Numerical simulation prediction of pressure distribution of guide vanes in a high-head pump turbine

Lei He 1*, Zhongxin Gao 1, Ying Chen 1, Jianguang Zhang 1, Bingquan Ma 1, Xiaochao Meng 1, Lei Rao 1

1 China Institute of Water Resources and Hydropower Research
A-1Fuxing Road, Haidian District, Beijing, China

*Lei He: Tel.: +86-17710756693, 867486518@qq.com

Abstract. In order to clarify the influence of different turbulence models on the numerical simulation of the pump turbine, 3D numerical steady simulations using four kinds of turbulence models: SST, k-ε, k-ω and RNG k-ε were applied to simulate the flow inside the mixed-flow pump turbine. 16 monitoring points were installed in guide vanes to obtain the relationship between pressure distribution of guide vanes in different monitoring locations and operation conditions. The pressure distribution of guide vanes was simulated using four kinds of turbulence models, and compared with the model test results. The results show that when the turbulence model is SST, the numerical simulation results are closer to the model test results.

Keywords: pressure, guide vane, turbulence model, numerical simulation, model test

1. Introduction

Guide vanes are critical to the hydraulic performance of pump turbines, which has been a hot topic in the field of hydro-mechanical research. Especially in high-head pump turbines, the hydraulic loss in the guide vanes is large.

Wang L Q [1] investigated the pump-turbine’s pumping mode at different openings of guide vane, which provide a guide for determination of operating condition and optimal design of pump-turbine. Shao W Y [2] studied the mechanism of the MGV device to reduce the volute inlet pressure and found that the MGV device reduced the maximum value of pressure on the case inlet to a certain extent. Li Q F [3] performed numerical analysis on the transient process of the guide vane of the pump turbine, and obtained the transient changes of speed and pressure with time, and discussed the flow field characteristics of the guide vane of the pump turbine. M Sick [4] studied the vibration problem of the guide vanes of the pump and turbine by using 3D numerical simulation methods and proposed a solution. He L [5] studied the influence of different circumferential offsets of guide vane on hydraulic efficiency of pump turbine, by using 3D numerical simulation methods. Li D Y [6] investigated the influence of Guide Vane
Setting in Pump Mode on Performance Characteristics of a Pump-Turbine. Zhu D [7] investigated the impact of guide vane opening angle on the flow stability in a pump-turbine in pump mode. Liu D M [8] investigated the characteristic at rated guide vane opening on pump-turbine by Numerical simulation and experimental research. Researchers [9]-[12] investigated on the comparison of characteristics in a hydraulic turbine with different turbulence models.

To date, there are few studies on the pressure distribution of guide vanes in the pump turbine. In this paper, the pressure distribution of guide vanes was obtained through model test and numerical simulation. In order to clarify the influence of the turbulence model on the numerical simulation results of high-head pump turbine, SST, k-ε, k-ω, and RNG k-ε are selected for numerical simulation.

2. Pump-Turbine model
The parameters of the model of pump-turbine are shown in Table 1. The properties of the fluid through the pump-turbine is water.

| Parameter | Value |
|-----------|-------|
| D1/m      | 0.548 |
| D2/m      | 0.250 |
| n_s (r/min) | 27 |
| Zg        | 20    |
| Zs        | 20    |
| Z         | 7     |

Table 1. Parameters of the model of pump-turbine

Figure 1. Hydraulic domain of the model of pump turbine.

Figure 2. Mesh of hydraulic components.

The whole geometry of the computational domain is showed in Figure 1, which contains a spiral casing, stay vane channels (20 stay vanes), guide vane channels (20 guide vanes), a runner (7 blades) and a draft tube.

3. Mesh Generation and Monitoring Points

3.1 Mesh Generation
The mesh for numerical simulations in the study was generated in ANSYS 18.0 ICEM. Unstructured mesh was generated in the spiral case, and structural mesh was generated in the stay vane, the guide vane, the runner, and the draft tube, as shown in Figure 2. The total number of nodes in the simulation domain is 2.21 million, the number of nodes in each simulation domain is shown in Table 2. In order to
improve the simulation accuracy of impeller area, guide vane and the stay vane, the grid is encrypted near the blade, and $y^+$ is controlled within simulation requirements. In this paper, average $y^+$ is 77.01 on the impeller surface, and average $y^+$ is 60.79 on the guide vane surface, where $y^+<100$, which meets the simulation requirements of various models.

3.2 The Locations of Monitoring Points
As shown in Figure 3, there were four guide vanes with sensors installed in the model experiment: the No. 20 guide vane and the No. 1 guide vane, the No. 10 guide vane and the No. 11 guide vane which were spaced 180° apart from No. 20 and No. 1. Four sensors were installed at one-half of the height of each guide vane to monitor the average pressure and pressure pulsations on the guide vanes surface in different conditions, numbered 1-4, as shown in Figure 4. And, the No. 20 guide vane and the No. 1 guide vane, the No. 10 guide vane and the No. 11 guide vane formed a flow passage, which were located on both sides of the same flow passage. In order not to affect the flow of guide vanes, the sensors’ wires were buried inside the guide vanes. After the installation is completed, the surface of the sensor is flush with the surface of the guide vane.

