Performance analysis of a modified Savonius hydrokinetic turbine blade for rural application

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Abstract. For rural areas situated in the deep topography of Sarawak, the distance from energy grids and plants are situated too far from the power appliances. Hence, sustainable alternative method of generating energy for the people should be put into consideration. For rural areas rich with riverine streams, the employment of hydrokinetic turbines (HKT) would be a good alternative to meet their daily requirements. The HKTs are fundamentally understood as a turbine that harnesses the kinetic motion of freestreams without the need of head. In the preceding years, the development of HKT turbines has undergone several breakthroughs in terms of efficiency and design. However, at low water depths cluttered with debris, it makes the implementation of certain HKT orientations limited. In such cases, the Savonius style SKTs would be one of the promising deployments in riverine systems. In this paper, a newly developed Savonius blade profile by Roy & Saha was simulated in a fluid medium of water through the CFD software StarCCM+. The two-dimensional unsteady Reynolds Averaged Navier Stokes equations was solved using the shear stress transport k-ω turbulence model at a Reynolds number of 0.71-1.88×10^5 and water speed ranging from 0.3-0.8 m/s. The maximum power coefficient generated by the modified blade was 0.43 at TSR=1.0 and Re=1.88×10^5.

1. Introduction
Energy plays a fundamental role and critical position in the social, economic, cultural and political sectors that moves the progress of civilization by sustaining all the needs of society. The demand has been too extensive in the past few decades, that the ever-increasing need of the community is not matched by the limited supply of energy resources, due to its over exploit to meet human demands. In the South Asian domain, most countries today still rely on the conventional energy sources that are depletable and non-renewable. It is straightforward to theorize that renewable energy is the better option as an energy source due to the outlying advantages. However, for the past century, civilization has an over reliance to fossil fuels as it is used as the main energy supply. The current projection of total electricity production is still dominated by conventional sources. In some of the developed countries such in US, UK and Europe, the trend of non-conventional energy generation is slowly increasing recently [1]. Hence, a regime for the incorporation of renewable energy is vital for the preservation of natural resources. The 2015 Paris Agreement had presented global ambitions to achieve stability between anthropogenic emissions by sources and removal of sinks of greenhouse gases by the second half of this respective century. The ambition of the Paris Agreement was to cultivate the increase in global average temperature to well below 2.0°C above the preindustrial levels while also enforcing the temperature limit of 1.5°C [2]. A solution to accommodate all these goals are
to reduce the consumption of non-renewable sources and integrate a large-scale renewable energy supply in energy systems [3]. Hence, the motivation for this study is to facilitate the movement of implementing a contemporary green energy solution for the rural communities of Sarawak.

In the current state, the people located in the deep topography of Sarawak still rely on small diesel-powered generators and solar panels. However, the cost to maintain and operate the diesel generators are not cost efficient for the low-income remote communities. The fuel to power the generators are required to be transported over vast distances by river or by terrain. Further, the solar panels along with their electrical components were tested to be too fragile for the operation in the tropical rainforest as it susceptible to corrosion [4]. Hence, to alleviate the strain encountered by the villagers which are situated close to the riverbanks, an alternative form of energy generation method such as hydrokinetic turbines was considered. The feasibility of incorporating hydrokinetic turbines in Sarawak is due to the land’s geographic characteristics. Sarawak is predominantly divided into nine districts which are Kuching, Samarahan, Sri Aman, Sarikai, Sibu, Bintulu, Kapit, Miri and Limbang. All of which are interconnected due to Sarawak being one of the largest river networks where the main rivers are the Sarawak river, Rajang river, Saribas river and the Lupar river [5].

Hydrokinetic turbines produce electricity by harnessing the flow of water in a river or stream, where turbines rotate the generator and capture the kinetic energy of the flow. Hydrokinetic turbines operate on the similar theory of wind power generation where the major significance of the respective configuration is the density of the fluid. For hydrokinetic turbines, the working fluid medium is water and it is approximately 800 times denser than air. Herein, this implies that the energy generated by hydrokinetic energy is far greater than the energy generated by wind turbines with similar geometry and flow speeds [6]. A hydrokinetic turbine operating at a rated speed of 2-3 m/s can produce four times the energy of a wind turbine with similar rated wind speed [7]. The power density comparison of hydrokinetic turbines and wind turbines conducted by Yuce & Muratoglu [7] found that the power density of a hydrokinetic turbine operating at flow speed 2 m/s is equal to the wind turbine operating at 16 m/s.

