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A Study on Diffuser Augmentation of a Tidal Turbine

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ABSTRACT

As tidal energy is progressively earning attention worldwide, there is a lot of existing research about the tidal current potency and the tidal turbine design. Especially on turbine design, existing studies deduced that a diffuser augmentation is a superior choice to increase the turbine performance. However, the research in finding the best diffuser angle whose efficiency is maximum, yet minim cavity risk is still limited. Therefore, this study proposes an innovative, optimized design method on diffuser augmentation of a tidal turbine by comparing four diffuser angles in three inflow velocity circumstances. In particular, three airfoil blades design with a rotor diameter of 0.3 m was developed. The combination of computational fluid dynamic and multi-objective optimization using a general algorithm coupled with the artificial neural network was applied by considering the turbine's power coefficient and cavitation inception as a trade-off objective. The numerical results display that the different inflow velocity affects the turbine performance insignificantly. The optimization analysis and comparison among four diffuser angles in three variations of inflow velocity show that the tidal turbine's optimal design with diffuser augmentation could be applied to all tidal current speed.

1. Introduction

Tidal energy is a potential resource to realize the Sustainable Development Goal (SDG) 7 about affordable and clean energy. Since the tidal current is stable and predictable, numerous studies about tidal energy have been published, including the tidal current potency and the tidal turbine design. Previous studies found that a diffuser augmentation is a superior choice to increase turbine performance. Diffuser augmentation causes an increase in the available pressure drop over the turbine by restoring some of the velocity head downstream as the pressure head [1]. Sun and Kyozuka [2] stated that the shrouded turbine achieved 2.5 times the maximum power coefficient than the bare turbine. Gaden and Bibeau [3] declared that a bare turbine's output power could be advanced 1.3 times by employing diffusers on a water turbine. However, the study in finding the best diffuser angle whose efficiency is maximum yet minim cavity risk is still limited. Besides, most existing research represent the performance of diffuser augmentation of a tidal turbine in one tidal current speed circumstance. Therefore, this study proposes four diffuser angle designs of horizontal axis tidal

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turbine at three variations of inflow velocity based on variations in Indonesian tidal currents. It also shows the impact of inlet velocity on the power coefficient and cavitation inception on each diffuser angle design. The optimal design in each inlet velocity is also discussed.

2. Numerical Method

This work adopted the turbine design of previous work by shrouded horizontal axis tidal turbine by Sun and Kyozuka [2], Nagataki *et al.,* [4], and Kyozuka *et al.,* [5]. Yet, for the modelling, the steady state and the k-ε model were applied, which refers to control equations by Zhang *et al.,* [6] and Huang *et al.,* [7]. Zhang *et al.,* [6] have proven that this CFD model was in agreement with an experiment conducted by Bahaj *et al.,* [8] and Batten *et al.,* [9]. The CFD model is based on Reynolds Averaged Navier-Stokes (RANS) to the computational method for analysing the turbine system in detail. Compared to other turbulence models, the k-ε model is widely used for turbulence model in order to effectively save much time and cost yet quite accurate. It resolves the turbulent effect on mean flow at the sub-grid scale.

2.1 Model Specifications and Parameters

1/2 scale geometry model has three blades based on NACA 4616 airfoil with a turbine diameter of 0.3 m. Figure 1 shows the turbine design in 2D and 3D model. This work considered four diffuser angles ranged from 10° to 36°, as in Table 1. The visualization of how these angles were designed could be seen in Figure 2. By controlling the water flow passively and analysing the flow field occurred surroundings the turbine, the diffuser shape leads to increase the turbine performance.

