

# Numerical prediction of inflow conditions influence on low-head bulb turbines performance

F J Zhao<sup>1</sup>, X J Zhou<sup>2</sup>, B Guo<sup>3</sup>, C J Zeng<sup>3</sup>, S H Ahn<sup>3</sup>, Y X Xiao<sup>3\*</sup> and Z W Wang<sup>3</sup>

<sup>1</sup> High Technology R&D Center of Tianjin, Tianjin 300000, China;

<sup>2</sup> Tianjin tianfa heavy machinery & hydro power equipment manufacture Co., Ltd & Tianjin Key Laboratory of Tianjin tianfa heavy machinery & hydro power equipment manufacture Tianjin 300405, China;

<sup>3</sup> State Key Laboratory of Hydrosience and Engineering & Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

xiaoyex@mail.tsinghua.edu.cn

**Abstract.** The bulb turbine is widely used in low-head hydropower stations. Due to its relatively short inflow channels, the flow patterns inside the turbines are easily affected by the upstream conditions. The oblique inflow may occur when then the overflow gates are closed, and the oblique angle differs with different installation positions for the turbines. In this paper, the effect of oblique inflow conditions on the turbine performances is numerically investigated for the low-head bulb turbine. Firstly, the effect of inflow conditions on the flow patterns inside the turbine was predicted. Secondly, the hydro performances of the turbines under different oblique angles are discussed. Results show that the oblique inflow can sufficiently affect the turbine flows patterns and turbine performances. A positive oblique angle would lead to a lower efficiency for the turbines compared to a negative oblique angle.

## 1. Introduction

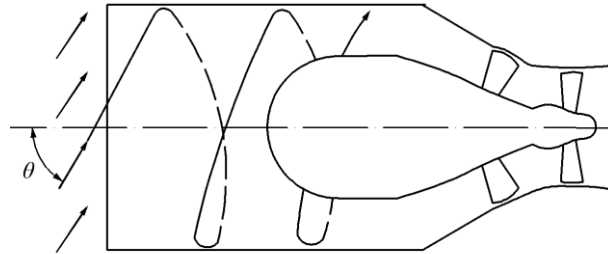
Tidal energy has been considered an alternative way to generate electricity compared to conventional energy sources due to the its potential in reducing the CO<sub>2</sub> emission. The tide is usually generated by the gravitational force caused by the movement of the moon and the sun. Generally, the tidal energy can be utilized through the tidal barrage units or the tidal current units, which can transfer the kinetic and potential energy of seawater to the power-generation equipment. Bulb turbines are widely used in tidal barrage units due to its ability to utilize the low-head water resources[1].

The operating head and flow rate for bulb turbines are usually small. The intake channels of the turbine is also shorter compared with high-head units[2], making it easily to be influenced by the upstream flow. Oblique water inflow often occurs when the overflow gate are closed[3]. The “dead water” concentrating in front of the gates tends to turn directions towards the unit axis, generating the oblique water inflow for the turbines. Circumferential velocity component will exist for the oblique water inflow [4], so the inlet water will flow into the conduit with swirls. The  $\theta$  can be used to define the oblique angle of the inflow water, as shown in Figure 1.

Much attention has been paid to the investigation for bulb turbines design and optimizations[5-7], as well as some characteristics studies[8-10]. CFD has been proven to be a reliable tool to predict the turbine performances[11-15]. The present work aims to numerically predict the effect of the intake



swirls on prototype turbine performances, for the design condition. The effect of inflow conditions under different oblique angles will also be discussed.

