The prediction of the hydrodynamic performance of tidal current turbines

B Y Xiao¹, L J Zhou¹, Y X Xiao² and Z W Wang²

¹ College of Water Resources and Civil Engineering, China Agricultural University, Beijing, 100083, China
² Department of Thermal Engineering, Tsinghua University, Beijing, 100084, China

E-mail: zlj09@263.net

Abstract. Nowadays tidal current energy is considered to be one of the most promising alternative green energy resources and tidal current turbines are used for power generation. Prediction of the open water performance around tidal turbines is important for the reason that it can give some advice on installation and array of tidal current turbines. This paper presents numerical computations of tidal current turbines by using a numerical model which is constructed to simulate an isolated turbine. This paper aims at studying the installation of marine current turbine of which the hydro-environmental impacts influence by means of numerical simulation. Such impacts include free-stream velocity magnitude, seabed and inflow direction of velocity. The results of the open water performance prediction show that the power output and efficiency of marine current turbine varies from different marine environments. The velocity distribution should be clearly and the suitable unit installation depth and direction be clearly chosen, which can ensure the most effective strategy for energy capture before installing the marine current turbine. The findings of this paper are expected to be beneficial in developing tidal current turbines and array in the future.

1. Introduction
Energy is the basis of human survival in the 21st century. The energy shortage, as a key factor, has become a restriction for sustainable economic development. Over-exploitation of traditional energy sources and conflicts caused by the uneven distribution of energy has become increasingly noteworthy, rely only on fossil energy sources cannot meet the needs for human and productive requirements. Therefore, to ensure the sustainable economic development, the society energy structure must change by developing new alternative energy sources to replace fossil fuels. Otherwise, large amount of CO₂ and other greenhouse gases emitting from the use of fossil fuels will cause global warming. From the climatic point of view, human beings must find and develop new alternative clean energy, and energy conservation technique to achieve sustainable development.

The tidal current energy is the most commonly used energy caused by tidal [1]. It’s often distributed in the near shore shallow, strait, mouth of gulf, waterways and other territorial waters between the islands which of great velocity. Development tidal current energy has the following salient features: 1. Tidal current energy development sites are mostly located in the centre of the shore, between the islands of the watercourse or bay mouth [2]. The tidal current energy has strong regularity and predictability, so the tidal current energy can also be forecasted. 2. The density of seawater is about 800 times more than air. The tidal current energy is caused by the lunar gravity more regularity than
the wind caused by uneven solar radiation [3]. 3. When the free-stream velocity magnitude is greater than the turbine starting velocity, the tidal current energy technically can achieve development. According to China’s national conditions, in general, a flow rate of 1.5 m/s can be carried out. Turbines installed will decrease the cross-sectional area, the general development depth of sea water cannot be less than 15 m [4]. 4. Velocity along the depth direction is logarithmically distributed and the velocity reaches the maximum at sea surface. The inflow direction of velocity can also be predicted by a certain means [3].

In this paper, based on the characteristics of the marine current turbine, we focus on the analysis of the effect of vertical distribution and the inflow direction for flow velocity to turbine hydraulic performance. And some advices are given on choosing suitable unit installation depth and direction to ensure the most effective strategy for energy capture before install the marine current turbine.

2. Numerical model and boundary conditions
To estimate the influence of the environment of the tidal turbine, a 3D CFD model has been built. The numerical model is constructed to simulate an isolated turbine. The diameter of the turbine is 15 m hub diameter is 7.5 m. The global domain size is 90×184 m, the vertical height $h$ of the domain varies with the sea surface; on figure $h$=60 m. The rotor whose centre is located at $x$=$y$=$z$=0 m and runner centre submerged depth is 35 m. An unstructured tetrahedral mesh technique enables to model this geometry. The whole mesh contains about 1.4M nodes [5]. The boundary conditions are defined as inflow velocity at inlet, static pressure of 0 Pa at outlet, symmetry wall at sides and top surface is ignored, no slip walls at the other boundaries. Mesh sensitivity is guaranteed by comparison with the variation of meshes.

