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Three-dimensional Unsteady Numerical Simulation of Reversible Flow Passage of Pump Turbine

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The purpose of this paper is to study the three-dimensional unsteady numeral simulation of the whole flow passage in the reversible pump turbine. To this end, the geometric model was established by CFD numerical simulation method, and the rated flow of the three-dimensional whole flow passage of the pump turbine was simulated by SIMPLE algorithm. Then, the pressure pulsation of each part in the pump turbine was monitored. The study found that under small flow conditions such as 0.19Qr and 0.473Qr, with the load increasing, the opening of the movable guide vanes increased. Thus, it can be concluded that as the load increases, the opening of the movable guide vanes increases, the jet flow decreases, and the flow field in the vaneless zone tends to be flat and stable.

1. Introduction

With the development of social economy, the demand for electricity consumption of residents in China has been increasing, and the capacity of China’s medium and large generating units and the power generation of nuclear power plants has ranked the highest in the world. At present, China’s hydropower development resources rank first, but after a long period of development, the actually developed hydropower resources in China account for less than 20% of total resources. In several major power system regions in China, hydropower generation is more affected by seasonal factors, and the problem of poor peaking ability in power systems is increasingly prominent. Pumped storage power stations are important energy storage regulators in power systems, which have a positive effect on improving hydropower stability. Based on this, in this paper, the geometric model was established by CFD numerical simulation method. Then, the SIMPLE algorithm was applied to simulate the rated flow of the three-dimensional whole flow passage in the pump turbine, and the pressure pulsation of each part of the pump water wheel was monitored in order to study the three-dimensional unsteady numeral simulation of whole flow passage in reversible type pump turbine.

2. Literature review

With the construction of pumped storage power stations, the research on the transition process of reversible pumped turbines has gradually developed. Especially since the 1960s, due to the large number of high head and large capacity pumped storage power stations in developed countries such as the United States, Western Europe and Japan, the start-up of pumped turbines and their load rejection have been promoted. The research on transient processes such as pump start-up and sudden power-off has achieved certain results, which has become an important basis for the design of reversible pump turbine. At the same time, the research on the operation stability of reversible pump turbine has been active in recent years. Compared with the working characteristics, the research on the operation stability is more difficult, and the reversible unit needs frequent switching conditions in operation. Among them, the conditions that may enter the "S" characteristic area are: turbine start-up working conditions, phase-modulated and power-forward working conditions, load rejection working conditions, pump power failure and guide vane failure to close in time, etc. There are a series of unstable problems in the process of transition. Scholars at home and abroad have done a lot of research work on transient problems of hydraulic systems. Wang et al. carried out the one-dimensional numerical calculation under the unstable condition of load rejection guide vane. The unsteady flow field of counter-rotating axial flow turbine was calculated based on data encryption standard using the full-channel three-dimensional numerical simulation method (Wang et al., 2017). Pavesi et al. applied the characteristic curve method to establish the mathematical model of hydraulic force when the pump condition changed to the turbine condition in the transient process. In addition, three-dimensional unsteady turbulent numerical simulation of Francis turbine's flight transient process was carried out, and comprehensive analysis of internal flow of turbine was made (Pavesi et al., 2018). Yang, et al., discussed load rejection condition and guide vane control law of reversible pump turbine, established four-equation model in time and frequency domain. The theory and method of pipeline coupled water hammer were systematically studied by theory and non-linear analysis method. Relevant prototype tests were carried out in several high head and long pipeline stations. Xiaoran et al. studied the transient process and stability of other units under hydraulic disturbance during shutdown of some units, established a mathematical model which can calculate both large fluctuation and small fluctuation, and put forward the method of virtual impedance method and zero flow state method to solve the initial value of the system. Moreover, the numerical calculation of transient process of pump-turbine-pump condition was carried out to investigate the effect of static and dynamic interference (Xiaoran et al., 2018). Fu et al., established a mathematical model to simulate the transient process of load rejection of reversible pump turbine with manual guided vehicle device. The flow instability in the flow passage of pump turbine was numerically simulated and experimentally studied. The velocity fluctuation caused by dynamic and static interference was measured and analyzed in detail (Fu et al., 2018). Cavazzini et al. analysed the correlation between the total characteristics of pump turbine runner and the transient process of pumped storage power station (Cavazzini et al., 2018); Yang et al., studied the change of the characteristic curve of reversible pump turbine with different specific speeds and its influence on the transient process (Yang et al., 2015). Li et al. discussed the control of the transient process of pumped storage power station and established the mathematical expression of the full characteristic curve of pump-turbine. Furthermore, the corresponding theoretical analysis and formula derivation for the "S" characteristic region of pump-turbine were carried out in detail. Based on the digital and experimental analysis of the runner of pump-turbine with "S" characteristic and without "S" characteristic, the runner of pump-turbine was obtained. A new design standard for stable operation of wheels was presented, and a new runner was designed with it. The test results showed that the runner operated steadily (Li et al., 2018). Zhou et al. put forward a new method for calculating the transition process of complex hydraulic devices in high head pumped storage power stations. The generation of "S" characteristics of pumped turbines was discussed in relation to the return vortices in the vaneless zone between runner blades and between runner and guide vanes (Zhou et al., 2018); Huang et al. explored the basic equation and numerical method of transient transitions of pumped storage power stations. The compressible pipe flow was discussed through numerical simulation and peak inverse voltage test. The feasibility of using different static and dynamic interference models was also discussed. At last, the single stage reversible pump turbine was experimentally studied. They pointed out that the use of asynchronous guide vanes could overcome the difficulty of obtaining stable speed after load rejection (Huang et al., 2018).

