Performance Evaluation of Over-Opening of Runner Blade and Vane Blade with the Internal Flow Simulation of Tubular Turbine

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Abstract. Tubular turbines have been widely used because of their good hydraulic performance and energy characteristics. During the operation of tubular turbine, the runner blades and guide vanes may be over-opened. This article uses computational fluid dynamics methods to numerically simulate the internal flow of a tubular water turbine under two operating conditions: the runner blades and guide vanes are over opened. Then, a comparative analysis was conducted on the effects of over opening of the impeller blades and guide vanes on the performance, internal flow rate, and energy loss of the unit. The research results show that when the runner blade is too open, the unit has a larger flow rate, but there will be a strong vortex in the outlet section, resulting in increased energy loss and low efficiency. When the guide vane is over opened, the unit has small flow rate, chaotic flow in the outlet section, small energy loss and high efficiency.

Keywords: Tubular Turbine, CFD simulation, Over opening, Operation safety.

1 Introduction

In recent years, due to the saturation of the development of medium to high head hydraulic resources, people have gradually begun to pay attention to the development of low head hydraulic resources such as ocean tidal energy [1]. Tubular turbines are widely used in the development of low head and high flow hydraulic resources due to their excellent hydraulic performance and energy characteristics [2]. Especially in terms of tidal energy utilization, tubular water turbines have natural advantages [3]. In terms of water turbine operation, efficient and stable operation is our common goal. Therefore, the stable operation and design and development of tubular water turbines have received widespread attention from domestic and foreign scholars.

The operating conditions of power plants are important factors that affect the stable operation of water turbines. When the water turbine needs to operate under different

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flow conditions, we adjust the angle of the runner and the opening of the blade to ensure that the water turbine is in the optimal operating state. Nam et al. [4] used numerical simulation methods to find the optimal flow coefficient and blade opening under fixed guide vane opening. Hagheii et al. [5] studied the cavitation phenomenon under different impeller opening and speed states, and demonstrated the influence of impeller blade angle and turbine speed on the hydraulic efficiency curve and turbine efficiency curve. Muntean et al. [6] studied the effect of different guide vane openings on flow velocity and internal flow rate based on a mixed flow turbine model

In actual operation, there are certain limitations on the maximum opening of the impeller blades and guide vanes. If the opening of the runner blades and guide vanes is always kept below the maximum opening, it may result in the inability of the tubular turbine to operate under optimal conditions due to insufficient opening, thereby reducing the efficiency of the turbine. If the opening of the impeller blades and guide vanes exceeds the maximum opening, which may cause vortex and cavitation phenomena inside the impeller, leading to cavitation erosion and vibration of the unit, seriously threatening the safe operation of the unit [7].

In summary, for a tubular turbine, the over-opening of the runner blades and guide vanes is of great significance in certain special situations. However, due to the limited research on the over-opening of the impeller and guide vanes, we have maintained an overly cautious attitude towards the over-opening of the impeller and guide vanes during actual operation. In this case, this paper deeply studies the influence of excessive opening of impeller blade and guide vane on the performance, internal flow and energy loss of the unit, which provides a theoretical basis for the safe and stable operation of tubular turbine.

2 Turbular Turbine Model

This article takes a tubular turbine as the object including four components: inlet section, guide vanes, runner, and outlet section. The function of the guide vane is to introduce the water flow from the inlet section into the impeller at a certain speed and direction. The impeller is the core component of the unit, used to convert the energy of water into the rotational mechanical energy of the impeller. The guide vanes consist of 16 blades, and the impeller is equipped with 4 blades. The rotational speed of the impeller is 85.71 r/min, and the diameter of the impeller is 5.65 m. The schematic diagram of the fluid domain of the tubular turbine is shown in Figure 1.

This article uses numerical simulation methods to study the effects of turbine blade and guide blade over-opening on unit performance, internal flow, and flow losses. Under the condition of over opening of the impeller blades, the opening of the impeller blades is set to 57.24 ° and the opening of the guide vanes is 60 °. Under the condition of over opening of the guide vanes, the opening of the guide vanes is 90 °, and the opening of the impeller blades is 20 °.

3 Numerical Method

At present, the Reynolds Averaged N-S equation considers the operability, economy and effectiveness in engineering practice, which is the main calculation method to solve engineering practice problems. The k-ε turbulence model belongs to the two-equation model in RANS. The turbulent kinetic energy k and energy dissipation rate ε are expressed as follows:

$$\frac{\partial k}{\partial t}+\overline{u}_i\frac{\partial k}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(c_{\varepsilon 0}\frac{k^2}{\varepsilon}+\gamma\right)\frac{\partial k}{\partial x_i}\right]+P-\varepsilon \tag{1}$$

$$\frac{\partial \varepsilon}{\partial t}+\overline{u}_i\frac{\partial \varepsilon}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(c_{\varepsilon}\frac{k^2}{\varepsilon}+\gamma\right)\frac{\partial \varepsilon}{\partial x_i}\right]+c_{\varepsilon 1}\frac{\varepsilon}{k}P-c_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{2}$$

Where P is turbulent generation term, $c_{\varepsilon 0}$, c_{ε}, $c_{\varepsilon 2}$ are empirical coefficients.

