Performance investigation of an innovative Vertical Axis Hydrokinetic Turbine – Straight Blade Cascaded (VAHT-SBC) for low current speed

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Abstract. Research on the development and innovation of Vertical Axis Hydrokinetic Turbine (VAHT) to improve performance has been done. One of the important indicator that affects VAHT's performance is Coefficient of Performance ($C_p$). Theoretical $C_p$ value for the VAT (Darrieus) turbine is 0.45. This paper presents the results of a performance investigation for an innovative Vertical Axis Hydrokinetic Turbine – Straight Blade Cascaded (VAHT-SBC) by modifying the number and the arrangement of blades using CFD simulation. Symmetrical NACA 0018 is used for this study, each model is simulated with current speed variation (U - m/s) of 0.5, 1 and 1.5. An increase in $C_p$ value is shown in variation of 9 blades (3 blades cascaded in each arm) with $C_p$ value of 0.396 at TSR of 2.27 which is reach 88% of the theoretical value. Furthermore, the streamline velocity of the pressure contour, velocity streamline and torque fluctuations are also presented in this paper to gain in deep information.

Key words: hydrokinetic turbine; darrieus straight blade; turbine performance; vertical axis turbine; computational fluid dynamics.

1. Introduction

One of the largest and cheapest renewable energy is hydropower. There are two mainly methods for energy harvesting from water, called hydrostatic and hydrokinetic methods. Hydrostatic method is the conventional technique of producing electricity using head and extracts the potential energy of water using turbo-machinery. While hydrokinetic method is a modern technique to extract the kinetic energy containing in a flow water with zero head [1].

A feasibility study of ocean current in Alas Straits [2] and Larantuka Straits [3] of Indonesia shows that the current speed is relatively high, i.e. could reach up to 2 m/s and 4 m/s respectively. A preliminary study for ocean current in several small islands in Indonesia shows that ocean current speed in Berhala, Anambas, and Biawak island have their mean on 0.135 m/s, 0.055 m/s, 0.272 m/s respectively, and Miangas island has the highest speed of 0.835 m/s, means that Indonesia has varying low current speed potential for hydrokinetic energy harvesting. Hence, hydrokinetic technology which
having good capability to operate at low current speed is essential. The minimum workable current speed for hydrokinetic is about 0.8–1 m/s, but the preferably current speed is 1.3–1.5 m/s and goes up to a maximum of 3 m/s [4]. The approximate fluid densities are 1000 kg/m$^3$ and 1.223 kg/m$^3$ for water and wind, respectively.

Darrieus is the most attractive type of turbine to develop because of its simplicity and because the turbine permits the high rotating turbine to develop in low current speed. Various researches have been conducted to gain the best performance of darrieus turbine. Kobold turbine is originally vertical axis turbine that modified the blade by adding the rough sand strips along the span to postponing the stall condition [5]. A research of vertical axis turbine straight blade in the effect of number of blade is done by adding arm to keep the blade as the turbine rotates. As a result, it is clarified that the power coefficient decreases with the increase of numbers of blades [6].

Innovative approaches are required to meet the needs for electricity production especially for isolated islands in Indonesia which has lower current speed compare to the straits. Although these ocean currents have suitable characteristics, their costs of energy are considered to be higher than that of wind power in Research and Development. To alleviate this problem, Computational Fluid Dynamics (CFD) is used to reduce the future experimental cost and optimizing the design of Vertical Axis Hydrokinetic Turbine Straight Blade Cascaded (VAHT-SBC) which is an advance development of vertical axis hydrokinetic turbine that has a favourable self-starting proposed by the author [7].

This paper describes the main factor that affect the performance of the turbine by modifying the number and the arrangement of blades without adding the number of arm. Furthermore, the flow profile of the pressure contour, velocity streamline and torque fluctuations are also presented in this paper to gain in deep information.