Table 1
Diffuser angles

θ_1	θ_2	θ_3	θ_4
10.43°	20.04°	28.6°	35.97°

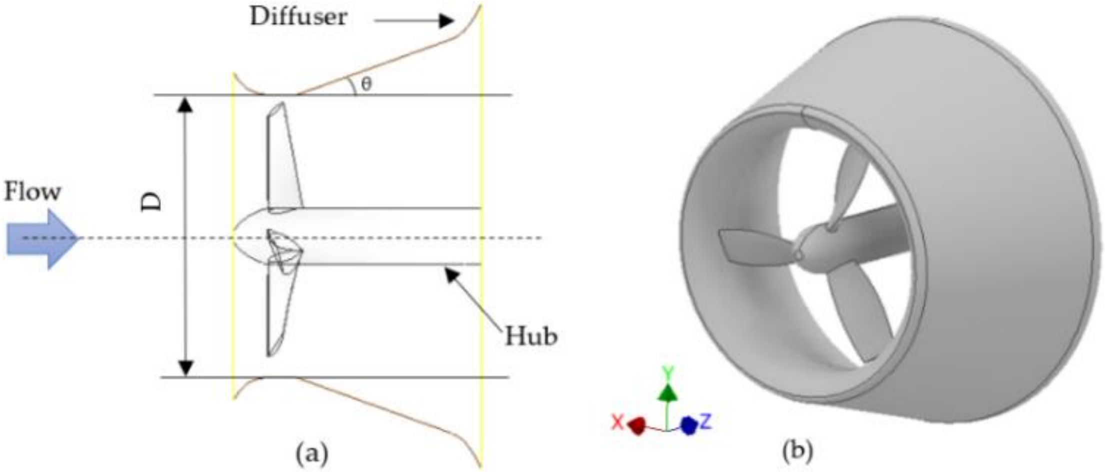


Fig. 1. The tidal turbine design in (a) 2D and (b) 3D models with diffuser augmentation

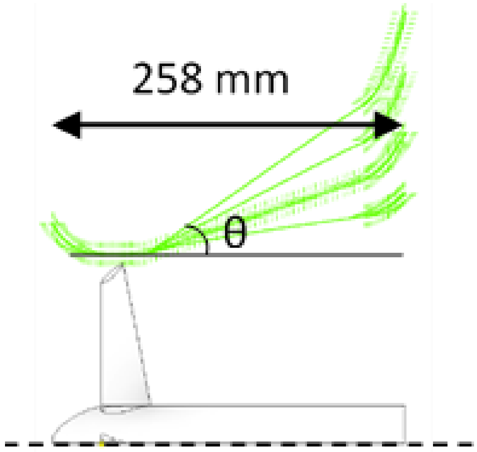


Fig. 2. The visualization of four diffuser angles (θ)

The analysis parameters of the computational method to all cases in three variations of inflow velocity are listed in Table 2. It can be seen in Figure 3 the domain and boundary condition. The mesh size was set fine default whose minimal size is 0.0025 of the turbine diameter as shown in Figure 4.

Table 2
Analysis parameter

Parameter	Values
Inlet velocity (*V*)	1 m/s, 1.25 m/s, 1.5 m/s
Inlet turbulence intensity	5%
Pressure outlet	0 Pa
Convergence absolute	1.00E-05
The density of fluid (ρ)	998.2 kg/m^3
Viscosity	0.001003 kg/m.s