![Figure 1. CFD Calculation domain and boundary conditions.](image-url)

This 3D model is used to analyze different influences:
- Influence of the free-stream velocity magnitude (see fig. 1).
- Influence of the upstream velocity direction (see fig. 1).
- Influence of the sea bed by introducing a boundary layer profile at upstream inlet of the domain (see fig. 1).

3. Influence of the environment of the tidal turbine
According to the simulation in ANSYS-CFX, the power coefficient is defined as
\[ \eta = \frac{2T}{\rho \omega U_3 S} \]
where \( T \) is the torque generated by the rotor, \( \omega \) is the rotational speed of rotor, \( \rho \) is the water density and \( S \) is the cross sectional area of rotating rotor, \( U \) is the velocity at the runner centre.

3.1. Turbine operating characteristics under ideal conditions
Figure 2, 3 demonstrates different inflow velocity across a tidal current turbine, based on a turbine in 25 m depth. For each upstream velocity the rotation speed corresponds to the velocity speed obtained by the numerical simulation (see fig. 2, 3). The rotation speed corresponding to the maximal power output is shown on the figure below (see fig. 2). For other upstream velocities the rotation speed corresponding to the maximal efficiency is shown on the figure below (see fig. 3).

![Figure 2. Evolution of tidal turbine power output versus rotation speed and upstream velocity.](image1)

![Figure 3. Evolution of tidal turbine efficiency versus rotation speed and upstream velocity.](image2)

3.2. Effect of the upstream velocity direction
Upstream velocity is non-symmetrical about the runner centre in the horizontal plane. Inflow direction should be taken into consideration when choosing the location or mounting current turbines. To estimate the influence of the inflow direction of the tidal turbine preliminary study focuses on the tidal turbine efficiency, power output and axial thrust on runner affected by different inflow direction of upstream velocity through numerical simulation.

![Figure 4. Evolution of tidal turbine efficiency and flow rate versus upstream incidence.](image3)

The result shows that the upstream inflow direction has a great influence on hydraulic performance of tidal turbine (see fig. 4, 5). The axial thrust on the runner has also been evaluated in order to estimate the friction and the thrust applied on turbine bearing bearings (see fig. 6). The tidal axial thrust \( (F_{Dz}) \) almost unchanged, the force perpendicular to the axis \( (F_{Dx}, F_{Dy}) \) is larger than before.
The upstream inflow direction should be kept in 10° so as to ensure the most effective strategy for energy capture and satisfy on turbine bearing.

3.3. Effect of tidal velocity profile

Upstream velocity distribution is affected not only by the form of the terrain on the sea, but also by the seabed. For coastal waters, the velocity is non-symmetrical about the runner centre in the vertical plane. The tidal boundary layer is generally assumed to extend to the full tidal depth, H. An approximate tidal velocity profile can be estimated assuming a power law of the form:

\[ U(z) = U_0 \left( \frac{Z}{0.32H} \right)^{0.7} \]  

Where \( U_0 \) is the maximum velocity, \( Z \) is the vertical position (See figure 7).

Preliminary measurements of tidal velocities over the Arklow Bank suggest that Eq. (1) is suitable for these initial calculations [6]. For detailed design of a farm of current turbines, measurements would need to be taken for a particular site over a period of a month in order to derive accurate velocity profile data. For these preliminary studies, Eq. (1) has been used to demonstrate the scale of the possible dynamic
forces. Figure 7 demonstrates a typical velocity profile across a marine current turbine, based on a 15 m radius turbine in 60 m deep sea and different tidal speed.

Based on the power law and this design, the powers and oscillations in forces on current turbines will be changed. The predicted efficiency at different velocity magnitude shows in Fig. 4. There will be a 5% efficiency decrease at most rotation speed (see fig. 8). The axial thrust on the runner has also been evaluated in order to estimate the friction and the thrust applied on turbine bearings (see fig. 9). In addition to considering the impact of sea vessels, the tidal current energy moves in sine wave cycle [7]. Therefore, turbine installation is not infinitely close to the sea surface. This clearly indicates that to ensure the most effective strategy for energy capture we should choose the suitable installation depth where the velocity magnitude is almost the same.

