Optimum design of exit guide vane on the bidirectional tubular turbine

X B Zheng², X Zheng¹, J Y Ma¹

¹ Institute of Water Resources and Hydro-Electric Engineering, Xi’an University of Technology, No.5 South Jinhua Road, Xi'an, 710048, China
² FINE Institute for Hydraulic Machinery, 10F Zanyu Technology Building, No.702 Gudun Rd, Hangzhou, 310013, China

E-mail: zhengxbb@163.com

Abstract: Performance prediction about the forward generation condition based on a bidirectional through-flow turbine runner was conducted. The model characteristic curves and efficiency curve under reverse generation condition were plotted. In order to improve the reverse performance, exit guide vanes were lied behind the runner, the forward and reverse operating performance about a runner lied post-guide vane were numerically simulated. The results shows that the flow field distribution on forward generation condition did not significantly change after exit guide vanes were lied, and the energy conversion efficiency decreased. After exit guide vanes were lied, flow pattern of runner intake on under reverse generation condition were bettered, and the energy conversion efficiency increased. This study confirms that the exit guide vanes can improve the hydraulic performance of the turbine on reverse generation condition in view of numerical simulation.

1. Introduction
The turbine applied to tidal power plant operation must be able to work in a very small head, own a great over-current capacity, and can meet the requirements of bidirectional power. Bulb tubular unit has the advantages of small head loss and large unit flow, suitable for large-medium tidal power station in low head. However, Tidal power station has been built in our country exists the problem of generally hydraulic efficiency low, hydraulic loss is obvious, therefore it's a very important significance that simulating the bidirectional bulb turbine and improving performance through the hydraulic optimization design under the condition of analyzing the internal flow. It has become a trend by using the CFD method to optimize the turbine design and study of internal flow field.

2. Performance prediction of bidirectional bulb turbine

2.1. Performance prediction method of a bidirectional bulb turbine
For a tubular turbine with an certain geometry, the relationship between head H and discharge Q is one to one corresponding under a given opening α₀, blade angle φ₀ and speed n. Therefore, when it comes to the calculation in the performance prediction, only giving the opening α₀, blade angle φ₀ and speed n.
When calculating the CFD numerical simulation in this paper, it was given a flow $Q$ first, then comparing the difference between the calculation head $H$ and the experimental head $H_e$, if $|H - H_e| \leq \epsilon$, it was considered this flow matched with the operating condition, but if the difference is greater than a certain value, then to give another flow until meet the requirement, where the $\epsilon$ is 0.07m. The turbine numerical calculation can be completed when the flow is determined.

2.2. The three-dimensional steady computation of bidirectional bulb turbine

2.2.1. Forward condition performance prediction For the purpose of saving time, select the single channel when take a calculation because of the computer resource constraints. Parameters of model hydraulic turbine as follows: head 7.73m; runner diameter 0.34m; hub ratio 0.38; blade number 3; guide vane number 16. Calculation region as shown in Figure 1.

![Figure 1. Forward calculation region.](image)

To select 75 operation points for calculation, which comprises 5 groups of different unit speed, 3 blade angle(18°, 22°, 26°) and 5 guide vane opening (45°, 50°, 55°, 60°, 65°). Due to the computational time and computational resources are limited, only selected 5 operating points to calculation with same blade angle 18° and opening fixed at 95° but different unit speed, the calculation results are shown in Table 1. According to the energy characteristics date of each point numerically calculated, can plot equal efficiency curve 18°, 22°, 26° blade angle, draw some forward operating model turbine characteristic curve of the bidirectional through-flow turbine, as shown in figure 2.

| Table 1. Calculation results of gate opening |
|---------------------------------------------|
| Gate opening (°)  | 90 | 95 | 100 | 105 |
| Blade angle (°)  | 18 | 18 | 18 | 18 |
| Experiment head $H$ (m) | 7.73 | 7.73 | 7.73 | 7.73 |
| Calculation head $H_e$ (m) | 7.69 | 7.72 | 7.67 | 7.74 |
| Discharge (L/s) | 2423 | 2428 | 2432 | 2421 |
| Runner head (m) | 6.484 | 6.587 | 6.488 | 6.511 |
| Device efficiency (%) | 48.98 | 49.34 | 49.17 | 48.51 |
| Vane loss (m) | 1.206 | 1.135 | 1.185 | 1.232 |
| Vane loss/$H_e$(%) | 15.68 | 14.70 | 15.45 | 15.92 |

It is seen from table 1, the guide vane opening 95° runner efficiency is the highest, the minimum hydraulic loss, so the 95° determined to be the guide vane opening of reverse operating condition.
From Figure 2 that the parameters corresponding to the optimum operating point about this model of turbine as follows: blade angle 22°, guide vane opening 55°, unit speed of 200 rpm, 1840 l/s unit flow.

2.2.2. Reverse condition performance prediction The reverse condition calculation, model turbine has the identical geometry parameters and calculation head with the forward condition's. The current flows from runner to guide vane under reverse condition.