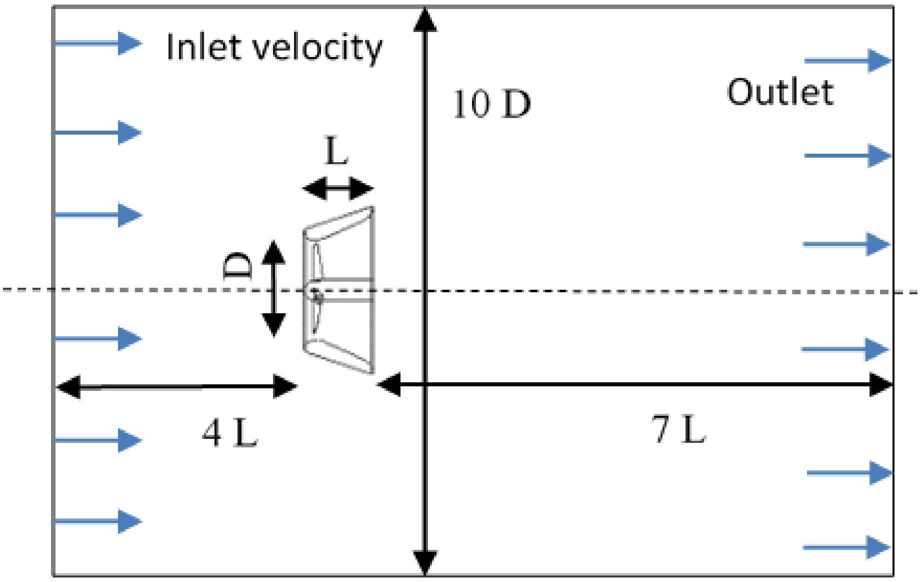


Fig. 3. The boundary and domain condition

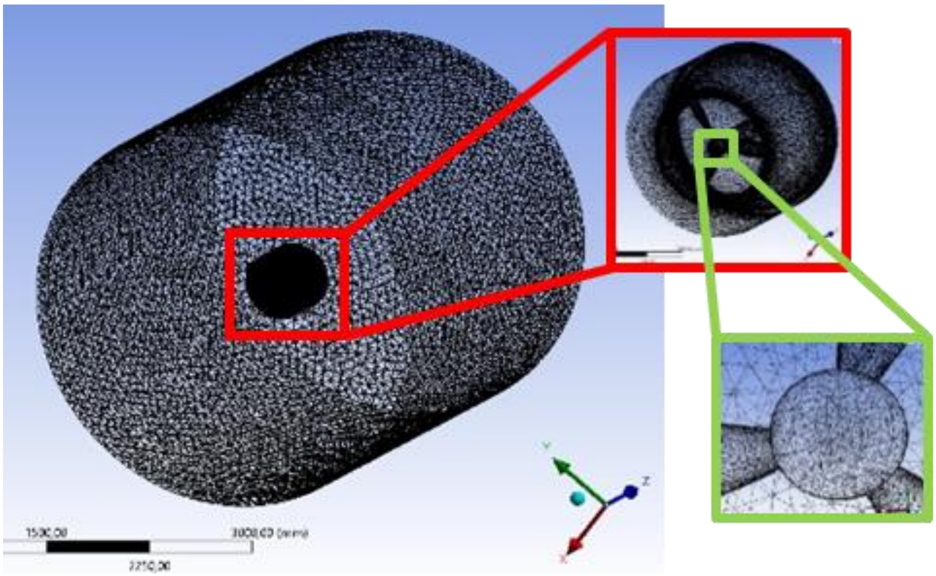


Fig. 4. Number of grids set fine default

2.2 Multi-objective Optimization

An optimization system applied in the current study is multi-objective optimization using General Algorithm (GA) merged with Artificial Neural Networks (ANN). The ANN algorithm is a mathematical algorithm model for the processing of distributed parallel information, which imitates the behavior of animal neural networks. In the optimization system, the performance parameters of the temporary turbine are measured by ANN [10]. GA is a method to resolve optimization problems inspired by the natural selection process and to produce potential solutions from all possible solutions. ANN is adjusted in this study and combined with GA to resolve numerically. The objectives for the optimization system in this study are to maximize the power coefficient and to minimize the cavitation inception of diffuser angle design at each inlet velocity.

3. Results and Discussion

3.1 Turbine Efficiency

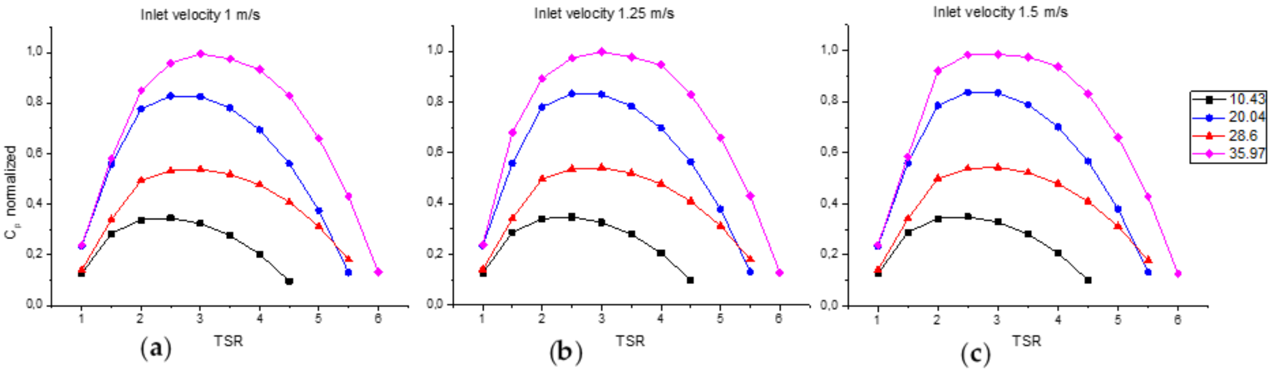
The main aim of this study is to explore the performance characteristic of the diffuser angle to advance the efficiency of a tidal turbine which applied in three variations of inflow velocity. The output power is normalized as a power coefficient (C_P) by using the swept area (A) at blade inlet, as in

