Blade design and performance analysis on the horizontal axis tidal current turbine for low water level channel

C C Chen, Y D Choi and H Y Yoon
Graduate School, Mokpo National University, Mokpo, 534-729, Korea
E-mail: chen_chch@qq.com

Abstract. Most tidal current turbine design are focused on middle and large scale for deep sea, less attention was paid in low water level channel, such as the region around the islands, coastal seas and rivers. This study aims to develop a horizontal axis tidal current turbine rotor blade which is applicable to low water level island region in southwest of Korea. The blade design is made by using BEMT(blade element momentum theory). The section airfoil profile of NACA63-415 is used, which shows good performance of lift coefficient and drag coefficient. Power coefficient, pressure and velocity distributions are investigated according to TSR by CFD analysis.

1. Introduction
There are a myriad of islands in the southwest coast of Korea. Although the population of the islands falls annually, the power consumption in the region annually increases due to the growth of the convenient facilities.

Under the economic growth circumstances, small islands that face difficulties in connecting to electric power network, and seek to expend their independent diesel power plants, so more power generations are required [1].

Less tidal current turbine system is applied to the southwest coast of Korea island region, as the sea area near the islands are shallow, the middle or large scale tidal can not be set up. But the shallow sea area is rich in current tidal energy and produces reliable, predictable and continuous energy source throughout the year.

Tidal current turbine is designed as a high efficiency machine that extracts energy from moving water. The higher density of water relative to air (water is about 800 times the density of air) means that a single generator can provide significant power at low tidal flow velocities compared with similar wind turbine. The blade is the key component that extracts energy from tidal and primarily dictates the performance, loads and dynamics of the whole turbine system. Therefore, an efficient blade design is critical to the success of the system.

Research for this kind of power production is necessary for the people in this area, and to attract more attention for remote area energy development.

2. Tidal Current resource review in Korea
An overview of the average energy density around Korea, the energy areas can be categorized into five groups: high energy areas with $> 10 \text{MWh} \cdot \text{m}^{-2}$; moderately high energy areas with $5$ to $10 \text{MWh} \cdot \text{m}^{-2}$; intermediate energy areas with $3$ to $5 \text{MWh} \cdot \text{m}^{-2}$ and $2$ to $3 \text{MWh} \cdot \text{m}^{-2}$; and low energy areas with $< 2 \text{MWh} \cdot \text{m}^{-2}$, as shown in Figure 1. These results reveal that environments exhibiting
very high annual tidal current energy densities are likely to be relatively around Korea. Figures 3 shows the greatest concentration of high-energy density sites was found off the coast of south and west of Korea: including the highest energy density in Uldolmok Strait; 9MWh · m⁻² in the Geocha Waterway; and 6.9 MWh · m⁻² in the Jaingjuk Waterway. Figure 1 also shows that the high annual average energy densities are mainly found in waterways characterized by narrow widths, since this landform leads to strong, rectilinear tidal current flows [2].

In this paper we consider a 100 kW turbine deployment in the Uldolmok Strait between Jindo and Haeman.

Figure 2 presents the channel landform condition clearly. The channel is an excellent likeness to a pipe, no sharply extruding ledge on the channel bed, and the smooth bed focus on the range of depth 15m - 30m. It’s an ideal setting location of tidal current turbine [3].

Due to the narrow widths, strong tidal current is produced in the strait: the maximum current speeds > 3.5 m·s⁻¹ and no significant neap reduction, as shown in Figure 3. The stronger observed currents result from the highly dominant nature narrow landform. When examining the magnitude and variability of tidal current speeds and water level variation range, Uldolmok strait appears to be one of the most suitable sites for tidal current turbine.

3. Blade Hydrodynamic Design

3.1. Aerodynamic Characteristics Analysis of Airfoil

NACA63-415 is one of NACA series which widely known for its good aerodynamic characteristic. Also, NACA63 series airfoil delay stall and are less sensitive to leading edge roughness than the most other series airfoil [5]. Figure 4 shows the $C_l$ and $C_l/C_d$ of NACA63-415 airfoil at $Re = 2 \times 10^6$. The aerodynamic characteristics data of airfoil were calculated by the open 2D software Xfoil. The range of $C_l$ is from 0.083 to 13.120 with the angle changed from -3 to 15. The attack of airfoil distributes along the blade is focus on 0 to 10, and the value of $C_l/C_d$ is focuses on 70 to 100.

| Table1. Parameters of Blade design |
|------------------------------------|
| **Design parameter** | **Values** |
| $P_{\text{rated}}$: Rated power | 100 kW |
| $C_p$: Estimated power | 0.46 |
3.2. Blade Design
The turbine rotor is determined with a 3-piece blade and a 0.15D hub. For a 3-piece blade, the start flow velocity is low compared to a 2-piece blade and ranges from favourable to complex due to the lower effect of the wake [6].

Blade element-moment theory (BEMT) is used for the blade design, which is based on a combination of momentum theory and blade element theory. The chord length and twist angle in Figure 5 are used to define the blade shape. In the main part of blade, NACA63-415 was used as the section. In the root part, a suitable size ellipse was used as the section.

4. Performance Analysis Method
4.1. Analysis Pre-process
One blade and one third of the fluid is analysed in this study, as shown in Figure 6. To predict the torque, pressure and velocity streamline occurring on the blade surface, the O-grid is used for the blade surface mesh. The total number of hexahedral grids is about 6.5 million, and the $y^+$ on the blade surface is below 10. For a turbulence model, $\kappa-\omega$ SST model is used, which has been well known to estimate both separation and vortex occurring on the wall of a complicated blade shape.
5. Results and Discussion

5.1. Power Coefficient

The performance curve in Figure 7 shows the power coefficient as variation as the tip speed ratio, based on the torque value of CFD analysis. The curve shows a close $C_p$ of 0.459, 0.467 and 0.449 at TSR 6, 7 and 8, respectively.