Hydrokinetic turbines can be classified as three separate subgroups; horizontal axis, cross flow and vertical axis. These subgroups are established on the arrangement of rotor axis with respect to the flow direction. Horizontal axis turbines or alternatively called an axial flow turbine, operates on the principle that the turbines rotate about the axes parallel to the incoming flow. These turbines predominantly utilize propeller type rotors. There exist two variations of horizontal axis hydrokinetic turbines (HAHKT), straight axis and inclined axis. HAHKT utilize the similar concept of aircraft wings, propeller blades and wind turbines [8]. The advancement of wind turbines and marine propellers have contributed greatly to the design and performance of most HAHKT in ocean and tidal energy extraction. There exist a multitude of literature on the respective configurations. However, the performance of HAHKT reduces substantially in riverine conditions. The presence of suspended particles or materials (eg; fish, debris, rocks, branches and twigs) could also be a problem for horizontal flow turbine as it could possibly damage the respective turbine [9].

The vertical axis hydrokinetic turbines (VAHKT) operate on the principle that the turbines axes are orientated orthogonal to the incoming water flow while being parallel to the water surface [10]. There exist three main configurations of the vertical axis hydrokinetic turbines in modern day research and commercial use. The three main configurations are classified as: (a) Darrieus Type Turbine, (b) Gorlov Turbine, and (c) Savonius Turbine. The VAHKT has been chosen to be the configuration of interest for this study due to the capability of having a generator configuration above water level, versatility towards changes of flow direction, horizontal configuration of shaft which allows turbines to sweep wide-shallow channels, low cost blade configuration, no need for yawing mechanism for reversing tidal flow and a marginally lower impact to aquatic life due to lesser noise, lower rotational speed and large hollow space. Furthermore, riverine currents offer lower energy content as opposed to ocean current and therefore, the turbines should have simple resolutions for the generators and rotor speed control. The generators and power transmission assembled at the surface of the water and this allows the configurations to ease in terms of design, operation and maintenance of the system [11].
2. Literature Review

Known as the simplest turbine configurations amongst the three other vertical turbine arch-types. The Savonius turbine can be described as a turbine with two semi-circular buckets cut from the top to bottom and placed sideways along the cutting plane. The cross section of the turbine forms an indistinguishable “S” letter [12]. The respective turbine operates on the principle of drag force difference between the concave side and convex side of the blade which exhibits excellent starting capabilities. However, Savonius turbines suffer from low aerodynamics efficiencies when compared to HAHKT and Darrieus turbines. The performance of a Savonius turbine in water is far efficient in than its original counterpart. Savonius turbines operates at lower tip speed ratios when placed in a denser fluid such as water, due to the greater drag force imposed by water. Since drag force is a product of density, it is only logical that the drag encountered in water is greater than that encountered in air. Furthermore, the pressure gradient that is subjected in water is adversely different than that of air. Where in water, the hydrostatic pressure gradients increase with the depth in the fluid [13]. Therefore, the analysis of hydrokinetic Savonius turbines are significantly different than that of wind energy generation due to the governance of gravity on the pressure difference [14].

There is a plethora of studies carried out devoted in improving the performance of Savonius rotors. The issue that engulfs the performance of conventional Savonius turbines are the large variations of static torque [10]. Numerous studies correlate the enhancement of performance of Savonius turbines with rotor blade profile, where research have varied the Savonius rotors from having twisted blade, helical blade and alternate blade geometry as opposed to the norm semi-circular shape. The prevalent criteria for a desired blade profile would be cost effectiveness and design simplicity yet offering a reasonable amount of coefficient of power. Therefore, a wide range of literature has been reviewed prior conducting this study [14-22]. It is worth noting, that the performance of certain blade profiles has yet to be tested in a working fluid medium of water and would serve as an additional motivation for this research. The summarization of literature along with the key aspects are shown in Table 1.0.