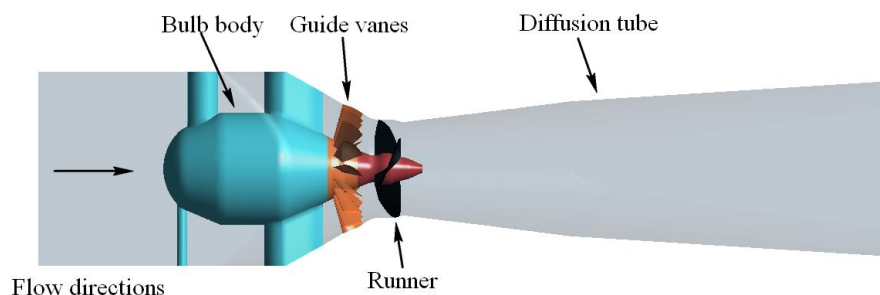


**Figure 1.** Swirl flow in the turbine conduit

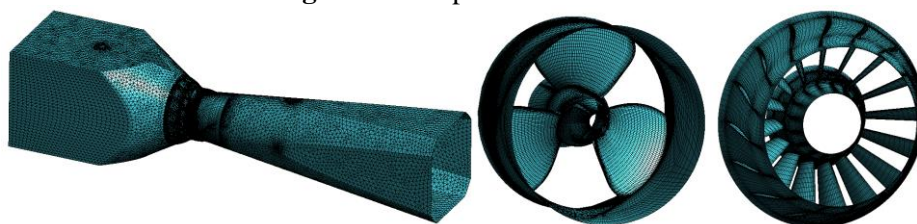
## 2. Prototype bubble turbine and numerical simulation method

### 2.1. Bulb turbine and mesh

The prototype bulb turbine adopted in this paper consists of a bulb body, 16 guide vanes, a runner with 3 blades and a diffusion tube. The diameter of the runner is 2.5m with a design rotational speed of 125r/min. These 5 parts mentioned above are all included in the calculation domains to give a better prediction for the turbines, as shown in Figure 2. Hexahedron mesh was generated for the runner and guide vanes by Turbogrid, while unstructured mesh was used for the rest parts. The mesh for all the domains has about 1470000 elements and 980000 nodes.



**Figure 2.** Computation domains



**Figure 3.** Computation grids for the bulb turbines

### 2.2. Numerical scheme and boundary conditions

ANSYS CFX was adopted to solve the incompressible Navier-Stokes equations. Direct coupling method for pressure and velocity were used to accelerate the convergence process. The convection terms were discretized using high-order resolution method. SST  $k-\omega$  model was adopted to simulate the turbine flows. At the inlet of the model, a velocity inlet was used, where a cylindrical-coordinate system was adopted to define the inlet velocity. The axial velocity was defined as the  $u$ , while the circumferential velocity component is considered to be  $u \cdot \tan\theta$ . The radial velocity component is set as 0. For all the cases with different oblique angle, the  $u$  is assumed to be constant as the comparisons were performed

under the same flow rate. 5 cases were simulated for different oblique angle from  $\theta = -60^\circ \sim 60^\circ (0, \pm 20^\circ, \pm 60^\circ)$ .

### 3. Results and discussions

#### 3.1. Influence on the hydraulic performance of turbines

Figure 4 gives the performance comparisons of the turbines under different oblique angles. In order to effectively compare the oblique inflow conditions with the normal inflow conditions, the head and efficiency are all divided by the values obtained from the normal conditions. This makes the value under normal inflow flow conditions 1, while values for other conditions are lower or higher than 1. It can be seen from Figure 4 the effective head for turbine under oblique inflow conditions, whether for a positive or a negative  $\theta$ , are higher than a normal inflow condition. This may be accounted by the increase of circumferential velocity component. The  $H_\theta/H_0$  for  $\theta = -60^\circ$  is 1.05, 5% higher than that for  $\theta = 0^\circ$ . It can also be found that the positive and negative oblique angles exert differently to the turbine head. With the same oblique angle, the positive one will generate a higher pressure difference between the inlet and outlet.

