Numerical Analysis of a Model Pump-turbine Internal Flow Behavior in Pump Hump District

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Abstract. The hump region of head-discharge characteristic curve has great influence on the operation stability of pump-turbine. Therefore, it is significant to conduct deep research on the flow characteristic in the hump district of pump mode. Detailed study of the internal flow in hump district has been made combined with model experiments in this paper. Research discussed the adaptability of different turbulent model toward calculation in pump mode conditions and carried on three-dimensional numerical simulation of the whole pump-turbine flow passage. Then the head, efficiency and power characteristic curves of different pump modes were analysed. The numerical simulation results are in good agreement with experimental data. Comparing flow field both in hump district and of optimal operating point, it is found that the formation of hump area is concerned with complex flow in the runner and guide vanes domains, such as secondary flow, backflow and vortex patterns. The study aims to explore the cause for hump district generating of pump-turbine and its internal flow mechanism.

1. Introduction

With the development of pumped-storage power station technology, the unstable operation issues have drawn more and more attention as pump-turbine’s working condition is relatively complicated. The “S” characteristic region is the typical unsteady region which threaten the turbine mode’ operating stability of pump-turbine, thus there are lots of experiments and theory researches investigating it[1-3]. While the hump region is a main factor threatening pump mode’s operating stability. When a unit runs in the hump district, its unsteady characteristics are very obvious with working conditions changing automatically and noises increasing immediately. There may be large pressure fluctuations and the efficiency of the unit will also decline[4]. So it is necessary to research deeply on running conditions in hump region of pump mode.

Study regarding to hump characteristic of pump-turbine in pump mode is not adequate so far. Gabriel Dan Ciocan conducted experimental study of pump-turbine in pump mode and obtained the velocity field in the positive-slope zone using PIV technology and found that the vortex and backflow patterns in the diffuser is responsible for the hump region[5]. Ran Hongjuan performed analysis on the instability of a high-head pump-turbine in the pump mode condition and found that the unsteady flow between the runner and the guide vanes caused by the rotor-stator interaction is related to the formation of hump region[6]. Wang Huanmao gained accurate head-discharge characteristic curve from...
numerical simulation of the whole passage of pump-turbine in pump mode and found that the formation of hump region analyzing velocity triangle of the runner domain\(^7\). Liu Jintao found that it more accurate to take cavitation into consideration than single phase model and the cavitation on the suction side of blades is related to the formation of hump region\(^8\). Braun numerically simulated the single channel of pump-turbine and discovered that secondary flow within diffuser section was responsible to the rapid drop of head in pump mode\(^9\). R Tao explored the nonunion flow condition of the rotor-stator interface had great influence on hump characteristic\(^10\). All the researches above lay a foundation for later related study.

In this paper, different conditions of pump-turbine were simulated in the optimal opening. The internal flow field was obtained through steady numerical calculation and causes for the formation of hump region in pump mode were discussed.

2. Simulation model

2.1. Geometry of the model pump-turbine

Three-dimensional view of the whole flow passage is shown in Figure 1. The water successively passes through the draft tube, runner, guide vanes, stay vanes and spiral case when operated in pump mode conditions. The model consists of a runner with 9 blades and a diffuser with 20 guide vanes and 20 stay vanes (including the spiral case node). The largest diameter of runner is 0.47 m and the optimal opening for the guide vanes is 27 mm. The rated speed of the model pump-turbine reaches 1300rpm. In addition, the flow rate of the design point is 408 L/s.

2.2. Mesh generation

The hexahedral meshes were generated in stay vanes, guide vanes and draft tube domains, while tetrahedral meshes were adopted in the spiral case and runner domains. Under the optimal pump condition, numerical simulation was respectively conducted of different mesh methods named mesh1, mesh2 and mesh3. The details of each mesh type are shown as table 1. Taking both calculation speed and precision into consideration, mesh2 is chosen eventually. The head calculation error of mesh 2 is the least and its grid quantity is large enough to catch the complex flow of the flow field.

| Type     | Draft Tube | Runner | Guide vanes | Stay vanes | Spiral case | Total     | Error (%) |
|----------|------------|--------|-------------|------------|-------------|-----------|-----------|
| mesh1    | 295,000    | 403,000| 105,000     | 141,000    | 322,000     | 1,266,000 | 0.24      |
| mesh2    | 377,000    | 703,000| 257,000     | 251,000    | 481,000     | 2,069,000 | 0.12      |
| mesh3    | 540,000    | 969,000| 444,000     | 524,000    | 750,000     | 3,227,000 | 1.19      |