| Author(s)                | Methodology                                      | Parameters Investigated                  | Maximum $C_p$          |
|-------------------------|--------------------------------------------------|------------------------------------------|------------------------|
| Mabrouki, Driss and Abid [16] | Experimental (Hydrodynamic Test Bench)          | Internal OR=0-0.3                         | $C_{p_{max}} = 0.327$  |
| Golecha, Eldho and Prabhu [17] | Experimental (Open-Channel)                     | Double Deflector Plate Deflection Angle=$15^\circ - 60^\circ$ | $C_{p_{max}} = 0.35$  |
| Patel, Bhat, et al. [14]       | Experimental (Laboratory Channel and Irrigation Canal) | Varying AR and OR                        | $C_{p_{max}} = 0.23$  |
| Roy and Saha [15]               | Experimental (Low speed wind tunnel)            | Modified Blade Profile                   | $C_{p_{max}} = 0.31$  |
| Current Study               | CFD Simulation                                   | Modified Blade Profile                   | $C_{p_{max}} = 0.431$  |
According to an experimental analysis conducted by Roy and Saha [15], altering the blade profile of a 2-bladed Savonius wind turbine has shown significant increase in the turbine performance. The altered blade profile was described as a newly developed blade profile that was generated from numerous experimental studies on Bach and Benesh type turbines by altering the geometric arcs, overlap distances and dimension of blade profile. The experimental analysis conducted was done to compare the inherent performance of several altered blade profiles with the inclusion of the newly developed blade profile, to that of conventional Savonius wind turbine blade profile. The respective experimental testing was conducted in an open-type low-speed wind tunnel at Reynolds number, ranging from $6.0 \times 10^4$ to $1.5 \times 10^5$ with reasonable blockage correction factor of 4-9%. The highest obtainable coefficient of power generated by the newly developed blade profile was 0.31 at Reynolds number, $Re=1.2 \times 10^5$ corresponding to TSR of 0.82 [15]. In this study, the modified Savonius blade profile was integrated into a fluid medium of water and the performance was assessed in order to determine the feasibility of incorporating the respective blade for rural area deployment.

3. Numerical Methodology

3.1. Performance parameters

The performance of the Savonius HKTs are calculated in terms of averaged power and moment coefficient as shown:

$$TSR = \frac{\omega R}{V}$$  \hspace{1cm} (1)

$$C_M_{average} = \frac{T}{0.5 \rho A V^2 R}$$  \hspace{1cm} (2)

$$C_P_{average} = \frac{T \omega}{0.5 \rho A V^2} = \frac{T R \omega}{0.5 \rho A V^2 R} = C_M_{average} \times TSR$$  \hspace{1cm} (3)

where $\rho$ is the density of water [kg/m$^3$], $V$ is the free stream water speed [m/s], $A$ is the swept area of the turbine [m$^2$], TSR is the tip speed ratio, $R$ is the radius of the turbine [m], $\omega$ is the rotational speed of the turbine [rad/s], $T$ is the average moment generated on the turbine [Nm] respectively.

3.2. Mathematical model

The prevalent criterions for the utilization of a reliable CFD model are appropriate turbulence model, suitable definition of the spatial discretization refinement level and optimal time step dimension which ensure the capture of all relevant time scales [18]. Hence, a fully turbulent SST $k-\omega$ model with two additional equation for triggering the correct onset of the laminar to turbulent boundary layer transition is employed in this following thesis. Generally, the $k-\omega$ turbulence model can be separated as two entities: standard $k-\omega$ and SST $k-\omega$. For the case of this research, the SST $k-\omega$ is known as the combination of a $k-\omega$ and $k-\varepsilon$ turbulence model such that the $k-\omega$ model is incorporated in the inner regions of a boundary layer while the $k-\varepsilon$ model is incorporated in the free shear flow outside a boundary layer. This allows the SST $k-\omega$ an optimal choice for the research as it allows for the utilization for low velocity conditions without any external energy input [19]. The SST $k-\omega$ can be expressed as:

$$\frac{D\rho k}{Dt} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[ (\mu + \sigma_k \mu_{E}) \frac{\partial k}{\partial x_j} \right]$$  \hspace{1cm} (4)

$$\frac{D\rho \omega}{Dt} = \frac{\gamma}{\nu_t} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[ (\mu + \sigma_{\omega} \mu_{E}) \frac{\partial \omega}{\partial x_j} \right] + 2 \rho (1 - F_1) \sigma_{\omega} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_j}$$  \hspace{1cm} (5)