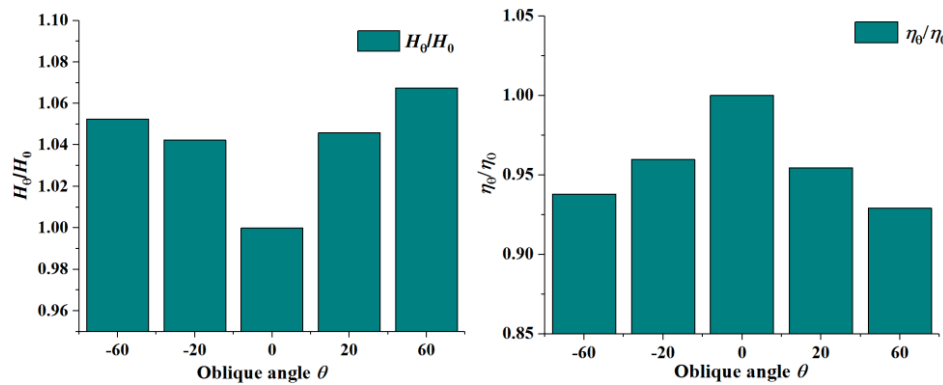


Figure 4. Performance comparisons under different inflow angle

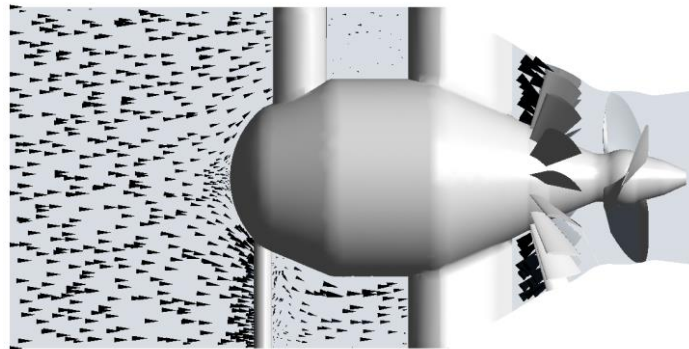


Figure 5. Flow patterns in the bub turbine ( $\theta=0$ )

The efficiency under different  $\theta$  shows a contrary trend compared with the head variation. The normal inflow condition enjoys the highest efficiency, and the efficiency decreases with the increase of  $|\theta|$ . The efficiency with a positive oblique angle will be slightly higher than a negative one. The lowest efficiency occurs when  $\theta = 60^\circ$ , which is nearly 5% lower compared to the normal inflow condition for the relative value.

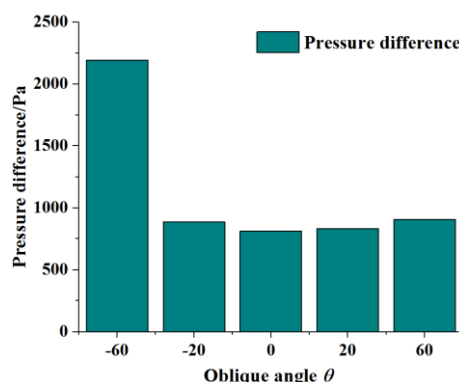
With the same oblique angle, the negative one usually make a more efficient use of the water energy, which can be explained by the flow patterns in the turbine, as shown in Figure 5. The bulb body is designed non-symmetrically from top and down. A larger pillar is put in the upper region of the inlet

conduit, which may lead a more serious blockage for the inlet flow. A positive  $\theta$  will usually lead more water towards the upper region, so a larger pressure loss will occur for a positive oblique angle.

### 3.2. Influence on the flow field in the turbine

After the oblique flow passes through the inflow conduit, the guide vane will begin to get in touch with the incoming flow. As the oblique flow has additional circumferential velocity component, the guide vane inlet will be strongly affected compared to the normal conditions. Therefore, the blade-to-blade plane for the guide vane were extracted, where analysis were conducted for the total pressure distributions and streamline distributions, as shown in Figure 7 and Figure 8.