$$C_P = \frac{\tau\, \omega}{0.5 \rho A V^3} \tag{1}$$

where τ represents torque, and ω is blade angular speed changed by varying the tip speed ratio (TSR) at blade radius constant, as in

$$\mathrm{TSR} = \frac{\omega R}{V} \tag{2}$$

Figure 5 shows the turbine performance of each diffuser angle at three variations of inflow velocity. The power data was normalized to the free stream power for determining the power coefficient graphically. It can be said that the tidal current speed affects the turbine's power coefficient insignificantly.



(a) (b) (c)

Fig. 5. Normalized C_P vs TSR on varying diffuser angles at inlet velocity (a) 1 m/s; (b) 1.25 m/s; (c) 1.5 m/s

All graphs represent a similar phenomenon in which maximum C_P is owned by the largest angle of 35.97° reaching up to 98%. The worst performance is denoted on the smallest angle of 10.43° offering at best C_P of 35%. The maximum C_P is achieved at TSR of about 2.5 and 3 on all cases. It can be said that the different diffuser angle significantly affects the turbine performance by up to 50%. The larger space affects the rotor rotation and the water movement around the device resulting in a higher pressure drop, which impresses the current velocity change. The current velocity increases as entering the interior diffuser so rotating the rotor blade. The higher the pressure drop, the greater the velocity difference in the device. Since the velocity change increases so does the extracted kinetic energy, which produces in bigger momentum appended to the rotor torque [11].

3.2 Cavitation

Unlike the wind turbines, the consideration of the cavity effect is a must to the water turbine application. Cavitation happens when the absolute pressure of the fluid passing through the blade surface drops below the vapor pressure, then the fluid starts evaporating, and bubbles are established [12]. The damage caused by cavitation on the blade surface affects the turbine dynamic characteristic, thereby decreasing the turbine performance.

This study only considers the pressure variable to evaluate the cavitation inception of the tidal turbine. Pressure coefficient is a significant parameter to represent the relative pressure throughout the entire flow field and to analyse incompressible flow. The fundamental of cavitation inception creation can be expressed based on the cavitation number (σ) and pressure coefficient (C_{press}) as in Eq. (3)-(5) [13].

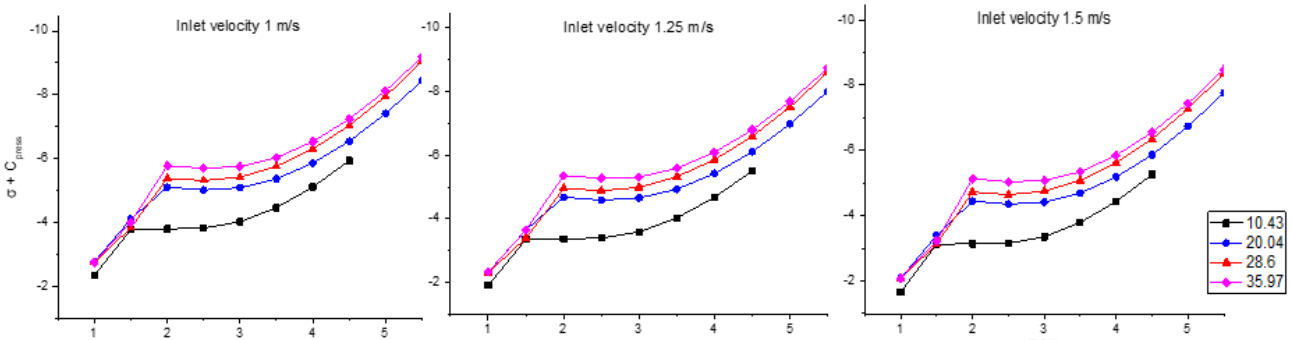
$$\sigma = \frac{P_\infty - P_v}{0.5\,\rho\,V^2} \tag{3}$$