![Figure 3. Sensors layout](image1)

![Figure 4. Sensors installation location](image2)

Table 2. Number of nodes simulation domain
4. 3D Numerical Steady Simulations with Four Kinds of Turbulence Models

4.1. Model Test
The model test was carried out at 4 different unit speeds, as shown in Table 3, under turbine mode, at the unit speed of each operation, guide vane opening range is 8mm~30mm, and each interval is about 2mm, 11 different opening degree of the model test were carried out. Under pump mode, pressure tests were carried at 9 pump operating points, as shown in Table 4. \( \phi \) is discharge coefficient and \( \psi \) is pressure coefficient. The 3D numerical simulation is set and calculated according to the experiment condition parameters.

| operating point | turbine-1 | turbine-2 | turbine-3 | turbine-4 |
|-----------------|-----------|-----------|-----------|-----------|
| \( n_{11}(r/min) \) | 39.26     | 38.38     | 37.02     | 34.0      |

Table 4. Pump operating points

| operating point | pump-1 | pump-2 | pump-3 | pump-4 | pump-5 | pump-6 | pump-7 | pump-8 | pump-9 |
|-----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| \( \phi \)      | 0.3134 | 0.3075 | 0.3005 | 0.288  | 0.2693 | 0.27   | 0.2552 | 0.2386 | 0.234  |
| \( \psi \)      | 4.814  | 4.8602 | 4.9326 | 5.0001 | 5.0837 | 5.1508 | 5.236  | 5.3044 | 5.3301 |

4.2. Numerical simulation
The commercial software ANSYS 18.0 CFX was used for the numerical simulation. Under turbine mode, three different guide vane openings are numerically simulated under four different unit speeds. The guide vane openings are selected as shown in Table 5. Under pump mode, three working points: pump-2, pump-6, and pump-8 are selected for numerical simulation. The four turbulence models: SST, \( k-\varepsilon \), \( k-\omega \), and RNG \( k-\varepsilon \) are applied for numerical simulation at each working conditions.

| guide vane opening number | 1 | 2 | 3 |
|--------------------------|---|---|---|
| guide vane opening (mm)  | 10| 20| 30|
Dynamic and static interface type is Frozen Rotor. The residual error was set as $10^{-4}$.

5. Analysis of numerical simulation results

5.1. External characteristics

The external characteristics of the numerical simulation results under four different turbulence models are analyzed and compared with the model test results. The results are shown in the Table 6 and Table 7.

Table 6 shows the efficiency and head of the four turbulence model at four unit speeds under turbine mode when the guide vanes openings are 10mm, 20mm, and 30mm. Table 7 shows the efficiency and head of four turbulence models at three different operating point conditions under pump mode. It can be known from Tables 6 and 7 that under various operating conditions, the choice of turbulence model has little effect on efficiency and head.

| guide vane opening (n/1)  | turbulence model | 10mm |    | 20mm |    | 30mm |    |
|--------------------------|------------------|------|----|------|----|------|----|
|                          | efficiency (%)   | head (m) | efficiency (%) | head (m) | efficiency (%) | head (m) |
| 34                       | SST              | 90.40  | 21.17 | 92.46 | 20.19 | 87.77 | 19.92 |
|                          | k-ε              | 90.45  | 21.98 | 92.42 | 20.39 | 88.37 | 20.10 |
|                          | RNG k-ε          | 90.17  | 21.25 | 92.44 | 20.34 | 87.05 | 20.54 |
|                          | k-ω              | 89.90  | 21.99 | 92.14 | 20.27 | 88.17 | 19.76 |
|                          | exp              | 84.87  | 20.13 | 86.81 | 20.21 | 81.36 | 20.21 |
| 37.02                    | SST              | 88.19  | 21.38 | 93.80 | 20.18 | 91.70 | 19.77 |
|                          | k-ε              | 89.93  | 21.82 | 94.08 | 20.34 | 91.87 | 20.04 |
|                          | RNG k-ε          | 88.06  | 21.08 | 94.05 | 20.30 | 90.79 | 20.41 |
|                          | k-ω              | 89.50  | 21.83 | 93.58 | 20.23 | 91.47 | 19.72 |
|                          | exp              | 80.74  | 20.11 | 86.56 | 20.14 | 83.47 | 20.21 |
| 38.38                    | SST              | 86.96  | 23.52 | 92.90 | 22.01 | 92.17 | 20.00 |
|                          | k-ε              | 85.78  | 23.68 | 92.99 | 22.26 | 92.26 | 20.32 |
|                          | RNG k-ε          | 86.22  | 23.88 | 93.23 | 22.35 | 92.31 | 20.44 |
|                          | k-ω              | 85.38  | 23.66 | 92.62 | 22.04 | 91.80 | 19.99 |
|                          | exp              | 77.91  | 20.21 | 86.01 | 20.28 | 83.80 | 20.23 |
| 39.26                    | SST              | 85.02  | 23.58 | 92.61 | 21.77 | 92.05 | 19.99 |
|                          | k-ε              | 85.46  | 23.66 | 92.91 | 22.00 | 92.25 | 20.30 |
|                          | RNG k-ε          | 85.92  | 23.82 | 93.19 | 22.08 | 92.34 | 20.42 |
|                          | k-ω              | 85.15  | 23.57 | 92.37 | 21.80 | 91.74 | 19.96 |
|                          | exp              | 74.76  | 20.30 | 85.72 | 20.20 | 84.16 | 20.22 |