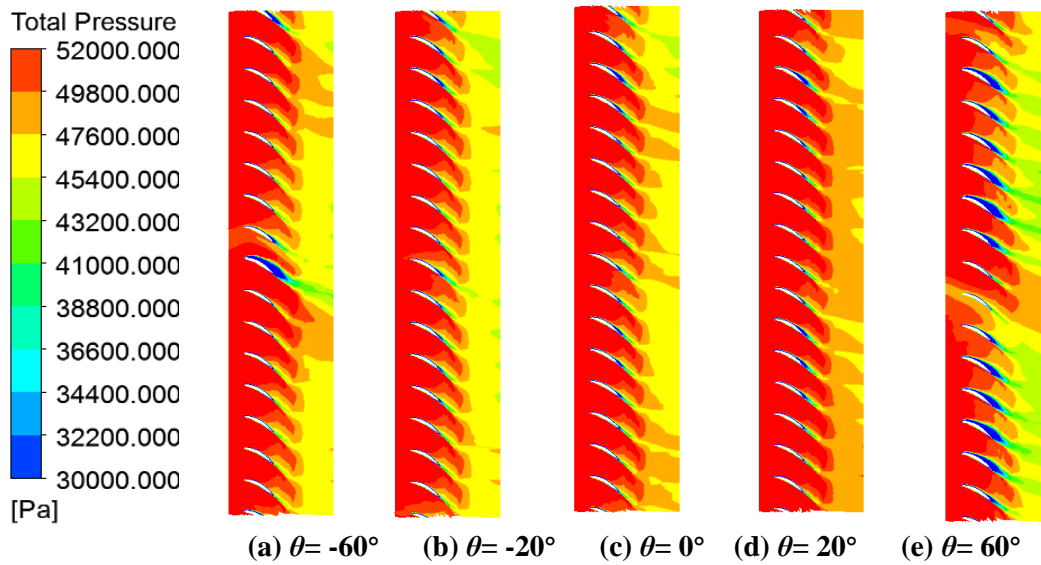
The variation of total pressure through the flow path can be used to reflect the energy loss in the guide vane. The Figure 6 shows the variations of average total pressure between the inlet and outlet of the guide vane. The pressure loss for guide vane under normal inflow condition is 813Pa, the smallest among the five cases, which also corresponds the variation trend for turbine head. As shown in Figure 7, the total pressure decreases along the flow directions, with higher pressure locating near the inlet of the guide vane. Low pressure zones mainly occur at the rear of leading edge on the guide vanes. The increases of  $|\theta|$  helps the development of the low pressure zone, where the smallest low pressure zone is observed for  $\theta = 0^\circ$ .



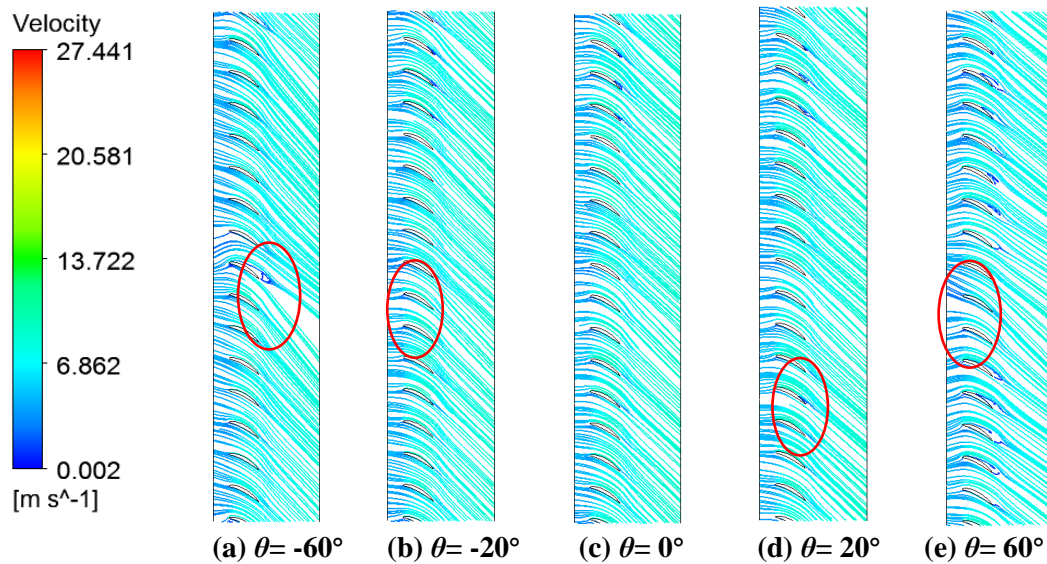
**Figure 6.** Pressure difference between the inlet and outlet for the guide vane

From Figure 8, it can be found that the streamlines in the flow channel of the guide vane are closely affected by the inflow conditions at the guide vane inlet. It can be observed that the inflow angle for the incoming flow obviously varies with  $|\theta|$ . In addition, the streamlines are not uniform around the circumferences under the same  $\theta$ . For most vanes, the streamlines show similar trends. But irregular streamlines would always exist in the middle of the plane as they may be influenced by the bulb body. With the increase of the  $|\theta|$ , streamlines become more disorderly, and flow separations can be clearly observed for  $\theta = -60^\circ$  and  $60^\circ$ . For  $\theta = -60^\circ$ , the flow separations mainly occur near the rear of the guide vane, while separations happen in the front side of the guide vane for  $\theta = 60^\circ$ . For smaller oblique angles ( $\theta = -20^\circ$  and  $20^\circ$ ), the separations can be suppressed and only a few irregular streamlines exist for some areas.