Where, $F_1 = \tanh \left( arg_1^4 \right)$  \hspace{1cm} (6)
\[ \text{arg}_1 = \min \left( \max \left( \frac{\sqrt{k}}{0.09\omega y}; \frac{500\nu}{y^2 \omega} \right); \frac{4\rho \sigma_{\omega_2} k}{CD_{k\omega} y^2} \right) \]  
\[ CD_{k\omega} = \max \left( \frac{2\rho \sigma_{\omega_2}}{\omega_1}; \frac{1}{\omega_j}; \frac{\partial k}{\partial j}; \frac{\partial \omega}{\partial j}; \frac{10^{-20}}{10^{-20}} \right) \]

and \[ \nu_t = \frac{a_{ik}}{\max(\omega_1, \omega_2)} \]

Where, \( F_2 = \tanh(\text{arg}_2^2) \)

\[ \text{arg}_2 = \max \left( \frac{2}{\omega_1}; \frac{500\nu}{y^2 \omega} \right) \]

Two sets of constants which are generally used are as follows:

**First Set** (\( \varphi_1 \)) – Wilcox

- \( \sigma_{k_1} = 0.5 \)
- \( \sigma_{\omega_1} = 0.5 \)
- \( \beta_2 = 0.0750 \)
- \( \beta^* = 0.09 \)
- \( k = 0.41 \)

\[ \gamma_1 = \frac{\beta_1}{\beta^*} - \frac{\sigma_{\omega_1} k^2}{\sqrt{\beta^*}} \]

**Second Set** (\( \varphi_1 \)) – Standard \( k - \varepsilon \)

- \( \sigma_{k_2} = 1.0 \)
- \( \sigma_{\omega_2} = 0.856 \)
- \( \beta_2 = 0.0828 \)
- \( \beta^* = 0.09 \)
- \( k = 0.41 \)

\[ \gamma_1 = \frac{\beta_2}{\beta^*} - \frac{\sigma_{\omega_1} k^2}{\sqrt{\beta^*}} \]

### 3.3. Computational domain

For the computational modelling of this study, a rectangular computational domain is utilized to simulate the flow condition of an ideal riverine system. An enlarged computational domain is used in the following simulation to mitigate the wall boundary and blockage effect that would regularly affect the performance of turbines. The large computational domain also minimizes the impact of boundary condition uncertainties [20]. Figure 1 illustrates the computational domain of the modified Savonius turbine in two-dimensions confined by an upstream, far field downstream and symmetry type boundary. The respective boundary is circumscribed by a no-slip wall boundary condition on the blades along with a rotating mesh region. The inlet velocity and pressure outlet velocity are located 6D and 8D from the turbine center respectively. The diameter of the turbine (D=0.21) is used based on literature. The respective domain is discretized by unstructured polyhedral mesh with the inclusion of the boundary layer region. A 3-D CAD geometry is imported to StarCCM+ in order to generate a polyhedral mesh with a very small z-directional thickness (0.05 m). Generally, polyhedral meshes are reliable, quick to converge, generated easily in StarCCM+ and are more efficient than tetrahedral meshes. Once the mesh refinement is accepted, it is then projected into a two-dimensional plan for the generation of solution. The requirement for the two-dimensional is a very fine strutted grid generated on the blade surface with an overall thickness of 1 mm along with a wall normal growth of 1.2 mm. A secondary level of mesh refinement is applied at the surrounding of the rotor blades to accurately replicate the flow fields inside the rotational radius of a turbine, which incurs vortex shedding. The surrounding of the rotor blades will be discretized with a minimal cell size of 3.15 mm. Furthermore, a third level of refinement is set on the outer circular zone and the level of the downstream refinement will be kept constant up to eight times the of the blade chord length to represent the wake flow. Lastly, a fourth level of mesh refinement will be applied to the far wake region with a minimal sized cell of 0.053D for minimized velocity dissipations. The velocity of the water at the inlet will be varied from 0.3 m/s to 0.8 m/s which corresponds to Re=707-1.88 × 10^5 in order to assess the hydrodynamic performance of the modified Savonius hydrokinetic turbine. The \( y^+ \) value of the boundary layer was kept constant to ensure the same boundary layer resolution where values were less than or equal to 1. Meanwhile, the outlet is set at constant pressure \( P=0 \) Pa which adheres to the large computational domain size.
4. Validation