$$C_{press} = \frac{P_L - P_\infty}{0.5\,\rho\,V^2} \tag{4}$$

$$\sigma + C_{press} \leq 0 \tag{5}$$

where P_∞ is free stream pressure, P_v is the absolute vapor pressure of 610 Pa in terms of temperature 273.15 K and P_L is the local pressure.

Same as the power coefficient graphs in Figure 5, the phenomenon showing the cavity effect of each diffuser angle at three variations of inflow velocity which can be seen in Figure 6 is alike. The cavitation was analysed at TSR 2.5 and 5 as the maximum power coefficient of each design. All graphs in Figure 6 agree that the worst design is owned by the largest angle of 35.97° offering the cavitation around 5 to 6. The smallest cavitation occurs on the smallest angle of 10.43° around 3 to 4 in all cases of velocity variation. All angles represent a similar phenomenon with a little risk at TSR 1 then eventually increases drastically as TSR increases.



(a) (b) (c)

Fig. 6. Cavitation number + pressure coefficient vs TSR on varying diffuser angles at inlet velocity (a) 1 m/s; (b) 1.25 m/s; (c) 1.5 m/s

Goundar *et al.,* [14] declared that the chance of cavitation occurring on the blade surface advances more towards the turbine blade tip owing to the low immersion depth near the tip and the greatest relative speed developed near the blade tip which was in agreement with this work in Figure 7. On the other words, Figure 7 shows that the lowest contour of pressure coefficient and cavitation number is experienced close to the blade tip which accords to the study conducted by Lee *et al.,* [15].

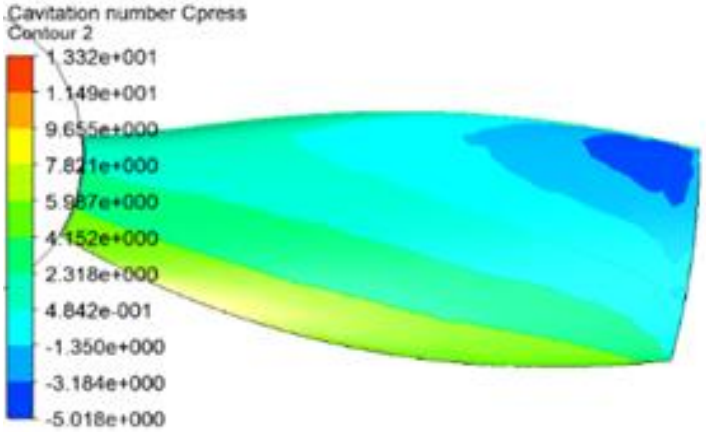


Fig. 7. The cavitation inception contour on the blade surface of 20.04° angle at best TSR in 1 m/s

3.3 Optimized Results

The performance parameters for training data are received from CFD. The variables concerning the objective 1, which is power coefficient (C_P) are τ, ω, and θ. Whereas cavitation as an objective 2 requires P_L and P_∞ variables with P_v constant. All these values can be seen in Figure 5 and Figure 6.

Figure 8 plots all potential solutions obtained from GA-ANN on each velocity case, in which each solution represents the optimal value responding to a trade-off of both objectives. Objective 1 is to maximize the power coefficient whose distance is far away from 0. Objective 2 is to minimize the cavitation inception, which closest to 0. The graphs display the optimal design either at the bottom right or the top left.

