Experimental study and numerical analysis of the flow types in the cascade under the slight opening

H RUAN¹, W L LIAO¹, H G FAN²*, Q F JI¹ and H X YANG²

¹ Institute of Water Resources and Hydro-electric Engineering, Xi'an University of Technology, Xi'an, China
² State Key Laboratory of Hydrosience and Engineering Department of Thermal Engineering, Tsinghua University, Beijing, China

*Corresponding author: fanhg@tsinghua.edu.cn

Abstract: The flow types between the guide vanes have significant influence on the stability of a pump-turbine, especially when the guide vane opening is very small. In order to study the flow types between the adjacent vanes, the CFD simulation, which with the Reynolds Stress Model, of a cascade with three kinds of water foil were carried out, and a verification experiment about the cascade flow was conducted. The CFD simulation results indicated that the diffusion ratio and leading edge curvature ratio of the water foil are the important parameters which make the different flow types happened. Moreover, the experiment results show that the CFD simulation has a great agreement with it.

1. Introduction
The pump turbine has a complicated working mode conversion during the operation. Thus, it’s very important to guarantee the stability of the units when the working mode is alternating. Recent years, in some pumped storage power station such as Tian Huangping pumped storage power station [1] and Yixing pumped storage power station [2], the vibration and abnormal sound occurs at the distributor of the pump turbine during the startup and shutdown process when the guide vane opening is very small. In order to find out the root cause of this unstable phenomenon, H G Fan [3] studied the hydraulic torque of the guide vane of the pump turbine during the startup process and shutdown process in turbine mode by 2-D periodical CFD simulation. His work indicated that repeating reversal of fluid occurs when the guide vane at slight opening during the shutdown process in turbine mode. These phenomena result in the dramatically increasing of the hydraulic torque which makes the vibration happens eventually. Afterwards, H G Fan and Q F Ji etc. [4] has performed the 3-D CFD simulation of the startup process of the pump turbine of Tian Huangping pump storage power station which in the pump mode by implementing the dynamic meshing technique. The results indicated that the main flow between the guide vanes has experienced a deflection when guide vane opening is very small, and this deflection leads to the sharply changing of the hydraulic torque on the guide vanes, if the transmission of the distributor cannot adapt this changing immediately, the vibration and abnormal sound will occur in the unit. Addressing the issue of Yixing pumped storage power station, B Nennemann [5] has conducted a detailed research about the abnormal phenomena which happened in YiXing pump storage power station by using 2-D periodical CFD simulation. Eventually, the author acclaimed that the unexpected bi-stable flow conditions and a self-excited torsion mode flutter vibration of the guide
vane caused this problem, moreover, the vibration problem can be eliminated by modifying the shape of the guide vane successfully.

H X Yang [6] has conducted a CFD simulation and an experiment about the flow types (the flow type definition shows in figure 1) of the main flow in a cascade, but it’s hard to capture the type 2 of the mainstream. The results indicate that the flow types of the main flow between the vanes are related to the shape of the foil.

2. Water foil profile parameters
The geometry profile of the water foil is the most significant influence factor to the flow state between every single foil. In this paper, the most of two important parameters of the foil, diffusion ratio and leading edge curvature radius, was defined. The parameters were shown in figure 2.

2.1. Diffusion ratio $e$
Diffusion ratio $e$ was put forward by H X Yang [6] which is defined as follows:

$$ e = \frac{B-b}{L} \quad (1) $$

Where $B$ is the projection length of the maximum cross section of the cascaded passage, and $b$ is the minimum projection length of the cross section of the cascaded passage, and $L$ is the mean-streamline between the two sections which aforementioned.
But in this paper, the definition of B was simplified as the projection length of the parallel section (which at the leading edge point) of minimum cross section, and L was defined as the distance between these two parallel section.

2.2. Leading edge curvature radius ratio \( \rho \)
Proverbially, the flow type of the main flow in the cascaded is related to the Coanda effect [4], thus the radius of the wall, which the flow has attached to, is a very important factor to the flow direction. And in this research, we defined the leading edge curvature radius ratio \( \rho \) to control the profile of the foil as follows:

\[
\rho = \frac{r}{R}
\]

Where \( r \) is reference to the radius of the leading edge at the minimum cross section, and \( R \) is the radius of the leading edge at the maximum cross section.