In conclusion, the above researches mainly studied reversible flow passage of pump turbine, but very few scholars pay attention to the three-dimensional unsteady numerical simulation. Therefore, based on the above studies, the three-dimensional unsteady numerical simulation of reversible flow passage of pump turbine is carried out. And some experiments are made to test the performance of reversible flow passage of pump turbine.

3. Principles and methods

The CFD numerical simulation is essentially a numerical simulation calculation of the flow process in a fluid region under the control of the basic flow equations (mass conservation equation, momentum conservation equation, energy conservation equation). Through the numerical simulation process under the governing equation, we can obtain the distribution of basic physical quantities (such as speed, pressure, temperature, concentration, etc.) at various positions inside the flow field of complex fluid regions, and the changes of these physical quantities with time, e.g., vortex distribution characteristics, cavitation characteristics, and de-flow characteristics are determined. Other physical quantities related to the calculation, such as the torque of the rotary fluid machine, water loss and efficiency, can also be calculated accordingly. In addition, combined with the CAD design software before and after the numerical simulation calculation, the optimal design of the structure etc. can be performed.

For the pump turbine of pumped-storage power station, its main internal flow field can be divided into five parts from the volute inlet to the draft tube outlet, including: volute, stay vane, movable guide vane, runner and draft tube. Based on the powerful three-dimensional modelling software PROE, the water flow areas of the volute and guide vane, the runner and the draft tube were modelled and assembled respectively. Table 1 lists the basic parameters of the pump turbine.

Table 1: Basic parameters of pump turbine

	Basic parameters	Parameter value
Geometric parameters	Runner nominal diameter D1	4.8
	Runner nominal diameter D2	3.15
	Number of runner blades Z	7
	Vane height b (m)	0.656
Operating parameters	Maximum head Hmax	286.21
	Rated head H	244
	Minimum head HMIN	234.83

The water flow is introduced from the upstream reservoir, and the first component that enters the pump turbine is the volute. The function of the volute is: firstly distribute , the water flow is distributed from the pressure steel pipe evenly around the water guiding component so that the water flow can smoothly and evenly enter the water guiding component; secondly, the incoming flow changes from one direction to a uniform centripetal flow, so as to alleviate the impact of water flow, reduce water loss and improve efficiency; finally, a certain amount of circulation is formed before the water flows into the water guiding component, to improve the water flow energy utilization rate. Thus, the general idea for three-dimensional modelling of the volute is: point to line, line to face, face to body. At first, the centre point of each volute section is constructed; based on each centre point, the section line of each section is constructed; based on each section line, the outer surface of the volute is constructed. Finally, the closed volute surface is materialized to be the fluid region, as shown in Figure 1.

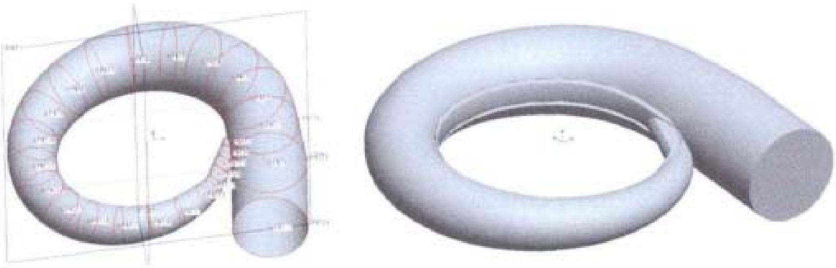

Figure 1: volute modelling process diagram

The function of the pump turbine runner is to convert the water energy into rotational mechanical energy. The performance of the runner plays a decisive role in the pump turbine. The runner blade of pump turbine is relatively long compared to the conventional one, since a large part of the blade is in the radial direction, its wrap angle is relatively large, and the connection parts with the upper crown and the lower ring of the runner are rather long. But compared to the conventional turbine, the main source of stress on the pump turbine blades is the centrifugal stress generated by their own rotation. The modelling of the pump turbine runner is mainly based on the modelling of the runner blade. The blade is composed of the space-distorted surface, making it rather difficult to make modelling. Multiple spatial blade centre-lines are generated by the actual runner wooden pattern. Then, the centre-line connecting curved surface constitutes a blade curved surface, which is assembled between the lower ring of the runner and the upper crown to constitute the entire runner. Figure 2 shows the entire runner calculation area.