From the analysis above, the flow patterns in the guide vanes are strongly affected by the oblique angle, which suggests that adjustments of the guide vane can be performed to use the water energies more efficiently under oblique inflow conditions.



**Figure 7.** Total pressure distributions for the guide vanes



**Figure 8.** Streamlines on the blade-to-blade plane for guide vanes under different  $\theta$

#### 4. Conclusions

In order to determine the effect of oblique inflow conditions caused by the overflow gate, flow patterns and performance comparisons under different oblique inflow angles were numerically investigated. The results indicate that the oblique inflow can sufficiently influence the turbine performances. A positive oblique inflow angle will lead to a lower efficiency. Flow separations are easily to occur for large oblique angles.

#### Acknowledgements

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## References

- [1] Keck, H. and M. Sick, *Thirty years of numerical flow simulation in hydraulic turbomachines*. Acta Mechanica, 2008. **201**(1-4): p. 211-229.
- [2] Luo, Y.Y., Y.X. Xiao, and Z.W. Wang, *The internal flow pattern analysis of a tidal power turbine operating on bidirectional generation-pumping*. IOP Conference Series: Materials Science and Engineering, 2013. **52**(5): p. 052022.
- [3] Benišek, M., I. Božić, and B. Ignjatović, *The comparative analysis of model and prototype test results of Bulb turbine*. IOP Conference Series: Earth and Environmental Science, 2010. **12**: p. 012091.
- [4] Ahn, S.H., et al., *Numerical analysis of Coriolis effect on low-head hydraulic turbines*. IOP Conference Series: Earth and Environmental Science, 2016. **49**: p. 022012.
- [5] Ferro, L.M.C., L.M.C. Gato, and A.F.O. Falcão, *Design of the rotor blades of a mini hydraulic bulb-turbine*. Renewable Energy, 2011. **36**(9): p. 2395-2403.
- [6] Ferro, L.M.C., L.M.C. Gato, and A.F.O. Falcão, *Design and experimental validation of the inlet guide vane system of a mini hydraulic bulb-turbine*. Renewable Energy, 2010. **35**(9): p. 1920-1928.
- [7] Yang, W., Y. Wu, and S. Liu, *An optimization method on runner blades in bulb turbine based on CFD analysis*. Science China Technological Sciences, 2011. **54**(2): p. 338-344.
- [8] Lemay, S., et al., *Velocity field investigation inside a bulb turbine runner using endoscopic PIV measurements*. Experiments in Fluids, 2015. **56**(6).
- [9] Li, Y., G. Song, and Y. Yan, *Transient hydrodynamic analysis of the transition process of bulb hydraulic turbine*. Advances in Engineering Software, 2015. **90**: p. 152-158.
- [10] Luo, Y., et al., *Numerical prediction of pressure pulsation for a low head bidirectional tidal bulb turbine*. Energy, 2015. **89**: p. 730-738.
- [11] Ahn, S.-H., et al., *Numerical prediction on the effect of free surface vortex on intake flow characteristics for tidal power station*. Renewable Energy, 2017. **101**: p. 617-628.
- [12] Xiao, Y., et al., *Analysis of the internal flow behavior on S-shaped region of a Francis pump turbine on turbine mode*. Engineering Computations, 2016. **33**(2): p. 543-561.
- [13] Xiao, Y., et al., *Prototype and numerical studies of interference characteristics of two ski-jump jets from opening spillway gates*. Engineering Computations, 2015. **32**(2): p. 289-307.
- [14] Xiaoran Zhao, Z.W., Yexiang Xiao, Yongyao Luo, Lei Cao, *Unsteady Flow and Pressure Pulsation Characteristics Analysis of Rotating Stall in Centrifugal Pumps under Off Design Conditions*. International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, 2016.
- [15] Yexiang, X., et al., *Numerical analysis of the effect of misaligned guide vanes on improving S-shaped characteristics for a pump-turbine*. Journal of Fluids Engineering, 2017.