3. Water tunnel test rig
The test rig configuration includes an upstream flow control value, an electromagnetic flowmeter, two transition sections, a steady flow section, a cascades section, a wake section, an exhaust valve and a downstream control valve. The overall layout of the test rig was shown in figure 3.

![Figure 3. Test rig overall layout](image)

In this paper, the cascade was fixed in a square tube (shows in figure 4) which size is 0.2m x 0.2m x 1.2m, the head about this test rig is 9m, the discharge range of the water in the tunnel between 11.3 m³/h and 100 m³/h. The orange line on the vanes was used to indicate the flow direction.

![Figure 4. Cascades section of the test rig](image)
4. CFD simulation

4.1. Turbulence model selection
This paper is focusing on studying the flow characteristics of the main flow between the cascades under the slight opening. It’s very necessary to choose a turbulence model which has higher precision and accuracy on solving the high Reynolds number clearance flow. Thus the RNG k-epsilon model and Reynolds Stress Model (RSM) was selected to simulate the cascade flow experiment which was conducted by H X Yang [6]. The opening of the cascade is 2 degree, and the velocity of the upstream is 0.2 m/s. And the results shows that the RSM has higher precision and accuracy than RNG k-epsilon model: Figure 5 shows that the stream line and velocity contour of RSM has a good agreement with the PIV result. Thus the RSM was selected in this paper.

![PIV result](image1)
![RNG k-e result](image2)
![RSM result](image3)

**Figure 5.** Comparison of different turbulence model

4.2. Computation domain
The cascades section was used as the computational domain in this paper. Because of the symmetrical characteristic of the cascades section, the 2D geometry model was chosen in this simulation. And the tetrahedral mesh was used in this study, the mesh number is about 1.5 million. The prism mesh was applied at the foil wall. The computation domain and the mesh at the gap of the cascade are shown in figure 6.

![Computation domain](image4)
![Mesh between the adjacent vanes](image5)

**Figure 6.** Geometry model of the cascade
In order to find out the relationship between the foil profile parameters and the flow types, three kinks of foil with the same opening (2 degree) were implemented. The detail data of the three kinds of foil was listed in table 1.

Table 1. Cascade Parameters (mm)

| NO. | Parameters | Value |
|-----|------------|-------|
| A   | L_1        | 32.68 |
|     | L_2        | 27.80 |
|     | R          | 5.36  |
|     | r          | 1.99  |
|     | B          | 3.08  |
|     | L          | 2.15  |
|     | b          | 0.86  |
|     | e          | 1.03  |
|     | ρ          | 0.37  |

|     | L_1        | 32.07 |
|     | L_2        | 31.61 |
|     | R          | 1.70  |
|     | r          | 4.58  |
|     | B          | 7.09  |
|     | L          | 3.27  |
|     | b          | 0.57  |
|     | e          | 1.99  |
|     | ρ          | 2.69  |

|     | L_1        | 30.78 |
|     | L_2        | 30.15 |
|     | R          | 5.54  |
|     | r          | 5.54  |
|     | B          | 9.14  |
|     | L          | 5.55  |
|     | b          | 0.50  |
|     | e          | 1.56  |
|     | ρ          | 1     |

Where the L_1 is the length of the foil, L_2 is the cascade space.

4.3. Boundary conditions
The velocity inlet and pressure outlet was selected in the simulation. And the working conditions are listed in table 2.
Table 2. Working conditions

| NO. | I   | II  | III | IV  |
|-----|-----|-----|-----|-----|
| Inlet velocity (m/s) | 0.1 | 0.14| 0.2 | 0.3 |

4.4. Results and discussion

Figure 7 to 9 show that, with the foil A, the main stream under all of the working conditions are stay in type 1. With the foil B, the vortex forced the mainstream flow toward downstream direction under all of the circumstances. But with foil C, the main stream under all of the working conditions are stay in type 2. It’s can be seen that the increasing of the velocity has no influence on the flow types with those three kinds of foil.