Based on the calculation of the reverse operation, temporarily assumes fixed guide vane, movable blades. In order to analyze the guide vane opening effect on the hydraulic performance of the reverse operation, model speed calculated for 180 rpm, guide vane opening for the reverse flow properties of 90°, 95°, 100°, 105° four cases respectively, the calculation results are shown in Table 2

| Unit speed \( n_{11} \) (rpm) | Unit discharge \( Q_{11} \) (L/s) | Experiment head \( H \) (m) | Calculation head \( H_e \) (m) | Efficiency (%) |
|-----------------------------|---------------------------|----------------|----------------|----------------|
| 140                         | 2095                      | 7.73           | 7.67           | 46.69           |
| 160                         | 2255                      | 7.73           | 7.71           | 48.98           |
| 180                         | 2438                      | 7.73           | 7.72           | 49.34           |
| 200                         | 2593                      | 7.73           | 7.70           | 49.16           |
| 220                         | 2752                      | 7.73           | 7.67           | 43.81           |

From the table 2, reverse the turbine efficiency is low, the maximum efficiency operating point parameters are: blade angle 18°, the guide vane opening 95°, 180 rpm of unit speed, 2438 l/s of unit discharge.

3. The rear diffuser's influence on the working condition of forward and reverse

3.1. the design of the rear vane

Widely used rear guide vane, usually used in fans, axial flow pump, fluid machinery, tubular pump, etc. Setting rear guide vane after the runner is rarely used. In pump turbine, the blade design is relatively reasonable, it can get a better hydraulic performance in inverted running. The model of turbine which is used in this turbine has a better forward condition performance than reverse condition performance. Therefore, as fan axial flow pump and tubular pump improve the performance after setting the rear vance, this paper set the rear vance after the runner under the premise of without changing blade shape, in order to improve the forward condition performance of the model turbine.

In this calculation, the number of rear guide vane is 16, if the rear guide vane is overmuch, it will reduce the flow performance, makes the unit output can not meet the design requirements. If the rear guide vane number is less, the model turbine rear vane in the reverse run time can't play the role of form wheel import circulation. Integrated forward and reverse operation requirements, therefore, refer...
to the tubular pump rear guide vane number set requirements, the paper used in the calculation model of water turbine rear guide vane number is temporarily set at six. The rear guide vane calculation area of the geometry model is shown in figure 3.

Figure 3. Geometry model computing area with exit guide vane

3.2. the determination of the rear guide vane opening
Turbine in forward operation, front guide blade and blade association relationship, can make the turbine in a wide area efficient operation. If rear guide vane design according to the forward conditions and to a certain fixed opening is installed on the guide vane hub, cannot adjust with the change of the conditions and opening, so when the model turbine off-design operation, often have head Angle of attack in guide vane, cause the hydraulic loss. If the rear guide vane design according to the working condition of reverse design, also with a fixed opening is installed on the guide vane hub, then there is no such as leader's leaf and leaf association relationship, when conditions change, will have big angle of attack at the edge of the blade inlet place, makes the hydraulic poor performance. Therefore, this paper design of the rear guide can be adjusted, can be at off design condition by adjusting the rear guide vane opening to reduce the impact of loss, in order to improve the efficiency of the model.

Figure 4 the import and export flow velocity triangle of model turbine blades:
In figure 4, it can approximate that of blade outlet flow relative speed w2 tangent direction and the blade surface, so the \( \beta \) value with the blade outlet Angle of approximately equal. In order to make the rear guide vane have minimal impact on forward conditions, if know the blade Angle and flow conditions, was laid by blade outlet velocity triangles to calculate the blade outlet absolutely Angle \( \alpha \),
then adjust the rear guide blade inlet Angle which have the equal effect to adjust the rear guide vane opening.
Turbine reverse running, to make the working condition of reverse inlet when the loss to minimum impact, can approximate the blade inlet water flow in the direction of relative velocity and blade bone line tangent, imported relative flow Angle and blade Angle was lapproximately equal. For rear guide vane can effectively improve the running performance of reverse under the condition of the blade known put Angle and flow, calculate the blade inlet absolutely Angle through the inlet velocity triangle, then adjust the rear guide vane exit flow Angle of the rear as adjust the guide vane opening.

