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CFD Simulation of Savonius Cross-flow Hydrokinetic Turbine Using Various URANS Turbulence Models

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Abstract **-** The utilization of hydrokinetic turbine technology is an innovative and sustainable method of generating electricity through the power of flowing water. The distinct advantage of this technology over traditional hydropower plants is its ability to operate without the need for the construction of dams or large water reservoirs, which can pose significant risks to local ecosystems and communities. Instead, hydrokinetic turbines can be directly installed in waterways, allowing for a more efficient and eco-friendly use of natural resources. This technology can provide clean, reliable electricity to millions of people globally, while also reducing greenhouse gas emissions and mitigating the effects of climate change. The present study presents two-dimensional computational fluid dynamics simulation of a cross-flow hydrokinetic turbine model. The simulation is performed by various Unsteady Reynolds-Averaged-Navier-Stokes models and then the results are compared to previous experimental and mathematical models. The flow field patterns and performance parameters of different models are presented and compared to compare the validity of different turbulence models available.

Keywords**:** Cross-flow Hydrokinetic Turbine; Sustainable Renewable Energy; Environmentally Friendly Energy Harvest Systems; CFD simulation; URANS models;

1. Introduction

Renewable energy sources have been playing an increasingly significant role in global energy production in recent years, contributing around 2179 GW or approximately 34% of global installed power capacity. Hydropower is the most prominent contributor, accounting for around 1,151 GW or roughly 18% of the total capacity [1]. However, given the current climate crisis and the ever-growing global demand for electricity, it is critical to accelerate this trend and shift toward a renewable energy-dominated portfolio that significantly reduces carbon emissions within the next ten years[2]. This can be achieved by rapidly expanding the deployment of cost-effective and mature renewable energy conversion technologies such as solar, hydro, and wind turbines for utility-scale projects and markets[3]. In addition, efforts should be focused on developing new renewable energy industries and markets that can extract untapped renewable energy reserves, such as low-head hydropower and hydrokinetic power from water currents and waves, using next-generation energy conversion technologies. Studies on the opportunities for energy development in water conduits, for example, provide valuable insights into available opportunities and pave the way for accelerated development [4]. Fig. 1 illustrates a type of energy conversion system [5].

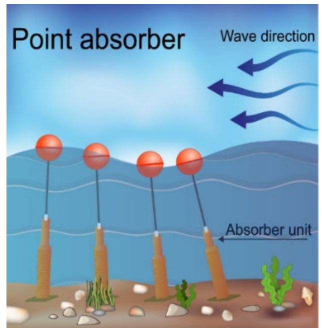


Fig. 1. A type of hydrokinetic energy conversion system. [5]

Innovative technologies have been developed in recent years, including low-head hydro technologies that can efficiently generate electricity at low heads of approximately 3 meters (9 feet) and near-zero head hydrokinetic (HK) devices, also known as current energy conversion (CEC) technologies, that can generate power without requiring local potential energy heads. According to the European Small Hydropower Association (ESHA) [6], low-head hydropower refers to electricity generation devices that can sustainably convey water at relatively low-pressure heads (up to 30 meters). HK energy, on the other hand, falls under the "zero-head" category. The conditions that create opportunities for low- to zero-head installations typically arise in various hydraulic structures such as irrigation canals, rivers, low-height dams, gauging weirs, and outflow structures. HK turbines can also be installed in canal sections where there is sufficient flow volume, velocity, and flow reliability [7]. These HK opportunities enable the exploration of new application areas and may unlock new potential in previously unexplored territories, such as flat and long river/canal sections where conventional hydropower, in the form of available potential energy, does not exist.