2. Description of VAHT-SBC

2.1. The Origin of VAHT-SBC

Hydrokinetic turbines could be categorized into two types. Firstly, the vertical-axis turbine, which the turning axis is perpendicular to the stream flow. Secondly, the horizontal turbine, which the rotational axis follows the direction of flow. Due to the omni-directional characteristic, vertical axis turbines are preferable in situations where flow direction changes, such as in tidal systems [4].

![Coefficient Performance of Different Turbines](image)

**Figure 1.** Coefficient Performance of Different Turbines

Theoretical coefficients performance of different free flow turbines for wind application are depicted in Figure 2 and the coefficient performance for darrieus turbine will not exceed 0.45 [8]. The conventional of darrieus straight-blade turbines with fixed pitch blades typically suffer from poor starting torque, low efficiency and shaking due to large fluctuations in both radial and tangential force with change of azimuth angle. The use of passive variable pitch can improve the aspect of performance of the three straight-blade vertical axis turbine [7].
Figure 2. The Change of Pitch Angle In Azimuth For (a) Fixed-Blade, (b) Passive-Variable Pitch Blade And (c) Prediction in The Changes of Azimuth Angle Of VAHT-SBC

VAHT-SBC is an adaptation from darrieus straight-blade turbine that designed to rotate at low current speed. The result of previous research with current speed variations of 0.6 – 1 m/s, provides data on capability of self-start rotating at speed 0.8 m/s for fixed-pitch condition, and at speed <0.6 m/s for passive variable-pitch which confirms better ability to start rotating at intermediate Tip Speed Ratio (TSR) of 2.3 - 2.4 [7]. The pitch angel change regarding to fixed-blade and passive-variable pitch blade is given in figure 2 (a). Both type of blades in two different turbines are combine as one turbine without enlarge the dimension of the turbine depict in figure 2 (c). Henceforth, this combination is called as VAHT-SBC (Vertical Axis Hydrokinetic Turbine – Straight Blade Cascaded).

2.2. VAHT-SBC Configuration
NACA 0018 has been used as the airfoil of the blades for VAHT-SBC. Initial analysis of 4 symmetrical NACA 4-digit foils suggested that NACA 0018 has the best characteristics for vertical axis tidal current turbine [7]. The three model turbine configurations analyzed in this work are consist of passive pitch blade (red color) and fixed blade (blue color) and the number of blades for model 1, 2 and 3 respectively are 3, 6 and 9 as depict in figure 3. The turbine has 10 cm of cord, 80 cm of span, 80 cm of diameter, 3 cm shaft of diometer, with the aspect ratio of 8 and H/D is 1.

Figure 3. (a) Model 1, (b) Model 2 And (c) Model 3.

3. Numerical Setup
CFD simulation was performed as preliminary study to gain deep information regarding to the effect of blade number to the performance of VAHT-SBC. The SST (Shear Stress Transport) k-ω turbulence model was used. Some applications have shown that the k-ε model has limitations in boundary layer flows with adverse pressure gradients [9]. In contrast, SST k-ω turbulence model gives accurate predictions of the amount flow separation under adverse pressure gradients, and has been successfully used in the CFD simulation of wind or water turbines [12-13].
3.1. Computation Domain and Boundary Condition
In this simulation, the turbine’s arms are neglected for simplicity and the economy of computational time. There are three domains used in this simulation, the external domain has dimension of $4.5D \times 2.1D \times 2D$, the height of dimension of rotating domain is 2D and the diameter is 1.5D.

![Figure 4. Mesh Generation](image)

The meshing size are divided according to its domain. Turbine and shaft are ranging between 0.0005 m to 0.1m, external and rotating domain are between 0.0095 m to 0.3m, while for the inlet and outlet the meshing size is ranging from 0.01 m to 0.3 m with the same angular resolution of 18°. Three different grids amount that produced for meshing in this study are $8.7 \times 10^6$, $12.5 \times 10^6$, $17.3 \times 10^6$ for model 1,2 and 3 respectively. The grid is fully tetrahedral unstructured in both external and rotating domains as shown in figure 4. The unstructured tetrahedral grids are chosen due the capabilities to discretize complex geometries with fast and minimum user intervention. The velocity condition for inlet boundaries are set into 0.5, 1, 1.5 m/s and the turbulence intensity is set for 5% with the outlet, right and left wall are set to opening condition.