Figure 8 shows that all optimal solutions on each velocity have the same maximum power coefficient of 0.84 and cavitation inception of about 4.36 to 5.02. With maximum power coefficient 0.84 and minimum cavitation inception of about 4.36 to 5.02 at TSR 2.5 and 3 in all velocity cases, the optimal design is owned by the 20.04° design. This angle agrees to the work taken by Sakaguchi amd Kyozuka [16] and previous work on inflow velocity only 0.7 m/s. Yet, the cavity effect is also examined at varying inflow velocity.

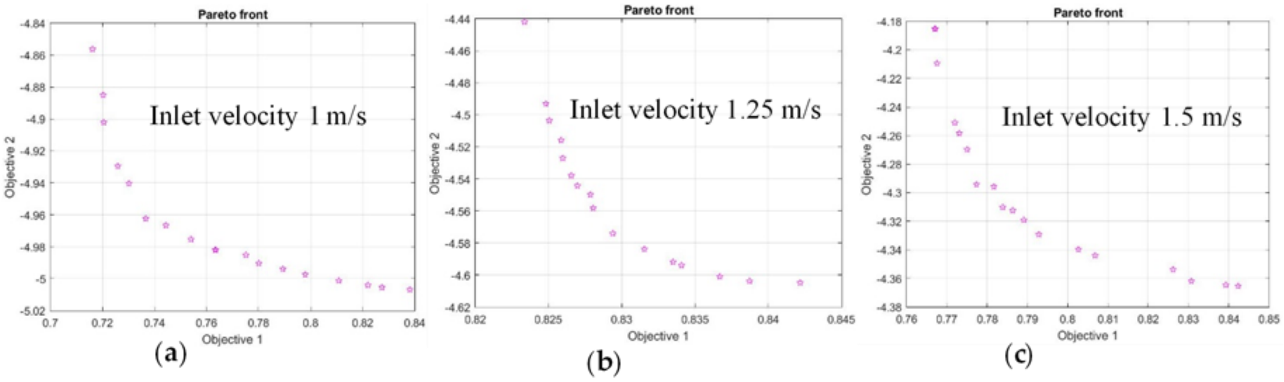


Fig. 8. The pareto front graph of the power coefficient and cavitation at inlet velocity (a) 1 m/s; (b) 1.25 m/s; (c) 1.5 m/s

4. Conclusions

The multi-objective optimization on diffuser augmentation of a tidal turbine designed based on NACA 4616 was pursued. Four design parameters of diffuser angles in three variations of inflow velocity are tested on CFD model. The tidal current speed affects the turbine performance insignificantly. Nonetheless, the recognition of the diffuser angle affects the turbine efficiency and cavity effect significantly. The diffuser angle can improve the turbine's power coefficient up to 50%. The more the turbine efficiency, the higher the cavitation risk on the tidal turbine. Accordingly, the multi-objective optimization using GA-ANN was applied to obtain the optimal design which has maximum power coefficient and minimum cavitation inception. This study concluded that the optimal design on diffuser augmentation of a tidal turbine is owned by 20.04° design which can be applied to all tidal current speed. The optimal design has a power coefficient of 0.84 and cavitation of 4.36 to 5.02.

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References

[1] Elbatran, Aly Hassan, Omar Yaakob, Yasser Ahmed, and Firdaus Abdallah. "Augmented diffuser for horizontal Axis marine current turbine." *International Journal of Power Electronics and Drive Systems* 7, no. 1 (2016): 235-245. https://doi.org/10.11591/ijpeds.v7.i1.pp235-245

[2] Sun, Huihui, and Yusaku Kyozuka. "Analysis of performances of a shrouded horizontal axis tidal turbine." In *2012 Oceans-Yeosu*, pp. 1-7. IEEE, 2012. https://doi.org/10.1109/OCEANS-Yeosu.2012.6263455

[3] Gaden, David LF, and Eric L. Bibeau. "A numerical investigation into the effect of diffusers on the performance of hydro kinetic turbines using a validated momentum source turbine model." *Renewable Energy* 35, no. 6 (2010): 1152-1158. https://doi.org/10.1016/j.renene.2009.11.023