Simplicity, self-starting capability and omnidirectional performance are some the excellent characteristics of Savonius type hydrokinetic turbines that attract the researchers. Various efforts have been done to predict and optimize Savonius cross-flow hydrokinetic turbines performance and to investigate flow-field patterns. Dewan et al. [8] provided a comprehensive review on previous literature as well as comparison of different RANS models performance in simulation and performance prediction of Savonius turbines. They claimed that SST k-ω is the most accurate RANS model for simulation of Savonius turbines; however, they also indicated the lack of high-fidelity research simulations such as LES model within this subject. Sharma and Sharma [9] used k-ε and SST turbulence models for simulation of a Savonius rotor with multiple miniature blades layered on a water Savonius rotor. They concluded that SST model seems to be more accurate for their 3-D numerical simulation. Kumar et al. [10] also validated their 3D computational analysis of hydrokinetic Savonius turbine using RSM, SST transition, Realizable and Standard k-ε models with wind tunnel experimental results of Hayashi et al. [11]. The results illustrated that Realizable k-ε has the most reliable agreement with prior experimental data. Talukdar et al. [12] made a 2-D computational and experimental analysis of two and three-bladed Savonius water turbine which showed the supremacy of two-bladed type. They further compared semi-circular and elliptical profiles for the two-bladed rotor. They concluded that elliptical blade would result in the turbine inferior performance. It was also noted that apparently, 2D simulation seemed to fail to accurately predict the turbine's performance despite reasonable capture of flow characteristics and hence, suggested that 3D simulation can also be done to further study the proposed geometry. Table 1. summarizes the most important CFD simulations reviewed of Savonius type water turbine works for the recent years.

Table 1: Summary of numerical CFD works by different authors.

Author	Year	Method	Model	Reynolds	Blade Profile	Investigation
Rengma et al. [13]	2023	3D	Realizable k-ε	1.35 × 105	cubic Bezier curve	Blade shape optimization
Mosbahi et al. [14]	2021	3D	Realizable k-ε	-	Twisted/U-shaped/ W-shaped/ V-shaped semi-circular	Blade shape optimization
Shashikumar et al. [15]	2021	3D	SST k-ω	-	Semi-circular	Comparison of conventional and tapered Savonius water turbines
Ramadan et al. [16]	2021	2D	Realizable k-ε	1 × 105	Semi-circular/modified	Effect of blade profile and deflectors
Song et al. [17]	2021	2D	Realizable k-ε	-	Semi-circular/Benesh/modified Benesh/ elliptical/modified elliptical	Effect of blade profile and wave flume on performance
Chaudhari and Shah [18]	2023	3D	SST k-ω	2.5 × 105	NACA6409	Savonius turbine with airfoil blades and effect of deflector

Choosing a specific URANS model depends on factors such as flow characteristics, available computational resources, and desired level of accuracy. Each model has its strengths and weaknesses in capturing different aspects of turbulent flows. Conducting sensitivity analyses or validation studies can help determine the most suitable model for simulating a hydrokinetic turbine under specific operating conditions. The purpose of present study is to simulate a vertical axis cross-flow hydrokinetic turbine using different turbulence models, and compare and validate the modelling with performance parameters of previous literature experimental results; then output flow patterns are brought and discussed in details to justify the accuracy of models and compare the output resolutions.

2. Numerical Methodology

In this study, the Navier-Stokes equations have been solved with the commercial CFD software ANSYS FLUENT 2022 R2. The code is based on solving governing equations with a finite volume discretization technique. This method is a very popular and easier to implement for unstructured meshes.

No single turbulence model is universally accepted as being superior for all classes of problems. The choice of turbulence model will depend on considerations such as the physics encompassed in the flow, the established practice for a specific class of problem, the level of accuracy required, the available computational resources, and the amount of time available for the simulation.[19] For the present numerical modelling, four commercially available fluent models are investigated to be compared within the present investigation: SST k-ω, Reynolds Stress-omega Model (RSM), Spalart-Allmaras (SA) and Transition SST model.

2.1. Parameter Definition

- Maximum available power:

The maximum available power contained in free-flowing water streams can be calculated based on the following equation:

$$P_{max} = \frac{1}{2}\rho A V^3 \quad (1)$$

Where P_{max} is maximum available power (W), is the water density (kg/m3), A is the swept area of the turbine (m^2), and V is the freestream water velocity (m/s). For a vertical-axis hydrokinetic turbine, the swept area A= D × H where D and H is the diameter and height of the turbine (m) respectively.

- Extracted mechanical power:

On the other hand, the mechanical power extracted by the turbine is given by:

$$P_{rotor} = T\omega \quad (2)$$

Where P_{rotor} is the mechanical power extracted by the turbine (W), T is the torque generated by the turbine (Nm), and is the angular velocity of the turbine (rad/s).