The quality of the mesh is mainly influenced by the distributions and size of the grid. The grid sensitivity analysis test conducted in Figure 2 shows that at least 86,000 polyhedral mesh is required in order to obtain less than 1% of errors compared to the finest grid that corresponds to a cell size consistency of 0.1 mm at the blade surface. The respective meshing method is based on the literature published by Roy and Ducoin [21]. The convergence of the computational simulations is noted to be achieved after a few initial fluctuations. The quasi steady time convergence of the simulations is achieved at approximately 1.5 seconds. The standards for the continuity, momentum and the two transport equations from SST $k-\omega$ turbulence model is defined by RMS values less than $10^3$. For this study, the total cell count of polygonal mesh is 91,091 cells which accounts for 0.5% of error.

5. Result and Discussion

5.1. Average moment and power coefficient at varying water speeds

In this numerical assessment, the performance of the modified Savonius turbine blade profile is analysed with respect to the averaged moment coefficients and power coefficients, at varying TSR. The goal is to assess the feasibility of the modified Savonius turbine blade profile when subjected to a fluid medium of density 997.561 kg/m$^3$. Based on figures 3 and 4, the maximum average power coefficient, $C_p$ max at the lowest water speed was found to be 0.38064 occurring at TSR=1.0 while the maximum average moment coefficient was found to be 0.53406 occurring at TSR=0.4. The trend of the power coefficient is comparable to that of literature published by the Kerikous and Thévenin
(2019), where it generates peak Savonius turbine power coefficient capabilities at TSR above 0.79. However, at elevated TSR ranges the performance of the Savonius turbine degrades after reaching a certain capstone TSR. The overall maximum power coefficient, $C_p_{\text{max}}$ generated by the modified Savonius blade profile was 0.42603 at TSR 1.0 while the maximum overall moment coefficient was 0.6429 at TSR of 0.4 at water speed of 0.8 m/s. The minimum and maximum power coefficients occur at the lowest and highest water speeds respectively. Hence, there is a correlation that the water speeds play a role in determining the power output of the turbine. This inclination at water speed of 0.8 m/s can be attributed to the optimum decrease of moment coefficient. It is observed that the moment coefficient decrease is an s-like pattern, which stipulates the magnitude of torque generated at this respective speed is higher than average. Hence, the optimum operational speed and TSR can be drawn to be 0.8 m/s at TSR of 1.0. The highest average coefficient of power at TSR=1.0 would later be used to compare to conventional semi-circular Savonius blade profile. Based on figure 4, the progression of average power coefficient against TSR increases abruptly as opposed to the other water speeds.

![Figure 3. Average moment coefficient corresponding to TSR](image)

![Figure 4. Average power coefficient corresponding to TSR](image)

5.2. **Significant static pressure and velocity magnitude contour at water speed 0.8 m/s (TSR=1.0)**

The significant pressure and velocity contour that is considered occurs at water speed of 0.8 m/s. The relevance of the respective water speed is due to its peak power generation at TSR of 1.0. Coincidently, the correlation of elevated water speed to turbulence scale is also accounted for. For a higher water speed of 1.0 m/s, the peak power generation occurs at TSR of 1.2 and further degrades past the capstone TSR. In real-time conditions, it is not practical for the turbine to achieve the maximum power coefficient at a higher TSR. It implies that the turbine would require a substantial amount of rotational speed for it to achieve peak performance and would therefore defeat the purpose of implementing a VAHKT. Hence, the performance at water speed of 0.8 m/s is discussed.