Referencing to table 1, it’s easy to find out that $\rho_A < \rho_C = 1 < \rho_B$, $e_A < e_C < e_B$. With the increasing of $e$, the main flow stay away from type 1 and turns to type 2 (such as foil B and foil C). And when $\rho = 1$, the flow stays in type 2.

![Figure 7. Velocity contours of foil A](image-url)
Figure 8. Velocity contours of foil B
When the main flow past the clearance of the adjacent vanes, the flow separation will occur at the tail of the foil. Because of the Coanda effect, the main flow will attach to the large radius side. The foil A has a small radius at the leading edge, thus the vortex at the leading edge will force the mainstream stay in type 1. The foil B has a sharply changing of radius at the tailing edge, thus the main flow has a serious separation at the tailing edge, and the main flow turns toward to type 2 because of the radius of the leading edge is larger than foil A. But the radius of leading edge has a quick decreasing, the vortex which occurred at the pressure side forced the mainstream stay between type 1 and type 2. The foil has the largest radius at the leading, and the change rate of the radius is 0, thus the vortex occurs at the tailing edge of the foil and the flow stay in type 2.

5. Verification experiment
In order to verify the flow type 2 does exist, a verification experiment with foil C was carried out. The experiment was carried out on the water tunnel test rig which has aforementioned, the working conditions are as same as the CFD simulation, and the orange line which has been paste to the vanes were used for indicating the flow types.

The experiment results (figure 11 b) shows that the main flow are stay in type under all of the conditions. It has a great agreement with the CFD simulation.
0.1m/s

0.14m/s

0.2m/s
0.3m/s

(a) CFD results  (b) Experiment results

Figure 11. Comparison of the CFD and experiment results

6. Conclusion
The CFD simulation and experiment of the cascade in the water tunnel indicates that:

The mainstream in the cascade has two kinds of the flow type when the opening is very small. And these two kinds of flow types are caused by coanda effect.

The shape of the foil has a significant influence on the flow type. The foil which has a large diffusion ratio and when the leading edge curvature ratio close to 1, the main flow will stay in type 2. If the foil has a large diffusion ratio but the leading edge curvature ratio is far away from 1, the mainstream will stay between type 1 and type 2. And if the foil has a small diffusion ratio, the mainstream will stay in type 1.

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8. Reference
[1] Kong, L. H., 2004, “Analysis of abnormal sounds in working condition change-over for high-head pump-turbine,” Mechanical & Electrical Technique of Hydro power station, 27(6), pp. 12-14.
[2] Cai, J., Zhou, X. J., Deng, L., and Zhang, W. H., 2009, “The Research of the Abnormal Water Hammer Phenomenon based on the Unit 3 over Speed Test of Jiangsu Yixing Pumped Storage Power Station,” China Academic Journal Electronic Publishing House, Water power, 35(2), pp. 76-79.
[3] Fan, H. G., Yang, H. X., Li, F. C., and Chen, N. X., 2014, “Hydraulic torque on the guide vane within the slight opening of pump turbine in turbine operating mode,” 27th IAHR Symposium on Hydraulic Machinery and Systems, Montreal, Canada, September, 22-26.
[4] Fan, H. G., Ji, Q. F., Liao, W. L., and Yang, H. X., 2016, “Flow Analysis of the Guide Vanes Region of Pump Turbine at the Slight Opening in the Pumping Startup Process,” ASME HT/FED/ICNMM 2016, Washington. DC., USA, July, 10-14.
[5] Nennemann, B., and Parkinson, É., 2010, “YiXing pump turbine guide vane vibrations: problem resolution with advanced CFD analysis,” 25th IAHR Symposium on Hydraulic Machinery and Systems, Timisoara, Romania, September, 20-24.
[6] Yang, H X, 2016, “Research on Bistable Flow between Cascades within Slight Opening,” Master Thesis, Tsinghua University, Beijing, China.