![Figure 8. Evolution of tidal turbine efficiency versus rotation speed and upstream velocity.](image1)

![Figure 9. Evolution of tidal axial thrust on runner versus rotation speed.](image2)

3.4. Effect of tidal velocity profile and upstream velocity direction
Figure 10, 11 demonstrates a typical velocity profile and different inflow directions across a marine current turbine, based on a turbine in 25 m depth and a maximum tidal speed of 2 m/s. Based on the characteristics of the velocity distribution, the results shows the efficiency is decreased compared to the ideal conditions (see fig. 10). The tidal axial thrust (Fz) almost unchanged, the force perpendicular to the axis (Fx, Fy) is larger than before (see fig. 11).

![Figure 10. Evolution of tidal turbine efficiency versus rotation speed and inflow direction.](image3)

![Figure 11. Evolution of tidal axial thrust on runner versus inflow direction.](image4)

4. Results
The results with the maximum power output corresponding to the maximal tidal current velocity in the optimal inflow conditions. Otherwise, the axial thrust on the runner has also been evaluated in order to
estimate the friction and the thrust applied on turbine bearings. The results show that the force perpendicular to the axis is good for turbine bearings.

For coastal waters, the velocity is non-symmetrical about the runner centre in the vertical and horizontal plane. The speed is almost unchanged at a certain depth and the power output is of no difference with optimal inflow conditions. On the other hand, the inflow direction causes the decrease of power output and efficiency. While in the actual marine environment it’s difficult to ensure the inflow direction perpendicular to the runner. In order to ensure the most effective strategy for energy capture and satisfy on turbine bearings we have to ensure the inflow direction perpendicular to the runner or inflow deflection changes should be controlled within 10 degrees. In addition, the force perpendicular to the axis is larger than the optimal inflow conditions, and the thrust should be taken into consideration to estimate the friction and turbine bearings.

5. Conclusions
The present study deals with hydraulic performance of current turbine affected by velocity distribution. For coastal waters, the velocity is non-symmetrical about the runner centre in the vertical and horizontal plane. Thanks to a 3D CFD model, several environment effects (upstream magnitude, seabed, upstream inflow direction) have been quantified. The results show that the velocity distribution has a great influence on power output, efficiency and axial thrust on runner.

After having obtained the environment influence on the turbine has been studied. Therefore, we should conduct comprehensive assessments of the local tidal current resources on tidal current turbine site selection. Main assessment of the tidal current resources include the magnitude of the velocity, the depth of sea area and the inflow direction of velocity, so that we can choose the suitable unit installation depth and direction, ensure the most effective strategy for energy capture before installing the marine current turbine.

Acknowledgments
The authors thank the National Natural Science Foundation of China (No. 51279205), and National High Technology Research and Development Program of China (863 Program No. 2009AA05Z424 and 2009AA05Z425) for supporting present work.

Reference
[1] Yao Q G, Liu Y L, Li L and Tang Z B 2011 Journal of Changchun Institute of Technology(Natural Science Edition) 02 60-64
[2] Yang L L 2012 Ocean University of China
[3] Batten W M J, Bahaj A S, Molland A F and Chaplin J R 2008 The prediction of the hydrodynamic performance of marine current turbines Renew. Energy 33(5) 1085-96
[4] Lv X and Guo P F 2011 Transaction of Oceanology and Limnology, 01 26-30
[5] Kueny J L, Lalande T, Herou J J and Term L 2012 Optimal design of a tidal turbine Proc. of 26th IAHR Symp. on Hydraulic Machinery and Systems(Beijing, China, 19-23-August 2012 )
[6] Myers L E, Bahaj A S, Rawlinson-Smith R I, Thomson M 2008 27th International Conference on Offshore Mechanics and Arctic Engineering (Estoril, Portugal,15-20 June 2008 )
[7] Rippeth T P, Williams E, Simpson J H 2002 Journal of Physical Oceanography, 32 1242-51