Numerical study on the performance of bulb turbine by using runaway condition to flood discharge and sediment dredging

Z Yaping¹, L Weili¹, L Zhihua², R Hui¹ and L Xingqi¹
1. Institute of Water Resources and Hydro-Electric Engineering, Xi’an University of Technology, Xi’an, Shaanxi Province, China
2. Xi’an thermal power research institute co., ltd, Xi’an, Shaanxi Province, China

E-mail: zhaoyyp0168@hotmail.com
liaowei2008@hotmail.com

Abstract. When the floodwater of the bulb tubular type power station is released, a large number of sediment carried by the flood silts up at outlet of the tube, and has a serious impact on the later normal operation of the power station. In order to solve this problem, this paper presents a method that treats the tube sluice as the energy dissipation facility, use the small opening runaway conditions to carry out a regular and short time sediment flush during discharge, and set the sediment self-flushing corridor in the downstream river to achieve sediment flushing and dredging. Unsteady three-dimensional numerical study which considers free-surface of the Reservoir for different tube sluice conditions is conducted to reveal the flow capacity of the turbine and the flow characteristics in the draft tube. In particular, through analyzing the flow characteristics in the tube, the maximum particle size of the sand that can be washed away can be determined, assuming the outlet velocity of the tube is the starting speed, and then the sediment flushing capability of the turbine can also be estimated. The results show that: using the runaway conditions for flood discharge and dropping the height of the tube sluice to achieve the purpose of energy dissipation not only can improve the flood discharge capacity of the power plant, but also can increase flushing distance at the tailrace, and thus enhance the ability to remove silt. Setting the sediment self-flushing corridor at the downstream river would be a good solution to tailrace siltation problems of the bulb turbine.

1. Introduction

For hydropower stations in the sediment river, which are affected by the Siltation, many problems, such as Excessive Siltation in the reservoir, serious abrasion of the turbine components, failure to open the sluice and mechanical damage occur quite often [1-3]. Especially for the bulb turbine, as the discharge often has a sharp increase in the flood season and due to the output defects, the unit is forced to shut down and the sluice needs to open fully to flood discharge. So, it is a stagnant backwater zone at the tailrace, and a large number of sediment carried by the flood silts up at outlet of the tube sluice, which has a serious impact on the later normal operation of the power station. With regard to the dredging problem of bulb turbine, the literature [4] presents a method which uses the small opening runaway conditions to discharge and sediment flushing. The discharge in the runaway conditions is 1.41-1.56 times of that in conditions with the same guide vane and blade angle as the runaway conditions and the turbine runaway speed in the small opening conditions can be controlled near the...
unit normal operation speed [5]. So it is theoretically feasible for bulb turbine to flood discharge through a small opening runaway condition.

Research on the operating characteristics of bulb turbine with numerical and experimental methods has been very fruitful. However, using the runaway conditions to flood discharge is not common for domestic bulb turbine [6], and still under the theoretical development. Only small amount of literature [7] introduces the turbine characteristics under different discharge conditions. For this reason, studying the flow characteristics of the bulb turbine in the runaway and discharge conditions, and solving the tailrace siltation problems are particularly important.

In this paper, with free-surface on the reservoir, the unsteady three-dimensional numerical simulation for different tube sluice conditions are conducted to study the flow characteristics in the runaway conditions under the rated speed of the bulb turbine. By analyzing the flow characteristics under different conditions in the tailrace of the bulb turbine, the flood discharge and dredging capacity are studied, and the results can provide guidance for bulb turbine design and operation.

2. Geometric model and calculating operating point

In this paper, the numerical simulation is conducted for the whole turbine unit (consisting of the upstream and downstream reservoir, water diversion section, 16 guide vanes, 5 runner blades and the draft tube), The computational domain is shown in Figure 1. The calculating operating point is selected according to the turbine runaway characteristic curve in Figure 2, Q_{11} is 0.9m^3/s, n_{11} is 145r/min (The actual speed of the unit is normal operation speed). Three tube sluice openings shown in figure 3 are selected to study the runaway condition discharge performance, and analyse the discharge capacity and the flow characteristics of draft tube at different tube sluice openings.