Figure 2 gives the grid generation condition of mesh2. It is obvious that the mesh density of runner, stay and guide vanes is much larger than the draft tube and spiral case domain. The flow speed of the
former three domains is high and the internal flow conditions are complicated. Large mesh density is beneficial to capture the complex flow pattern in the three domains in order to improve the calculation precision. While the speed of draft tube and spiral case is comparatively low. It doesn’t have much effect on the overall performance. Small mesh density can save computing resources and improve calculation speed.

2.3. Boundary conditions and turbulent model selection

During the simulation process of pump mode, the inlet of the computational domain adopts the velocity-inlet boundary condition so as to get accurate discharge information consistent with the test data. A total of 10 conditions are tested including 0.55, 0.62, 0.69, 0.76, 0.85, 0.91, 1, 1.05, 1.10 and 1.19 \( Q_0 \) (\( Q_0 \) stands for the discharge under the optimum condition). Outflow boundary condition is taken at the outlet as the specific parameters are unknown. The operating pressure is set as 1 atm. Moving reference frame is taken to simulate the rotating runner domain. Standard wall functions are selected for the near-wall treatment. Pressure-velocity coupling method chooses SIMPLEC option. Second order upwind is adopted for momentum, turbulent kinetic energy and turbulent dissipation rate.

![Figure 2. Grid of the whole flow passage](image)

![Figure 3. Comparison of hydraulic performance parameter under different turbulent models](image)

Considering that the selection of turbulent model can affect the result, standard \( k-\varepsilon \) and SST turbulent model were compared and analyzed. Figure 3 demonstrates the results of the hump region and its nearby conditions using the two turbulent models. In the characteristic curves, the abscissa indicates flow coefficient \( \phi \), defined as \( Q/Q_0 \). \( Q_0 \) represents the discharge of the design operating point. It can be drawn from figure 3 that both two turbulent models can exactly simulate the pump-turbine’s hydraulic performance parameters in pump mode regardless of a certain error. Ultimately the standard \( k-\varepsilon \) model is adopted as its calculation error is relatively smaller and it is easier to achieve convergence during the computational process, while, the SST model is better for turbine operating conditions \([11-12]\).
It is necessary to compare the flow field in hump region and under other normal conditions in order to explore the causes for hump district. For the convenience of analysis, four operating points named A, B, C and D are defined according to the obtained characteristic curves as shown in Figure 3. Point A stands for the optimal condition of simulation, point B and point C respectively indicate the peak and valley condition point of the hump region. Point D is the minimum discharge point.

3. Analysis of numerical simulation and experimental results

3.1. Analysis of hydraulic performance

3.1.1. Analysis of experimental and simulation results. Operational parameters were measured at different opening to study the operating characteristic of pump mode through a hydraulic machinery rig. Steady calculation of different discharge conditions was conducted at the optimal opening in the pump mode of pump-turbine. In addition, two operating points were added near the peak of the hump region. Figure 4 shows the head, power and efficiency of both simulation and experiments. There is an obvious hump district in the small-discharge region. Starting from the large-flux side, head linearly increases as the discharge decreases until it reaches operating point B (0.85 $Q_0$). Then head decreases towards smaller discharge until reaching the valley operating point of the hump region. After that the head again increases towards smaller flux. The power decreases towards smaller discharge all the time. The efficiency characteristic curve possesses a broad high-efficiency area. Efficiencies between 0.85 and 1.2 $Q_0$ are all higher than 88%. While in the small-flux region less than 0.85$Q_0$, the efficiency drops rapidly toward smaller discharge.