4. Result and Discussion
In this research, CFD feasibility analysis can be used as a reference in preliminary design of a turbine. The used of CFD is done to minimize errors for further turbine design. In addition, CFD operation is zero cost and provide results that cannot be achieved from experimental studies such as torque fluctuation, streamline velocity and fluid pressure around the blade with the intention of improvisation design can be done before the fabrication.

![Figure 5. Number of Blade Effect To Average Torque Comparison in Freestream Velocity Variation](image)

4.1. Torque Fluctuation
In this study, each model is simulated with three current speed variations of 0.5 m/s, 1 m/s, and 1.5m/s. Figure 8 depicts the average torque for each model in current speed that mentioned above. The
magnitude of the torque is affected by freestream velocity, the higher the freestream velocity, the higher the torque can be generated by the turbine. The average torque (N.m) generated by the turbine model is 18.13, 23.59, 33.97 N.m for model 1,2,3 respectively with the highest torque of 46.18 N.m achieved by turbine model 3 at speed of 1.5 m/s. Further description of the torque per azimuth is given in Figure 6.

Simulations are performed 24 times for each model to get results at every 15° of azimuth in a full rotation (360°). Rotation of the turbine is an effect from kinetic energy that converted into different pressure and shear stress along the span. The sinusoidal pattern is formed by the change of angle of attack, as depicted in Figure 6. The pattern tends to be the same for every 120° due to three arm that also rotates in a full rotation. In all variation of current speed, the highest torque for model 1 are achieved in every 105°, 225°, 345° of azimuth, while for model 2 and 3 the highest torque are shifts and achieved in every 30°, 150°, and 270° of azimuth. The lowest torque for model 1 are also shifts compared to model 2 and 3, where the minimum torque for model 1 are in the azimuth of 60°, 180° and 300°, the lowest torque for model 2 are in the azimuth of 75°, 195°, 315°, and the lowest torque for model 3 are achieved in azimuth of 0°, 120°, and 240°. Further information of minimum and maximum torque will be discussed in figure 7 and figure 8.

The combination between passive-pitch and fixed pitch can shift both the highest and the lowest torque fluctuation pattern. The passive-pitch blade affects the Reynolds number which tend to be higher, the increment of Re number leads the fixed-pitch blade to get turbulence flow from passive-pitch blade and postpone the dynamic stall condition.

As the freestream velocity increases, the rises and falls of torque fluctuation for turbine model 1 tend to be more stable compared to model 2 and 3 in higher freestream velocity and vice versa for the lower current speed. In the real implementation, mostly turbines that have high magnitude of gap between maximum and minimum torque per-azimuth, also have higher intensity of vibrations, this phenomenon could directly impact on the turbine structure strength and generate poor power quality for electricity [12].

![Figure 6. Torque Comparison Per Azimuth in Velocity of (a) 0.5 m/s, (b) 1 m/s and (c) 1.5 m/s](image)

4.2. Pressure Distribution and Streamline Velocity
Since the freestream velocity and the fluid pressure relates to the aerodynamic force, the faster the freestream velocity, the greater the energy converted to the pressure that could be extracted by turbine. To gain more deep information for simulation result of VAHT-SBC performance, it is necessary to study detailed flow profile around the blade. Figure 7 and figure 8 present flow profile of pressure contour distribution and streamline velocity at minimum and maximum torque regarding to fluctuation torque mentioned in figure 6.
In order to simplify the analyses of the local flow pressure variations near the blade, for further descriptions one full rotation has been divided into 4 quadrants, i.e. 1st quadrant (0°-90°), 2nd quadrant (90°-180°), 3rd quadrant (180°-270°) and 4th quadrant (270°-360°).