In the forepart of curve, the smaller value of TSR means larger inflow velocity acting on the rotor blade. While the attack angle increasing into the stall angle range, the aerodynamic characteristic such as $C_l/C_d$ decrease obviously. As reflected from the curve, $C_p$ have a sharply decrease at TSR from the 5 to 3.

5.2. Pressure and Streamline Distribution on the Blade Surface

Figure 8 shows the positive and negative pressure distribution on the pressure and suction sides of the blade. At a lower TSR, the fluid on the blade leading edge is rapid flowing, which produces high pressure at the tip area, and the maximum pressure area decreases with the increasing TSR. The negative pressure occurs and enlarges at the tip, causes the power coefficient decrease at high TSR. For the suction side of blade, the negative pressure and area reduce with the increasing TSR.
Figure 8. Pressure on the blade surface.

Figure 9 shows the streamline distribute on the blade surface. The radial flow which is secondary flow extends from the hub to the tip. The stronger radial flow occurs in lower TSR. And the radial flow streamline become closer to the root in higher TSR. The radial flow appearance makes the flow on the blade surface irregular, it gives noticeably effect to the aerodynamic characteristic, decreases the output power and power coefficient.

Figure 9. Streamline on the blade surface.

5.3. Comparison Analysis of Blade Tip Chord Change

Two types of blade tip are commonly used in current wind turbine and tidal current turbine blade design, linearity and modifiability as Model A and Model B are shown in Figure 10.
The contrastive analysis is proceeded in the condition of TSR=6. The result indicates that a higher $C_P$ appears in Model A, and the maximum pressure increases from $6.3 \times 10^4 \text{ Pa}$ to $7 \times 10^4 \text{ Pa}$. It shows almost similar area of high pressure area and lower pressure area distribution on the blade surface.

![Pressure distribution on Model A and Model B.](image)

**Figure 10.** Pressure distribution on Model A and Model B.

The reducing of chord length in the blade tip leads to a decrease in power coefficient, which is carried out by the aerodynamic characteristic analysis result. However, the advantage of the modification reduces the material cost, that’s means an improvement in weight and reduction in manufacturing cost, especially in manufacturing large size blade.

6. Conclusions

In this paper, we consider a 100kW blade for low water channel. The study is processed in 2 steps: tidal current energy review in southwest of Korea and hydrodynamic design.

1. The tidal current recourse review indicates that large energy is contained in the low water level area, which close to the coast. The Uldolmok Strait is a representative and suitable location for tidal current turbine, because of high power density $10^{-25} \text{ W/m}^3$ and stability flow $> 2 \text{ m/s}$ throughout the year.

2. The using of Blade Element Momentum Theory (BEMT), Finite element Analysis (FEA) and Computational Fluid Dynamics (CFD) design and analysis the blade performance. Comparing with wind turbine blade design, the density of water is 800 times that of air and the small range of inflow velocity require a comprehensive consideration in tidal current blade design. The design shows a wide range of high efficiency of 0.459, 0.467 and 0.449 at TSR 6, 7 and 8, respectively, and the maximum $C_P = 0.467$ at TSR=7.

3. The radial flow appearance makes the flow on the blade surface irregular, it gives noticeably effect to the aerodynamic characteristic, decreasing the output power and power coefficient.

4. The influence of blade tip chord length is analyzed, the reduction of chord length in the blade tip leads to a decrease in power coefficient.

7. References

[1] Lee J Y, Choi N J, Lee J W, Yoon H Y and Choi Y D  2011 Shape Design and CFD Analysis on a 1 KW-class Horizontal Axial Wind Turbine for Hybrid Power Generation System *The 11th*
Asian Int. Conf. on Fluid Machinery and the 3rd Fluid Power Technology Exhibition (Chennai, India, 21-23 November 2011) pp1-8

[2] Byun D S, Hart D E and Jeong W J 2013 Energies 6(2) 566-78
[3] Esteban M. and Leary D 2012 Applied Energy 90(1) 128-36
[4] LEE K S 2009 Tidal and Tidal Current Power Study in Korea The East Asian Seas Congress 2009 (Manila, Philippines, 23-27 November 2009)
[5] Bir G S, Lawson M J, and Li Y 2011 Structural design of a horizontal-axis tidal current turbine composite blade The ASME 30th International Conference on Ocean, Offshore, and Arctic Engineering (Rotterdam, the Netherlands, 19-24 June 2011) pp 195-206
[6] Joa C H, Yin J Y, Lee K H and Pho Y H 2011 Renewable Energy 42 1-9
[7] Batten W M J, Bahaj A S, Molland A F and Chaplin J R 2006 Renewable Energy 31 249-56
[8] Batten W M J, Bahaj A S, Molland A F and Chaplin J R 2006 Ocean Energy 34 1013-20
[9] Ahmed M R 2012 International Journal of Energy Research 36 829-44
[10] Burton T, Sharpe D, Jenkins D and Bossanyi E 2001 Wind Energy Handbook (New York John Wiley & Sons, Ltd) pp 41-65.
[11] ANSYS Inc., 2010, “ANSYS CFX Documentation” Ver. 12, http://www.ansys.com