Table 7. Efficiency and head under pump mode

| operating point | pump-8 |    | pump-6 |    | pump-2 |    |
|-----------------|--------|----|--------|----|--------|----|
| turbulence model | efficiency (%) | head (m) | efficiency (%) | head (m) | efficiency (%) | head (m) |
5.2 Average pressure of guide vanes under four turbulence models

The average pressure of the guide vanes collected by the sensors in model test is compared with the 3D numerical steady simulation results with turbulence model: SST, k-ε, k-ω, and RNG k-ε, which is under turbine operating point: n11=34r/min and the guide vane opening is 10mm, 20mm, 30mm. The comparison of average pressure at four guide vanes are shown in Figure 5. For example, NO.20-exp is the model test result at NO.20.

The comparison of average pressure in guide vanes also carried out under pump mode: pump-2, pump-6, and pump-8, shown in figure 6.

When the guide vane opening is 10mm, as shown in Figure 5 A.1 and A.2, under the turbulence model SST, the simulation result is the closest to the test result at NO.20 and NO.10; the simulation results under four turbulence models at NO.1 and NO.11 have little difference.

When the guide vane opening is 20mm, under the turbulence model SST, the simulation result is the closest to the test result at NO.20, NO.1, NO.10 and NO.11, showed in figure 5 B.1 and B.2.

When the guide vane opening is 30 mm, the simulation results are not well under four turbulence models at NO.20, NO.1, NO.10 and NO.11, showed in Figure 5 C.1 and C.2.

In summary, under the turbine mode, the turbulence model SST can simulate the model test better at small opening and medium opening. And the simulation results are not well at big guide vane opening under four turbulence models.

| Turbulence Model | Pressure 10mm | Pressure 20mm | Pressure 30mm |
|------------------|---------------|---------------|---------------|
| SST              | 87.57         | 88.14         | 88.35         |
| k-ε              | 87.03         | 88.33         | 88.41         |
| RNG k-ε          | 86.44         | 87.88         | 88.04         |
| k-ω              | 86.77         | 87.08         | 87.90         |
| exp              | 83.62         | 86.06         | 87.90         |

![Figure 5](image1.png)

A.1) NO.20 and NO.1, guide vane opening=10mm

![Figure 6](image2.png)
Figure 5. Pressure distribution with four turbulence models under turbine mode

At the operating point pump-8, as shown in Figure 6 A.1, simulation result is closer to the test results under the turbulence model SST at NO.1; simulation result is closer to the test results under the
turbulence model k-ε at NO.20. As shown in Figure 6 A.2, under the turbulence model SST, the simulation results are closer to the test results at NO.10 and NO.11.

At the operating point pump-6, as shown in Figure 6 B.1, under the turbulence model SST, the simulation result is closer to the test results at NO.20 and NO.1. At the No. 10 and No. 11, the simulation results obtained under turbulence models: k-ω and k-ε are better, showed in Figure 6 B.2.

At the operating point pump-2, as shown in Figure 6 C.1, under the turbulence model SST, the simulation result is closer to the test result by numerical simulation at NO.20 and NO.1. At NO.10 and NO.11, the simulation result obtained under k-ω is closer to test results, but the simulation results under four turbulence models have little difference, showed in Figure 6 C.2.

In summary, under pump mode, the turbulence model SST can simulate the test conditions better at guide vanes: NO.20 and NO.1. At NO.10 and NO.20, the turbulence model k-ω is better.
B.2) NO.10 and NO.11, operating point:pump-6

C.1) NO.10 and NO.11, operating point:pump-2

C.2) NO.10 and NO.11, operating point:pump-2

**Figure 6.** Pressure distribution with four turbulence models under pump mode

6. Conclusion

1. In the model test, on the premise of not affecting the flow of guide vanes, install sensors (two sets of sensors, 180 degrees apart) on the surface of guide vanes on both sides of the same flow passage to obtain the pressure distribution of guide vanes.

2. The results of numerical simulation are compared with the results of model tests. Based on results and analysis: under the turbine mode, the turbulence model SST can simulate the model test better at small opening and medium opening; under pump mode, the turbulence model SST can simulate the test conditions better at guide vanes: NO.20 and NO.1. The SST turbulence model is recommended in the numerical simulation of high-head pump turbines.
Acknowledgments

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