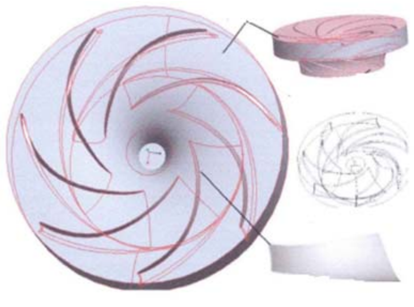

Figure 2: 3D geometric model of the runner area

The draft tube is used as the water discharge component of the pump turbine (PT). It is also an important part of the water energy recovery, and the last part of the pump turbine flow passage component. The performance of the pump turbine draft tube has a significant impact on the efficiency, cavitation characteristics and stability of the turbine. In the pump working condition of the pump turbine, the draft tube is changed from the drain pipe to the suction pipe. The section of the traditional water pump suction pipe follows the law of continuous shrinkage. It is proved by a large number of engineering practices that the draft tube of the pump turbine can also adapt to the flow of water during the pump working condition. The three-dimensional geometric modelling of the draft tube is also similar to that of the volute: from point to line, from line to surface, from face to body (Figure 3).

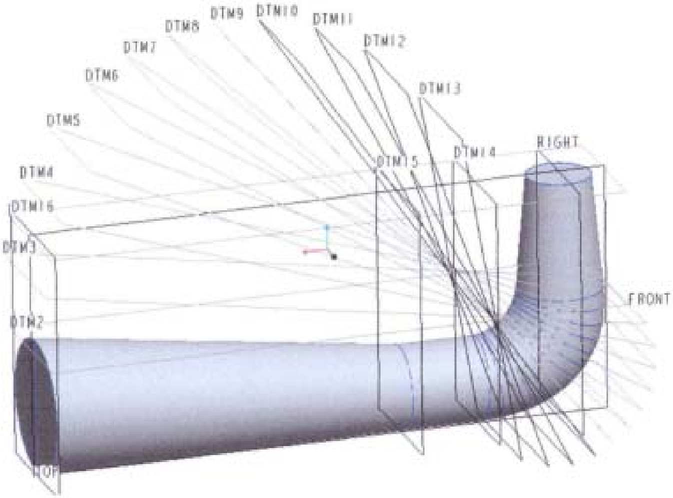

Figure 3: Geometry modelling of the draft tube calculation area

4. Results and analysis

Figure 4 shows the flow diagrams of the volute and guide vane under the turbine working conditions and pump conditions at the same opening degree. Under the condition of turbine operation, the water is introduced from the entrance of the volute and flows around the volute to evenly enter the guide vane flow passage with uniform velocity moments. Then, with the flow diversion function of the guide vane, a certain circulation amount of water flow is formed into the runner. From Fig.4, it can be clearly seen that under the turbine working conditions, the flow state of the water flow in the volute and the guide vane is very good, the flow line distribution is relatively uniform, and the turbulence flow fluctuation is not observed in the entire flow passage.

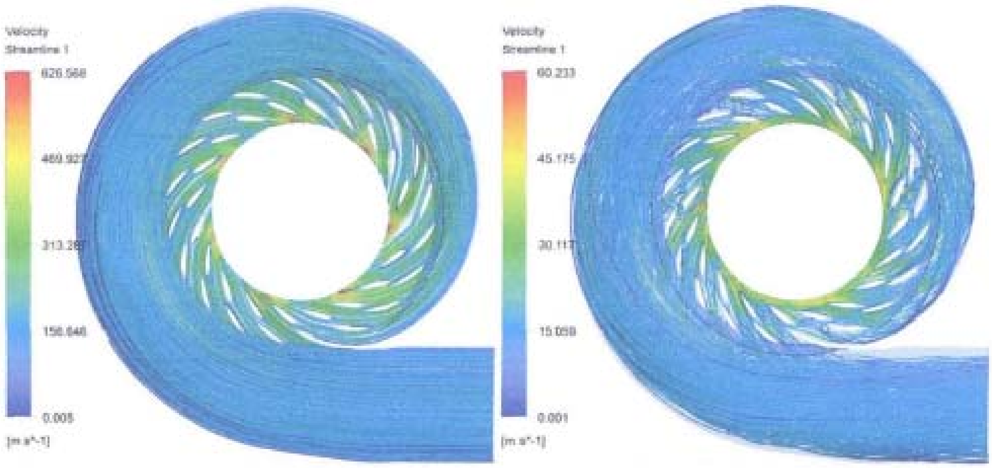

Figure 4: Flow diagram of the volute and guide vane of the pump turbine turbine working conditions and pump conditions