The position of blades in the minimum torque achieved by model 1 is in the azimuth of 60°, 180° and 300°. The blades in 2nd quadrant did not achieve a sufficient flow pressure (figure 7-A1) around it, while the blade in 4th quadrant obtained a low velocity due to the vortex created by the blade in 1st quadrant (figure 7-A2).

Due to the effect of adding a single blade cascaded into inner arm, greater vortex created by model 2 in the blade of 1st quadrant causes a minimum velocity obtained by the blade in 4th quadrant (figure 7-B2) as the consequences of minimum torque fluctuation achieved by model 2. Apart from the low pressure and velocity contour as seen in figure 7 B1 & B2, position of blade in 3rd quadrant is on the opposite direction against the freestream which affects the wrong position of the blade against the angle of attack.

By adding single more blade into the arm, model 3 obtains a great pressure in 2nd quadrant (figure 7-C1). As the consequences, a greater vortex also creates by the combination of cascaded blade and impinging the blades in 3rd quadrant as seen in figure 7-C2.

**Figure 7.** Pressure Distribution (1) and Streamline Velocity (2) of The Minimum Torque, Model 1(a) 60°, 180° and 300°, model 2 (b) 75°, 195°, 315°, model 3 (c) 0°, 120°, and 240°.
Figure 8. Pressure Distribution (1) and Streamline Velocity (2) of the Maximum Torque, Model 1(a) 105°, 225°, 345°, model 2 (b) and 3 (c) 30°, 150°, and 270° of Azimuth

The application of passive-variable pitch as the outmost blade, leads the angle of attack to adjust according to the azimuthal position and postpones the stall condition. Passive-variable pitch blades that employed in model 1 provide a greater performance as the increment of TSR. The maximum $C_p$ for model 1 is 0.31 at TSR 3.2, as shown in figure 9. The less of number blade in this turbine, the less vortex impinging another blade, as seen on figure 8-A2 for blade in 3rd and 4th quadrant for turbine model1. In addition of the vorticity, the higher flow pressure (figure 8-A1) are well-distributed to another blade compared to figure 7-A1.

Figure 9. Number of Blade Effect on Turbine Performance Characteristic

Adding a single fixed-pitch blade into inner arm as model 2, gives the enhancement of $C_p$ in lower TSR compared to model 1 (figure 8). The contribution of adding fixed-pitch blade can be seen on
figure 8-B1. In the 3\textsuperscript{rd} quadrant, the inner fixed-pitch blade tends to gain fresh current perpendicularly without interference from the movement of passive-variable pitch blade in the same quadrant as depict in figure 7-B2. The highest torque for model 3 is obtained in exactly same azimuth as model 2.

The highest of $C_p$ is obtained by turbine model 3 (figure 9) at 0.396 with TSR of 2.27 which is reach 88\% of the theoretical $C_p$ value of darrieus turbine (figure 1). As the freestream velocity is 0.5 m/s, the VAHT-SBC provides the lowest TSR at 1.6, but in higher $C_p$ compared to mode 1 and 2. Thus, this phenomenon confirms that VAHT-SBC is suitable for low current speed application which appropriate with ocean current condition in Indonesia.

5. Conclusions

Based on Computational Fluid Dynamics simulation investigation, it has been concluded that increase in the number of blades increases the torque output from VAHT-SBC. Three models of VAHT-SBC were studied in this research, which provides preliminary data for future experimental research.

As the results, the effectiveness of combining the passive-variable pitch blade and fixed-pitch blade is obtained. The interaction of the passive and fixed pitch blade to the incoming flow generate a complex flow profile that investigate into quadrants. The comparison of models, show that maximum $C_p$ is achieved by model 3 of 0.396 at TSR of 2.27 which reach 88\% of the darrieus turbine theoretical performance. The capability of model 3 to obtain a higher performance in lower TSR can make a significant contribution in the kinetic energy conversion for low speed ocean current application.

6. References

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