The performance of the modified Savonius turbine at water speeds of 0.8 m/s is the most efficient amongst other water speeds. It can be observed from figure 5 that the maximum average power coefficient generated was 0.42603 at TSR=1.0. Based on the static pressure contour, at rotational angle of 180° it is observed such that the pressure subjected on the suction side of the advancing blade is relatively high. This attributes to the self-starting capabilities of the Savonius turbine. Further, at rotational angles of 120° and 150° the convex side of the advancing blade exhibits high negative pressure which aids in the rotation of the turbine.
At TSR= 1.0 for rotational angle $\theta = 90^\circ$, it can be observed from figure 6 that an excited wake region occurred along the convex side of the advancing blade which abruptly increased the velocity at
the specific region. This phenomenon is only present at TSR=1.0, as it is regarded the contributory force to the increase turbine performance. According to Roy and Saha [22], the respective accelerating region near the trailing edge of the returning blade, increases the occurrence of air incidence on the concave side of the advancing blades. For this case, it is similar in nature with the inclusion that the incidence of air is substituted with water. Further, at angles of 120° and 150° similar effects of an excited wake regions occur along the leading edge towards the trailing edge of the returning blade which aids in accelerating the water to strike the concave side of the advancing blade. It is also noted that at angles 120° and 150° that a formation of vortices within the gap with occurs. The formation of vortices may or may not have an adverse impact on the overall performance of the turbine and may be considered in the future scope of this study.

6. Conclusion

The present work aims at improving the current performance of Savonius-style turbines with the implementation of a modified blade profile configuration at relatively low water speeds as it would be used for rural area deployment. Computational simulations have been performed to evaluate the performance of the modified Savonius blade profile which had never been tested in a medium other than air. The results of the computational simulations yielded that the modified Savonius blade profile exhibit excellent power generating capabilities as the water speeds increased. The modified Savonius blade profile also conforms to the norm of the majority of Savonius where its performance degrades after TSR=1.0. Hence, the feasibility of implementing the respective turbine blade profile in rural areas is viable. However, further testing should be conducted with respect to the future scope for the modified blade to be viable in real-time application. The modified Savonius HKT exhibit improved power generation capabilities at low water speeds up to 0.8 m/s. Based on the scope of this study, the influence of water speed at alternative TSR was tested and the results yielded that modified Savonius blade profile could generate a maximum average Cp value of 0.42603 at water speeds 0.8 m/s. The optimized performance of the modified Savonius HKT was found to occur at water speeds 0.8 m/s at TSR of 1.0. Also, the comparison of the modified Savonius blade profile to conventional semi-circular Savonius blade profile yielded an improved performance of 19.43% and modified Savonius blade exhibits excellent operational performance capabilities at low TSRs, all the modified Savonius turbines generated average Cm values above 0.5. Therefore, employment of the modified Savonius HKT is feasible for the employment in rural applications where water speed ranges from 0.3 m/s to 0.8 m/s. As a future research, the different designs will be studied for the hydro-kinetic applications.

References

[1] United States Energy Information Administration, “Annual Energy Outlook 2019 with Projections to 2050,” United States Energy Information Administration, Washington, 2019.
[2] W. Steffen, J. Rockström, R. Richardson, T. M. Lenton, C. Folke, D. Liverman, C. P. Summerhayes, A. D. Barnosky, S. E. Cornell, M. Cruxifix, J. F. Donges, I. Fetzer, S. J. Lade, M. Scheffer, R. Winkelman and H. . J. Schellnhuber, “Trajectories of the Earth System in the Anthropocene,” Proceedings of the National Academy of Sciences, vol. 115(33), pp. 8252-8259, 2018.
[3] K. Hansen, C. Breyer and H. Lund, “Status and perspectives on 100% renewable energy systems,” Energy, vol. 175, pp. 471-480, 2019.
[4] M. Anyi, B. Kirke and S. Ali, “Remote community electrification in Sarawak, Malaysia,” Renewable Energy, vol. 35, pp. 1609-1613, 2010.
[5] Z. Jamaluddin, E. Azrulhisham, M. Azri, N. M. Zain, S. Yusoff, M. Anyi and C. Peter, “Potential of Portable Hydrokinetic Energy Turbine Design for Remote Communities in Sarawak,” Journal of Adv Research in Dynamical & Control Systems, vol. 10(9), p. 121, 2018.
[6] H. J. Vermaak, K. Kusakana and S. P. Koko, “Status of Micro-Hydrokinetic River technology in
rural applications: A review of literature,” Renewable and Sustainable Energy Reviews, vol. 29, pp. 625-633, 2014.