Table 2 lists the error of head, power and efficiency between simulation and experiment under different working conditions. Through the comparison results, it can be found that the head errors are comparatively large on peak operating point of hump area and its nearby conditions with the maximum error of 2.81%. The errors of other conditions are relatively smaller with 0.12% on the optimal condition point. The computational head-discharge characteristic curve corresponds to the experimental one well. The errors of power are smaller in the large-flux area. While computational powers are all smaller than the test results and the errors get larger towards smaller flux with the maximum error of -5.33%. The calculation highest efficiency point migrates to the larger flux with the flux of 1.05 $Q_0$. Its errors are larger in the small-flux region with the maximum error of 5.32%. Generally speaking, the performance curves of numerical simulation are in good agreement with the experimental results in the tendency aspect. The errors of head, power and efficiency are all less than 5.5%.
### Table 2: Computational errors of head, power and efficiency under different conditions

| Operating point | φ Q₀ | H(%) | P(%) | η(%) | Illustration of condition |
|-----------------|------|------|------|------|---------------------------|
| 1               | 0.55 | -0.59 | -5.33 | 5.32 | Off-design(small-flux)    |
| 2               | 0.62 | -0.66 | -3.40 | 3.28 | Off-design(small-flux)    |
| 3               | 0.69 | -1.86 | -2.21 | 0.90 | Valley of the hump region |
| 4               | 0.76 | -1.21 | -1.04 | 0.65 | Hump region               |
| 5               | 0.85 | -2.81 | -1.11 | -0.87 | Peak of the hump region  |
| 6               | 0.91 | -2.80 | 0.64  | -2.50 | Off-design(small-flux)    |
| 7               | 1    | 0.12  | 1.28  | -0.73 | Optimal (Experiment)     |
| 8               | 1.05 | 0.72  | 0.71  | 0.65  | Optimal (Simulation)     |
| 9               | 1.10 | 0.17  | 0.82  | 0.15  | Off-design(large-flux)    |
| 10              | 1.19 | 0.73  | 0.22  | 1.15  | Off-design(large-flux)    |

#### 3.1.2. Energy loss analysis of the whole flow passage.

The energy loss of each domain and total input energy of pump mode under different discharge conditions are shown as Figure 5.

![Figure 5. Energy loss of each domain and total input energy](image)

The green curve is on behalf of the total energy. It is correspond to the scale on the right using m as its unit. The other five curves, corresponding to the scale on the left, respectively stand for the energy loss of pump-turbine’s five domains with the unit m. The green curve reveals that the total input energy per unit weight linearly increases towards smaller flux. The total energy increases from 49.07m to 73.76m as the discharge changes from 1.19 Q₀ to 0.55Q₀. The energy loss of runner is the greatest among all the five domains with 2.08m on the largest discharge condition. Its energy loss curve shapes like a parabola as the flux changes. In the large-flux region, the head loss of runner decreases towards smaller flux until it comes to the lowest point of the parabola 1.05 Q₀ (computational optimal operating point) with the head loss of 1.78m. The excursion of lowest-loss point accounts for the right shift of optimal operating point. Then the head loss of runner increases rapidly as the flow rate decreases. The energy loss of guide vane is the second largest among all the domains. There is no obvious change of head loss in the large-discharge area. But in the hump region, the energy loss increases quickly from 2.40m to 5.12 m as the condition changes from the peak to the valley of the hump region. When leaving the hump region in the small-flux region, the loss gently increases towards smaller discharge. There is no obvious change of the energy loss of stay vanes and draft tub. The main energy loss of draft tube consists of frictional-resistance loss and local-resistance loss. The
loss of draft tube is the least among all the five domains. It decreases towards smaller discharge with the maximum of 0.3m which is far smaller than the other domains.

According to Figure 5, the main loss of the whole flow passage lies in the runner and guide vanes domains. It can be concluded preliminarily that the formation of hump region of model pump-turbine is closely related to the 3D flow conditions of the runner domain and the guide vanes domain.

3.2. Analysis of three-dimensional flow characteristics

On the basis of energy-loss analysis, the formation of hump region is close relationship with the flow conditions within runner and guide vanes. Therefore, it is necessary to conduct deep research on the domains mentioned above.

Figure 6 gives the velocity distribution on the meridional plane of the runner and draft tube using tangential projection (magnified near the inlet of runner). It can be found that water flow smoothly from draft tube to the runner on both operating point A and B. When the flux decreases till reaching point C, flow separation occurs with backflow flowing from runner toward draft tube. The flow separation region is marked in the figure. The separation region of point C is small. When the flux continues decreasing, the separation region expands rapidly and the flow condition becomes more disorganized. The appearance of backflow can block the flow passage and increase the flow resistance. Then the mainstream can’t flow into the runner smoothly. In addition, part of the energy of the runner will dissipate in the backflow. It explains why the energy loss of point C and D is larger than point A and in the runner domain from one aspect.