The entropy generation law can quantitatively evaluate the energy dissipation of the turbine [8]. The entropy production rate is composed of direct entropy production rate S_{atv} and turbulent entropy production rate S_{PS}. The direct entropy production rate is the entropy production rate caused by the time average velocity per unit volume, and the turbulent entropy production rate is the entropy production rate caused by the turbulent fluctuation velocity per unit volume. The calculation formula is as follows:

$$S_{atv}=\frac{2\mu}{T}\left[\left(\frac{\partial \overline{u}}{\partial x}\right)^2+\left(\frac{\partial \overline{v}}{\partial y}\right)^2+\left(\frac{\partial \overline{w}}{\partial z}\right)^2\right]+\frac{\mu}{T}\left[\left(\frac{\partial \overline{u}}{\partial y}+\frac{\partial \overline{v}}{\partial x}\right)^2+\left(\frac{\partial \overline{u}}{\partial z}+\frac{\partial \overline{w}}{\partial x}\right)^2+\left(\frac{\partial \overline{v}}{\partial z}+\frac{\partial \overline{w}}{\partial y}\right)^2\right] \tag{3}$$

$$S_{ps}=\frac{2\mu}{T}\left[\overline{\left(\frac{\partial u'}{\partial x}\right)^2}+\overline{\left(\frac{\partial v'}{\partial y}\right)^2}+\overline{\left(\frac{\partial w'}{\partial z}\right)^2}\right]+\frac{\mu}{T}\left[\overline{\left(\frac{\partial u'}{\partial y}+\frac{\partial v'}{\partial x}\right)^2}+\overline{\left(\frac{\partial u'}{\partial z}+\frac{\partial w'}{\partial x}\right)^2}+\overline{\left(\frac{\partial v'}{\partial z}+\frac{\partial w'}{\partial y}\right)^2}\right] \tag{4}$$

Where $\overline{u}$, $\overline{v}$ and $\overline{w}$ are time average velocity components in x, y and z directions respectively; u', v' and w' are pulsating velocity components in x, y and z directions respectively; T is the temperature; μ is the hydrodynamic viscosity.

Kock and Herwig [9] proposed a simpler algorithm to calculate the turbulence entropy production rate for the k-ε turbulence model:

$$S_{ps}=\rho\varepsilon/T \tag{5}$$

4 CFD Setup

Grid generation is a key step of computational fluid dynamics (CFD) calculation. The number and quality of grid generation have a significant impact on the results of numerical simulation. Common grid generation methods include structured grid and unstructured grid. In order to ensure the accuracy of the calculation results and save the calculation cost, this study uses the hybrid scheme of structured grid and unstructured grid to divide the whole fluid domain into grids. The inlet section and runner adopt unstructured grid, and the guide vane and outlet section adopt structured grid. The total grid node number is 1.46×106. The schematic diagram of grid is shown in Figure 2:

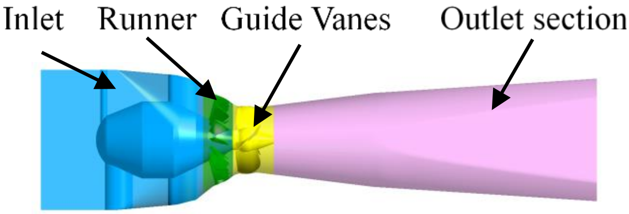


Fig. 1. Schematic diagram of fluid domain.

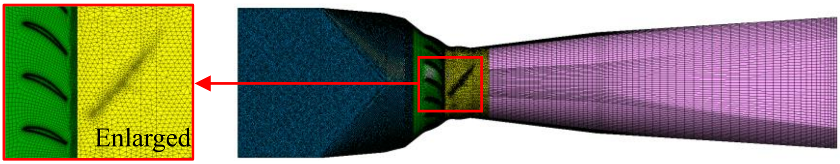


Fig. 2. Schematic diagram of grid division

In this study, the fluid medium is water at 25 °C, density ρ= 1000 kg/m^3, kinematic viscosity ν= 1×10^{-6} m^2/s, the reference pressure is 1 Atm. The inlet boundary condition is set as pressure inlet of 70828.2 Pa, and the turbulence intensity is set as 5%. The outlet boundary condition is also set as pressure outlet, and the outlet relative pressure is 0 Pa. The wall boundary condition is set as no slip wall. In the steady-state numerical simulation, the maximum number of iteration steps is set to 1×10^3, the convergence index of continuity equation and momentum equation is 1×10^{-6}.