[7] M. I. Yuce and A. Muratoglu, “Hydrokinetic energy conversion systems: A technology status review,” Renewable and Sustainable Energy Reviews, vol. 43, pp. 72-82, 18 March 2015.

[8] N. D. Laws and B. P. Epps, “Hydrokinetic energy conversion: Technology, research, and outlook,” Renewable and Sustainable Energy Reviews, vol. 57, pp. 1245-1259, 2016.

[9] M. Khan, G. Bhuyan, M. Iqbal and J. Quaicoe, “Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review,” Applied Energy, vol. 86(10), pp. 1823-1835, 2009.

[10] A. Kumar and R. Saini, “Performance parameters of Savonius type hydrokinetic turbine – A Review,” Renewable and Sustainable Energy Reviews, vol. 64, pp. 289-310, 2016.

[11] K. A. Ismail and T. P. Batalha, “A comparative study on river hydrokinetic turbines blade profiles,” International Journal of Engineering Research and Applications, vol. 5(5), pp. 1-10, 2015.

[12] S. J. Savonius, “The S-Rotor and Its Application,” Mechanical Engineering, vol. 53(5), pp. 333-338, May 1931.

[13] F. M. White, Fluid Mechanics, McGraw-Hill, 2003.

[14] V. Patel, G. Bhat, T. I. Eldho and S. V. Prabhu, “Influence of Overlap Ratio and Aspect Ratio on the Performance of Savonius Hydrokinetic Turbine,” International Journal of Energy Research, vol. 41, pp. 829-844, 2016.

[15] S. Roy and U. K. Saha, “Wind tunnel experiments of a newly developed two-bladed Savonius-style wind turbine,” Applied Energy, vol. 137, pp. 117-125, 2015.

[16] I. Mabrouki, Z. Driss and M. S. Abid, “Performance Analysis of a Water Savonius Rotor: Effect of the Internal Overlap,” Sustainable Energy, vol. 2, no. 4, pp. 121-125, 2 July 2014.

[17] K. Golecha, T. Eldho and S. Prabhu, “Influence of the deflector plate on the performance of modified Savonius water turbine,” Applied Energy, vol. 88 (9), pp. 3207-3217, 2011.

[18] S. Mauro, S. Brusca, R. Lanzafame and M. Messina, “CFD modeling of a ducted Savonius wind turbine for the evaluation of the blockage effects on rotor performance,” Renewable Energy, vol. 141, pp. 28-39, 2019.

[19] M. Basumatary, A. Biswas and R. Misra, “CFD analysis of an innovative combined lift and drag (CLD) based modified Savonius water turbine,” Energy Conversion and Management, vol. 174, pp. 72-87, 2018.

[20] N. Thakur, A. Biswas, Y. Kumar and M. Basumatary, “CFD analysis of performance improvement of the Savonius water turbine by using an impinging jet duct design,” Chinese Journal of Chemical Engineering, vol. 27 (4), pp. 794-801, 2019.

[21] S. Roy and A. Ducoin, “Unsteady analysis on the instantaneous forces and moment arms acting on a novel Savonius-style wind turbine,” Energy Conversion and Management, vol. 121, pp. 281-296, 2016.

[22] S. Roy and U. K. Saha, “Computational study to assess the influence of overlap ratio on static torque characteristics of a vertical axis wind turbine,” Procedia Engineering, vol. 51, pp. 694-702, 2013.