![Figure 6. Velocity vector on the meridional plane of runner and draft tube (magnified)](image_url)

The blade-to-blade relative velocity vector distribution on the mid-span plane on the four operating points is shown as Figure 7. The flow on point A is smoother than other three operating points. The velocity distribution of other off-design points is much more non-uniform than point A. The relative velocity orientation of other three operating points in the outlet of runner changes toward the inside of runner even form backflow. Secondary flow occurs as the flow departing from the mainstream. Moreover, as the flux decreases, the intensity of the secondary flow increases and the region where occurs secondary flow expands. The appearance of secondary flow can block the flow passage thus increasing flow resistance. In addition, some energy will be dissipated in the secondary flow. It increases the energy loss of the runner. The change of velocity direction is mainly due to the vortex and backflow caused by the striking of water to the guide vanes.
The streamline on the mid-span plane of the stay vanes and guide vanes is shown as Figure 8. The streamline on point A is uniformly-distributed. While the flow on point B, C and D is disorganized and there occur secondary flow even vortex pattern in the three cases. In addition, the smaller the flux is, the more the vortex pattern exists. On point B, there is only one vortex structure. The appearance of secondary flow and vortex pattern can block the flow passage and water from the runner can’t flow into the guide vanes domain smoothly. It also accounts for the secondary flow in the outlet of runner in smaller-flux conditions. In addition, the existence of vortex and secondary flow increases the energy of the guide vanes domain. Part of its energy will dissipate in the vortex flow. It explains why the head loss of guide vanes increases constantly from point A to point D.

3.3. Analysis of reasons for the formation of hump district of Francis pump-turbine
According to the analysis of head loss among the whole flow passage, the main loss of hump region is in the runner and guide vanes domains. In the runner domain, the flow on operating point A is smooth and the energy loss is small. The loss on point B is larger than point A due to the existence of secondary flow on the rotor-stator interface between the runner and guide vanes domain. The loss improves on point C as result of the combined impact of backflow in the entrance region of the runner and secondary flow in the outlet region of runner. The loss of point D is larger than point C as the region occurring backflow and secondary flow enlarges and the intensity is stronger. In the guide vanes domain, the flow on point A is smooth. Then the flow becomes disorganized from point B. In addition, the amount and intensity of vortex flow increases rapidly from point B to C. It results in the rapid increasing process of energy loss in the hump region in the guide vanes domain.

As the flux decreases, the flow inside the runner becomes more disorganized with the appearance of backflow in the inlet and outlet of runner. Consequently, the energy loss of runner increases rapidly towards smaller discharge. In addition, vortex and backflow pattern occur in the guide vanes domain as the flux decreases. Moreover, the energy of guide vanes increases towards smaller discharge with the increasing of vortex and backflow pattern. Especially near the valley of hump region, there is a rapid increasing process of energy loss in the guide vanes. The energy loss of runner and guide vanes is the main factor contributing to the formation of hump region. In the hump district, the total energy that the runner obtains is unable to make up for the large energy loss in the runner and guide vanes. Therefore the head drops towards smaller discharge. In the small-flux region, although the energy loss is larger, the total energy is large enough to make up for the energy loss.

4. Conclusions
The standard k-ε turbulent model is adopted to conduct steady numerical simulation of the whole passage under pump mode condition of a Francis pump-turbine in the optimal opening. Conclusions drawn from the research are as follows.

1) The standard k-ε model is adopted as its calculation error is relatively smaller and it is easier to achieve convergence during the computational process than SST model. The simulation accuracy in the hump region and nearby conditions remains to be improved.

2) The results of numerical simulation are in good agreement with experimental results. It is feasible to adopt the numerical simulation to analyze the reasons for the formation of hump region.

3) The main energy loss is in the runner and guide vanes domain. In addition, the energy loss increases rapidly in the hump region towards smaller discharge. The flow condition in the runner and guide vanes is closely related to the formation of hump district.

4) The flow becomes more disorganized as the flux decreases. The backflow flow in the entrance of the runner domain, the non-uniform of velocity distribution in the outlet of the runner and the complex secondary flow and vortex pattern inside the guide vanes domain are all related to the formation of the hump district.

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