5 Analysis of Simulation Results

5.1 Performance

Figure 3 and Figure 4 show the efficiency and flow comparison of the unit when the runner blades and guide vanes of the tubular turbine are over-opened. It can be seen from the figure that when the runner is over-opened, the efficiency of the unit is 0.39 and the flow is 240.58 m^3/s; When the guide vane is over-opened, the efficiency of the unit is 0.73 and the flow is 98.27 m^3/s. The efficiency of guide vane over opening is significantly higher than that of runner blade over opening, and the flow of guide vane over opening is significantly lower than that of runner blade over opening. When adjusting the operating state of the turbine, the efficiency and flow can be comprehensively considered.

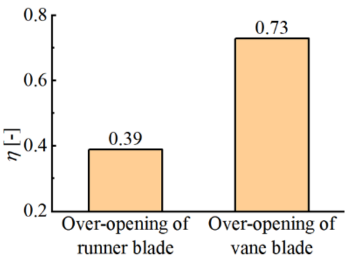


Fig. 3. Efficiency comparison

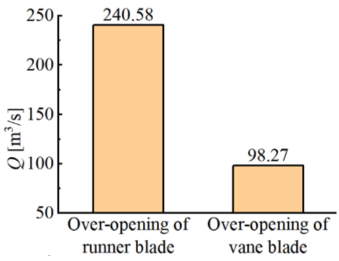


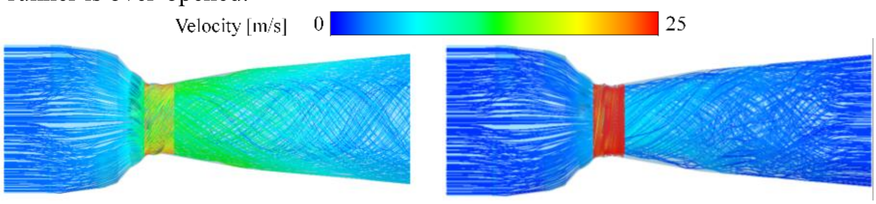
Fig. 4. Flow rate comparison

5.2 Flow Streamlines

Figure 5 shows the streamline of the tubular turbine when the runner blades and guide vanes are too open. It can be seen from the figure that when the runner blade is too open, the flow velocity on the streamline changes little, and the flow velocity at the runner increases slightly, with the maximum flow velocity of 25.6 m/s. When the runner blade is too open, the streamline in the inlet section, guide vane and runner fluid flow is smooth and stable, but in the outlet section, the streamline is strongly bent and vortices are generated. When the guide vane is too open, the flow rate increases rapidly when the fluid flows through the runner due to the large flow and the small opening of the runner, and the maximum flow rate is 29.0 m/s. When the guide vane blade is too open, the streamline is smooth and stable in the inlet section, guide vane and runner, and the streamline is disordered in the outlet section.

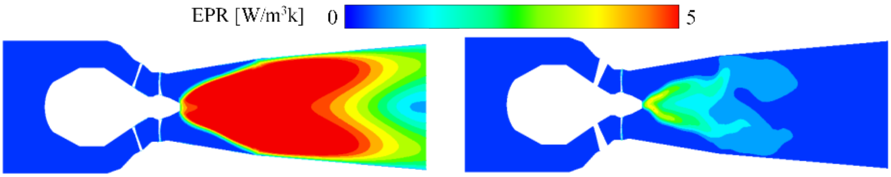
5.3 Flow Energy Loss

Figure 6 shows the internal flow loss of tubular turbine when the runner blades and guide vanes are too open. It can be seen from the figure that since the flow lines in the inlet section, guide vane and runner are stable, the flow loss is small, and the flow loss mainly occurs in the outlet section. When the runner is over-opened, due to the strong vortex in the outlet section, the flow loss under this condition is significantly greater than that when the guide vane is over-opened, which also leads to low efficiency when the runner is over-opened.



(a) Over-opening of runner blade. (b) Over-opening of vane blade.

Fig. 5. Streamline diagram under two working conditions.



(a) Over-opening of runner blade (b) Over-opening of vane blade

Fig. 6. Flow loss diagram under two conditions.

6 Conclusions

In this paper, the numerical simulation method is used to analyze the influence of runner blade and guide vane over opening on the performance, conclusions include:

(1) When the runner blade is over opened, the unit has a large flow and low efficiency; When the guide vane is over opened, the unit efficiency is higher but the flow is lower.

(2) Under the two conditions, the flow in the inlet section, guide vane and runner is very stable. When the runner blade is too open, the streamline at the outlet section is strongly bent and vortex is generated; When the guide vane is too open, the streamline at the outlet section is very chaotic.

(3) Under the two working conditions, the energy loss in the inlet section, guide vane and runner is small, and the energy loss mainly occurs in the outlet section, and the energy loss in the outlet section when the runner blade is over opened is significantly greater than that when the guide vane blade is over opened.

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