![Figure 1: Computational domain of Bulb turbine](image1)

![Figure 2: Turbine runaway characteristic curve](image2)

![Figure 3: Schematic of the tube sluice](image3)

(a) Case 1- fully opening of the tube sluice  (b) Case 2- 2/3 opening of the tube sluice  (c) Case 3- 1/2 opening of the tube sluice

3. Numerical methods and boundary conditions
In this paper, High-quality structured grids for all components of the turbine units are created by using the commercial software ANSYS ICEM-CFD with multi-block templates, and the numerical solution for the computing domain is computed by Fluent. The grids of the whole computational domain and turbine local region are shown in figure 4. The standard k-ε turbulence model is used for the numerical study of the bulb turbine hydraulic characteristics at the stability runaway condition in which the runaway speed is equal with the rated speed.

![Grids of the computational domain](a)

![Grids of turbine local region](b)

**Figure 4** Computational domain and grids

The flow simulation, with the free surface focuses on how to track the free surface. So in this paper, VOF method is used to solve the water-air two-phase flow in bulb turbine with free surface, and the position of the free surface is determined by establishing and solving the transport and diffusion equation of the volume function.

The transport and diffusion equation of the volume function:

\[
\frac{\partial F}{\partial t} + u_i \frac{\partial F}{\partial x_i} = 0
\]

\[F = \frac{\text{Volume of fluid in the element}}{\text{Volume of the element}}\]  

(1)

(2)

When the volume function F is equal to 1, the element is filled with liquid; when the volume function F is equal to 0, there is no liquid in the element; when the value of F is between 0 and 1, the element is half-filled with liquid.

In this study, the initial flow field is shown in figure 5. The red region indicates the initial position of the water, and the blue region indicates the initial position of the air. Boundary conditions are set as follows:

**Inlet of the upstream reservoir**: liquid height and hydrostatic pressure.

**Outlet of downstream reservoir**: liquid height and hydrostatic pressure.

**The top of reservoir**: opening surface (air inlet, the water volume fraction is 0).

**Rotating components**: the runner is rotating component, the rotating speed is given.

**Solid wall**: solid wall with smooth no-slip boundary.

**Medium**: water and air.
4. Result Analysis

Flood discharge and sediment dredging are the main purpose for bulb turbine operating at small opening runaway condition with the same speed as the rated speed. Therefore, this paper focuses on analysing these two performances of the bulb turbine. The table 1 and figure 6 show the turbine energy characteristics and the flow state in the draft tube, respectively.

| Case  | Q (m³/s)   | Turbulent kinetic energy at the outlet of draft tube (J/kg) | energy loss (%) |
|-------|------------|---------------------------------------------------------|-----------------|
|       | (Q)        |                                          | Intake section | Guide vane | Runner | Draft tube |
| Case 1| 179.88     | 3.226                                                   | 0.056          | 3.99       | 32.32  | 63.66     |
| Case 2| 187.39 (1.04Q) | 4.671                                                   | 0.052          | 3.68       | 29.83  | 66.52     |
| Case 3| 190.40 (1.06Q) | 5.099                                                   | 0.050          | 3.57       | 28.86  | 67.57     |

Due to the drop of tube sluice, the flow in draft tube is more disordered, and the head loss increases sharply. The turbulent kinetic energy increases relatively at the outlet of draft tube. So, by changing the tube sluice opening to increase energy loss of the draft tube, the discharge of the turbine will increase. As can be seen from table 1, with respect to the case 1, case 2 and case 3 have discharge pass-through the turbine increased by 4% and 6%, respectively. It is will enable more flood discharge for power station in flood season.

Figure 6 Flow state distribution in the draft tube

Due to the drop of tube sluice, the flow in draft tube is more disordered, and the head loss increases sharply. The turbulent kinetic energy increases relatively at the outlet of draft tube. So, by changing the tube sluice opening to increase energy loss of the draft tube, the discharge of the turbine will increase. As can be seen from table 1, with respect to the case 1, case 2 and case 3 have discharge pass-through the turbine increased by 4% and 6%, respectively. It is will enable more flood discharge for power station in flood season.
Figure 8 Velocity vector distribution in tailrace

Figure 7 and figure 8 are the streamline and the velocity vector distribution in the tailrace of different tube sluice heights, respectively. It can be seen from the figures that dropping the tube sluice leads to larger swirl in the tailrace, and the lower the position of the tube sluice is dropped, the greater the strength of the swirl becomes. Therefore this is an effective way to roll the sediment and to solve the tube siltation problem in flood season.