[4] Nagataki, Takumi, Ko Kurokawa, Reiko Yamada, Daisaku Sakaguchi, and Yusaku Kyozuka. "Optimization of a Horizontal Axis Tidal Current Turbine by Multi-Objective Optimization." In *International Conference on Offshore Mechanics and Arctic Engineering*, vol. 58882, p. V009T13A023. American Society of Mechanical Engineers, 2019. https://doi.org/10.1115/OMAE2019-95829

[5] Kyozuka, Yusaku, Makoto Sueyoshi, Kento Obara, and Changhong Hu. "A Floating/Submersible Tidal Current Power Generator Applicable In Low Speed Tidal Flow." In *Grand Renewable Energy proceedings Japan council for Renewable Energy* (2018), p. 235. Japan Council for Renewable Energy, 2018.

[6] Zhang, Da-hai, Lan Ding, Bin Huang, Xue-meng Chen, and Jin-tao Liu. "Optimization study on the blade profiles of a horizontal axis tidal turbine based on BEM-CFD model." *China Ocean Engineering* 33, no. 4 (2019): 436-445. https://doi.org/10.1007/s13344-019-0041-5

[7] Huang, B., X. M. Chen, D. H. Zhang, and T. Kanemoto. "Multi-objective optimization of blade profiles for a horizontal axis tidal turbine." In *IOP Conference Series: Earth and Environmental Science*, vol. 163, no. 1, p. 012086. IOP Publishing, 2018. https://doi.org/10.1088/1755-1315/163/1/012086

[8] Bahaj, A. S., A. F. Molland, J. R. Chaplin, and W. M. J. Batten. "Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank." *Renewable Energy* 32, no. 3 (2007): 407-426. https://doi.org/10.1016/j.renene.2006.01.012

[9] Batten, W. M. J., A. S. Bahaj, A. F. Molland, and J. R. Chaplin. "The prediction of the hydrodynamic performance of marine current turbines." *Renewable Energy* 33, no. 5 (2008): 1085-1096. https://doi.org/10.1016/j.renene.2007.05.043

[10] Sun, Zhaocheng, Zengliang Li, Menghao Fan, Meng Wang, and Le Zhang. "Prediction and multi-objective optimization of tidal current turbines considering cavitation based on GA-ANN methods." *Energy Science & Engineering* 7, no. 5 (2019): 1896-1912. https://doi.org/10.1002/ese3.399

[11] Cresswell, N. W., G. L. Ingram, and R. G. Dominy. "The impact of diffuser augmentation on a tidal stream turbine." *Ocean Engineering* 108 (2015): 155-163. https://doi.org/10.1016/j.oceaneng.2015.07.033

[12] Tahani, Mojtaba, Narek Babayan, Fatemeh Razi Astaraei, and Ali Moghadam. "Multi objective optimization of horizontal axis tidal current turbines, using Meta heuristics algorithms." *Energy Conversion and Management* 103 (2015): 487-498. https://doi.org/10.1016/j.enconman.2015.06.086

[13] Hakim, Muhammad Syahmi Abdul, Mastura Ab Wahid, Norazila Othman, Shabudin Mat, Shuhaimi Mansor, Md Nizam Dahalan, and Wan Khairuddin Wan Ali. "The effects of Reynolds number on flow separation of Naca Aerofoil." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 47, no. 1 (2018): 56-68.

[14] Goundar, Jai N., M. Rafiuddin Ahmed, and Young-Ho Lee. "Numerical and experimental studies on hydrofoils for marine current turbines." *Renewable Energy* 42 (2012): 173-179. https://doi.org/10.1016/j.renene.2011.07.048

[15] Lee, Ju Hyun, Sunho Park, Dong Hwan Kim, Shin Hyung Rhee, and Moon-Chan Kim. "Computational methods for performance analysis of horizontal axis tidal stream turbines." *Applied Energy* 98 (2012): 512-523. https://doi.org/10.1016/j.apenergy.2012.04.018

[16] Sakaguchi, Daisaku, and Yusaku Kyozuka. "Design of a shrouded tidal current turbine by multi-objective optimization." In *Grand Renewable Energy proceedings*, Japan council for Renewable Energy (2018), 2018.