Figure 5 shows the vector diagrams of guide vane and runner under the turbine working conditions and pump working conditions. It can be seen that under the pump working condition, the flow direction of the water flow is opposite to that of the turbine. The water flow from the runner blade channel directly hits the movable guide vane and brings a great impact to it, which forms strong turbulent disturbances and vortex structures in the flow passage of the guide vane, and the water flow in the volute is also particularly turbulent and accompanied by secondary reflow. Under the working condition of turbine, the flow field region with relatively bad flow state is in the draft tube, while under the pump operation, it is in the guide vane and volute.

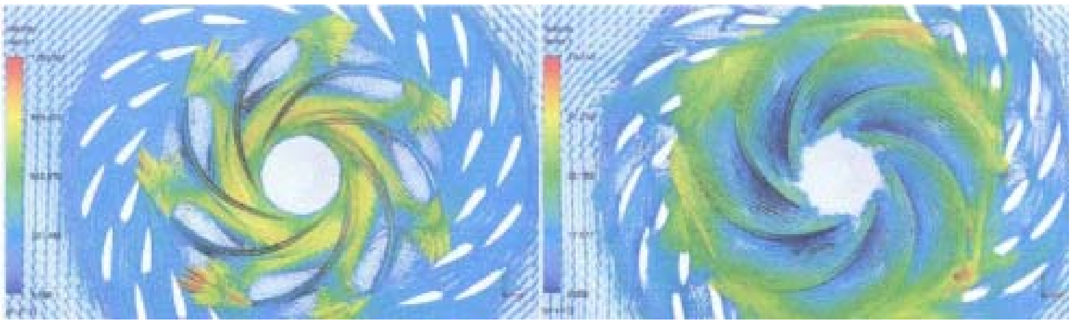

Figure 5: Pump turbine turbine working conditions and pump conditions Guide vane part and runner vector

Table 2 lists the dynamic head recovery rates of the draft tube under different working conditions. In the 0.473Qr flow condition, the recovery rate of the draft tube is the largest. From the flow diagram of the draft tube FF under different working conditions in Figure 5, it’s also found that the flow state of the pump turbine draft tube is very good under this condition, indicating that the flow state of the draft tube has a great relationship with its energy recovery rate. In the 0.655Qr flow condition, the recovery efficiency of the draft tube energy is the lowest, because the water flow in the turbulent flow state is in mutual convolution collision and causes a loss of energy. In addition, the energy recovery ability of the draft tube is related to its over-flow. The energy recovery of the draft tube increases with the increase of the flow rate, because with the larger flow rate of the fluid, the kinetic energy at the inlet of the draft tube shall be increased more, and its energy recovery ability is also better

Table 2: Dynamic head recovery rate table of draft tube under different working conditions

Working condition	0.19Qr	0.473Qr	0.655Qr	0.82Qr	Qr
Draft tube inlet speed m/s	5.406	16.381	18.482	25.157	32.623
Draft tube outlet speed m/s	0.953	1.970	3.316	3.919	4.935
Moving head recovery m	1.443	13.479	16.85	31.473	53.002
Kinetic energy recovery	96.87%	98.55%	96.78%	97.57%	97.71%

5. Conclusions

Under small flow conditions such as 0.19Qr and 0.473Qr, the opening of the movable guide vane is small, and the jet flow is formed at the outlet of the vane so that the flow field in the vaneless zone between the movable vane and the runner is bad and the vortex structure is formed near the inlet edge of the runner blade. With the increase of load, the opening of the movable guide vanes increases, the jet weakens, the flow field in the vaneless area tends to be gentle and stable, and the vortex structure near the inlet edge of the vane disappears. The energy recovery ability of the draft tube is related to its over-flow. The energy recovery of the draft tube increases with the increase of the flow rate, because the higher the flow rate, the greater the kinetic energy of the fluid at the inlet of the draft tube, and the more fully the draft tube functions to recover energy.

At present, many domestic power and hydropower design units have already made planning for the construction of pumped storage power stations, and accumulated a lot of practical design experience. Also, China’s turbine manufacturers and many hydropower research design units have achieved good results about the equipment research and manufacturing of the pumped storage power stations. But in general, there has still be a long distance from fully grasping the pumped storage power generation technology in China. The experience and existing problems in the development of this technology abroad have yet to be analysed and digested by our technical personnel.

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