The sediment characteristics of the river were obtained by conducting a research on the water quality of the power station. The sediment of the station mainly consists of quartz, calcite and clay, and the average density is 2.23 g/cm³. The average sediment concentration passing through the turbine of power station is 35.3 kg/m³, the sediment particle size and gradation of the power station is shown in Table 3. At the operation point studied in this paper, the water depth from the tail-water level to the bottom of draft tube is 25.4 m. According to the movement of the sediment [8], the characteristic speeds of sediment particles with different size are obtained and shown in Figure 9, $V_k$ is starting speed, $V_s$ is winnowing speed, $V_h$ is stopping speed.

| Particle size (mm) | Gradation of the sediment particle size (%) | $d_{50}$(mm) |
|-------------------|--------------------------------------------|-------------|
| < 0.005           | 27                                         | 0.013       |
| < 0.01            | 44                                         |             |
| < 0.025           | 70                                         |             |
| < 0.05            | 90                                         |             |
| < 0.1             | 97                                         |             |
| < 0.25            | 100                                        |             |

In the sediment movement, when the water velocity is greater than the starting speed of sediment, the sediment changes from stationary state to movement state. When the water velocity is greater than the winnowing speed, the sediment leaves the river bed and enters suspending motion. And when the water velocity is less than the stopping speed of the sediment, the sediment changes from movement state to stationary. It can be seen from the characteristic velocity distribution of sediment shown in Figure 11, for the sediment whose particle size is less than 0.04mm, the starting speed is greater than winnowing speed, and when water velocity is greater than the starting speed of sediment, the sediment will be carried with flow and start suspending movement.

Figure 9 Characteristic velocity of the sediment
In order to facilitate the analysis of the flow characteristics in the tailrace, a Cartesian coordinate system is established in the plane of draft tube outlet, as shown in Figure 10. The coordinate origin is located at the central bottom of the draft tube, and the –Z direction is the direction of the river downstream. By analyzing the numerical simulation results, the velocity distribution of the draft tube outlet at different tube sluice are obtained and the comparison of the water velocity against each characteristic velocity of the sediment is conducted. The dredging performance of bulb turbine under the each condition is also revealed by analyzing the movement state of the sediment at the tailrace.

![Figure 10 Geometric schematic](image1)

![Figure 11 Comparison between water velocity and starting speed of sediment at the draft tube outlet](image2)

Under different tube sluice heights, the water velocity at different heights of the draft tube outlet are compared with the starting speed of different sediment particle size as shown in Figure 11(a, b, c, d), respectively. As can be seen from the figures, the velocity distribution at the outlet of the draft tube has the following characteristics: (1) there is no regularity in the velocity distribution. The maximum velocity at the tube outlet is at the bottom, and the drop of the tube sluice can make the velocity distribute more evenly. (2) In case 1, the velocity near the left and right wall is smaller than the starting speed of the sediment whose particle size is less than 0.015mm. This is not conducive to
sediment entrainment. But the case 2 and case 3 could improve this problem. (3) In case 2 and case 3, affected by the tube sluice, the velocity near the top of the outlet is too small to flush the sediment, but the strong vortex behind the tube sluice contributes to the sediment entrainment.

