlet angle of guide vane is 28°) increases with the increase of flow rate. This is because the flow velocity of water into the runner increases with the decrease of the size of the inlet circular section of the volute, so unstable operation will occur in the runner and the hydraulic loss of the runner will increase. When the turbine operates at small flow conditions (less than rated flow), its efficiency increases with the increase of flow rate and is proportional to the runner loss. When the turbine operates under high flow condition (greater than rated flow), the efficiency of the turbine decreases with the increase of flow rate, which is inversely proportional to the runner loss. Scheme 5 (with inlet angle of guide vane 32°) has a good matching between turbine volute and runner, and the hydraulic loss of runner is less than 4.32m, which is more efficient than other schemes.
4 conclusion

a) The optimum inlet radius of circular spiral case for ultra-low specific speed diagonal flow turbine selected in this study is 127mm, and the guide vane inlet angle of this scheme is 32°. Compared with other schemes, this scheme has the highest efficiency and the best head.

b) With the decrease of the inlet circular section size of the volute, the average flow velocity in the volute increases, and the head of the turbine shows an increasing trend under design conditions. The hydraulic efficiency of the turbine decreases with the increase of hydraulic loss of each component.

c) When the turbine operates at small flow conditions (less than rated flow), the hydraulic efficiency of the turbine increases with the reduction of the inlet circular section size of the volute. When the turbine operates under high flow condition (greater than rated flow), the hydraulic efficiency decreases with the reduction of the size of the inlet circular section of the volute. The head and runner losses of the turbine increase with the increase of flow rate.

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