3.3. the rear vane impact on forward conditions
On the basis of the above settlement as a result, the blade outlet absolutely Angle is 72 °, as determine the basis of a rear guide vane Angle. This condition were calculated and found that the most efficiency is 93.39%, than not to set the rear guide blade fell by 2.62% traffic by 1840 l/s fell to 1815 l/s than the optimum conditions,.
Because of the rear guide vane occupies part of the tail pipe size, over-current area decreases, and makes the flow down. On the other hand, Water flow into the tail pipe, direct hit the rear vane, causing a certain hydraulic loss. Table 3 is there are ways of guide vane when forward the advantages of each components of hydraulic loss.

| parts          | Exit guide vane (yes/no) | Forward guide vane | runner | Exit guide vane |
|----------------|--------------------------|--------------------|--------|-----------------|
|                | no                       | yes                | no     | yes             | no               | yes             |
| Loss value (m) | 0.121                    | 0.138              | 0.196  | 0.254           | 0.116            |
| percentage (%) | 1.56                     | 1.79               | 2.54   | 3.30            | 1.51             |

Figure 5 and figure 8 is the pressure of the head of the blade and velocity vector contrast figure, it can be seen that wheel speed region near the stagnation point is still in the blade head partial pressure surface, the water flow under the condition of there is a small Angle of attack is α, other no flow and vortex flow regions flow regime is good except the import, we can see that put the rear vane have not big influence on the inside flow condition.
Figure 7. Head velocity vector diagram without exit guide vane.

Figure 8. Head velocity vector diagram with exit guide vane.

Figure 9. Comparison of runner outlet circulation.

Figure 9 shows that the distributions of runner outlet circulation is quite even with the position in the radial direction, because of high water exit velocity in the flange section, the circulation is the highest. When erection exit guide vane, the maximum in the flange becomes smaller than that there is no exit guide vane, and the current nearby the draft tube wall surfaces can better adhibit the wall flows, without flow separation.

In a word, there are no obvious changes of internal flow status in model water turbine after erection exit guide vane. However, exit guide vane can improve the flow properties of the draft tube.

3.4. Influence of Exit Guide Vane on Reverse Optimum Operating Condition

According to the calculation results of the reverse condition (see 2.1.1), blade inlet absolute angular is 66°. Hereby the placed angel of exit guide vane is determinate. The calculation result shows that efficiency of the reverse optimum point is 50.78% which increased 1.44% than does not set the exit guide vane. What’s more, flow rate is decline.

Table 4. Hydraulic loss of reverse optimum operating condition point.

| Components        | Front Guide Vane | runner | Exit Guide Vane |
|-------------------|------------------|--------|-----------------|
| Exit Guide Vane (yes/no) | no | yes   | no | yes |
| Loss Value (m)    | 1.135            | 1.326  | 2.776          | 2.384 | 0.105 |
| Percentage (%)    | 14.7             | 17.1   | 32.9           | 30.7  | 1.3   |

Table 4 shows hydraulic loss of different components reverse optimum point when there is or not exit guide vane. It can be seen that after placed exit guide vane, hydraulic loss of runner is reduced. Figure 10 to figure 13 shows comparison diagram of pressure and velocity vector on the head of blade at reverse optimum condition. After placed exit guide vane, low pressure area of the blade suction surface is reduced; minimum pressure of the low pressure area is promoted. According to the head blade vector diagram, after placed exit guide vane, the vortex region of the back of vane is reduced and impact on the blade head slightly reduced.
When there is not placed exit guide vane, the current circulation of the runner inlet caused by runner itself. The function of placed exit guide vane is forming and changing circulation into the runner. Making the circulation difference between runner inlet and outlet can satisfied the requirements of runner energy conversion. So that can improve the performance of reverse condition of runner. Figure 14 and figure 15, respectively, shows comparison diagram of circulation of runner inlet and outlet with or without exit guide vane.

As shown in figure 14, runner inlet circulation has been improved after placed exit guide vane. Figure 15 shows that by placing exit guide vane, outlet circulation in most range is smaller than do not placed exit guide vane. It shows that after placed exit guide vane, the difference of circulation of runner inlet and outlet is bigger; the energy conversion efficiency is promoted.
According to the result of runner flow comparative analysis and hydraulic loss and the result of runner outlet circulation comparison, when placed exit guide vane, runner internal flow of model turbine is improved to some extent and reverse flow performance is also promoted.

4. Conclusion
In this paper, prediction performance for the forward and reverse condition based on a bidirectional through-flow turbine runner was conducted. At forward operation, 75 operating point was chosen under the condition of different blade angels, different guide vane opening and the combination of specific speed, to carry out numerical calculation and depict forward characteristic curve. Reverse efficiency curve was obtained under the calculation of reverse operation at the condition of 18°blade angle position. According to the calculation result, the model turbine performance is quite different between forward operation and reverse operation.

Through the numerical calculation of bidirectional through-flow turbine to placed exit guide vane, when the forward optimum operation point efficiency drop 2.62% the exit guide vane opening is 72°. Meanwhile, the internal flow of model turbine was basically unchanged. when the exit guide vane opening is 66° the optimum operation point efficiency promoted 1.44%. At the same time, the internal flow of turbine was quite improved. Therefore, it confirmed exit guide vane can quite improved reverse operation performance at the view of numerical calculation.

This paper makes a contrastive analysis of the exit guide vanes role and the optimization on aerofoil of exit guide vane is not involving. The influence of exit guide vanes number and position and other geometric parameters on the forward and reverse condition of turbine is not further study. Therefore, the hydraulic performance promotion result of exit guide vane on the reverse condition is limited.

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