**Figure 12** Comparison of the maximum velocity at the draft tube outlet and winnowing speed of sediment

Based on the above analysis, the maximum velocity at the outlet of the draft tube occurs at the bottom of the tube. Therefore, Figure 12 shows the comparison of the maximum velocity at the outlet of the draft tube against winnowing speed of the sediment. In case 1, except the sediment near the left and right wall of the draft tube whose velocity is smaller than the winnowing speed of the sediment bigger than 0.15mm, the velocity at other position is big enough to drive the sediment to suspending movement. In case 2 and case 3, the water velocity at the outlet of the draft tube is more evenly distributed and greater than the winnowing speed of most of the sediment, so this condition enhances dredging. Figure 13 shows the comparison of water velocity distribution along the channel direction against stopping speed of sediment and demonstrates that the velocity decay rate in the downstream channel reduces slowly in case 2 and case 3. In case 1, when the sediment movement distance is more than 30 meters, the water velocity is less than the stopping speed at various sediment particle sizes, so the sediment changes to stationary state and start accumulating. In case 2 and case 3, the distance that the sediment be pushed forward by the water can reach 51m and 57m, respectively, these values are 1.7 and 1.9 times compared to the distance in case 1. Therefore at the runaway discharge conditions, reducing the tube sluice is a good solution to tailrace siltation problems of the bulb turbine.

After flowing out from the draft tube, the water velocity decreases gradually in the river. The sediment stops and accumulates in the river when the water velocity is smaller than the sediments’ stopping speed. This leads to the raising of river bed and prevents the movement of the upcoming sediment, which in turn causes the sediment to keep accumulating towards the tube sluice. Because of these reasons, this paper suggests to set the sediment self-flushing corridor at the downstream river [9], shown in the Figure 14. The Water flows to the deflector and enters into the corridor, the transverse spiral flow caused by the deflector will agitate and carry the sediment downstream.

**Figure 14** Sediment self-flushing corridor

5. Conclusion
In this paper, with considering the free-surface of the reservoir, the unsteady three-dimensional numerical analysis for bulb turbine at the small opening runaway is conducted to reveal the flow characteristics in the turbine at different tube sluice heights and estimate the sediment flushing capacity of the turbine at such condition. The results indicate that: it is feasible to flood discharge for bulb turbine under runaway condition, and the flow rate pass-through the turbine increases with the decreasing tube sluice height. When reducing the tube sluice height, water swirl formed in the tailrace help to roll up the sediment deposition and discharge to the downstream. The velocity attenuation in the tailrace slows down with the decreasing tube sluice height; therefore, the sediment movement distance driven by the flow is increased significantly. After flowing out from the draft tube, the water velocity decreases gradually, and the sediment will stop when the water velocity is smaller than the sediment stopping speed, which will lead to the sediment accumulation and river bed raising. This paper presents a method that sets the sediment self-flushing corridor at the downstream river to solve the tailrace siltation problems of the bulb turbine. In order to avoid serious cavitation and vibration when the unit is running under this operating condition, the paper suggested that the method described in this paper should be used for a regular and short time sediment flushing method.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (51179152), National Natural Science Foundation of China (51339005), and National Natural Science Foundation of China (51379174).

Nomenclature

- \( Q_{11} \): Unit discharge \([\text{m}^3/\text{s}]\)
- \( Q \): Flow rate \([\text{m}^3/\text{s}]\)
- \( v_s \): Stopping speed \([\text{m/s}]\)
- \( n_{11} \): Unit speed \([\text{r/min}]\)
- \( v_k \): Starting speed \([\text{m/s}]\)
- \( v_h \): Winnowing speed \([\text{m/s}]\)

References

[1] Li Shaoming CF 2012 Design of spillway flushing tunnel for wenjing hydropower station Yellow River 34(9) 111-114
[2] Michell F, Ettema R and Muste M Case study: sediment control at water intake for large thermal-power station on a small river Journal of Hydraulic Engineering 132(5) 440-449.
[3] Bogen J, Bønsnes T E 2001 The impact of a hydroelectric power plant on the sediment transport downstream water bodies The Science of the Total Environment 266(1-3) 273-80
[4] Xilin S, Xinfang C and Zanpei Y 1999 Tubular hydropower station China Water Power Press
[5] Zanpei Y 1992 A study on the utilization of flood discharging characteristics of bulb units Pearl River 10-14
[6] Jian Z 2001 Study on runaway protection and quitting runaway transient process of hydraulic turbine China Agricultural University
[7] Wei H 2011 Test introduce about Feilaixia tubular unit runaway discharge conditions Guangdong Water Resources and Hydropower 69-70
[8] Yuqing S 1967 Sediment kinematics Introduction China Industry Press
[9] Chen C, Wen C, Yi Q 2011 Tong guan elevation reduction by using flushing gallery Hydro-Science and Engineering 4 115-120