- Coefficient of power:

Since the continuity of the streaming water moving past the turbine rotor needs to be preserved, added with some losses in the process of energy conversion, only a fraction of the kinetic energy can be extracted by the turbine. This measure of turbine performance is quantified through the coefficient of power, C_P, which is the ratio between the extracted and available power, expressed as:

$$C_P = \frac{P_{rotor}}{P_{max}} \quad (3)$$

- Coefficient of torque:

In addition to the C_P, another measure of the turbine performance is the coefficient of torque (C_T), given as the ratio of the torque generated by the turbine rotor to the maximum available torque:

$$C_T = \frac{T}{\frac{1}{4}\rho D^2 H V^2} \quad (4)$$

The functional relationship between C_P and C_T, reduced from all the equations above, is:

$$C_P = C_T \times \text{TSR} \quad (5)$$

- Tip-speed ratio:

The C_P of the turbine depends on its tip-speed ratio (TSR, or λ), i.e., the ratio of the tip velocity of its rotor blades to the freestream velocity of the water, given as:

$$\mathrm{TSR} = \frac{\omega D}{2V} \quad (6)$$

- Angular velocity:

The ω is obtained by converting the rotational speed of the turbine model to revolutions per minute, RPM as follows:

$$\omega = \frac{2\pi}{60} \times RPM \quad (7)$$

- Aspect ratio:

Aspect ratio is the ratio of height to diameter of the turbine.

$$\mathrm{AR} = \frac{H}{D} \quad (8)$$

2.2. Geometry and Boundary Conditions

Fig. 2 depicts two domains which are detached by a sliding region created by means of ANSYS Design Modeler in ANSYS 2022 R2. The modeled turbine is a typical two bladed Savonius hydrokinetic turbine with semi-circular blades. The geometry of the turbine is obtained from previous experimental literature [12].

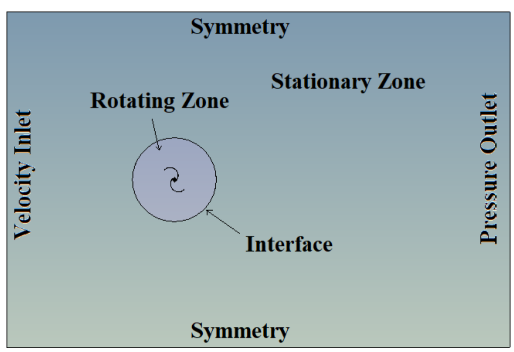


Fig. 2. Turbine geometry used for current investigation.

2.3. Meshing

In this research, the complexity of the geometry necessitated the use of a combination of quadrilateral elements for the stationary zone and triangular meshes for the rotating zone. ANSYS meshing interface was employed. To accurately represent the rotating domain, a finer mesh was utilized compared to that used for the fixed domain. Figure 3 illustrates 25 inflation layers applied to the rotor blades with a growth rate of 1.2. This specific choice aimed to capture rapid variations in velocity, pressure, and vorticity around the rotor. To ensure accuracy in computational analysis, it is important to consider non-dimensional wall distance (y+). In this study, maintaining a y+ value below 1 was crucial. Higher values can lead to decreased accuracy as they prevent proper determination of boundary layer behavior using ANSYS-prescribed wall functions. Furthermore, to enhance credibility and reliability, it is worth noting that an independent finding demonstrating mesh independence has been reported as part of this study.

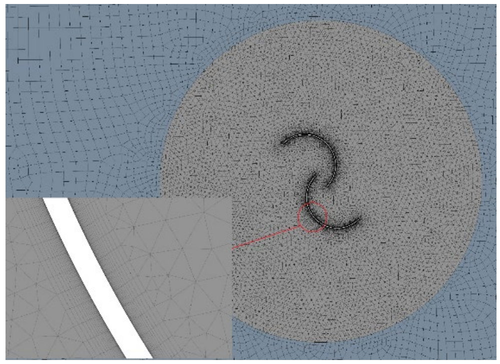


Fig. 3. The meshing used for the studied model.

3. Numerical Results

3.1. Mesh sensitivity analysis

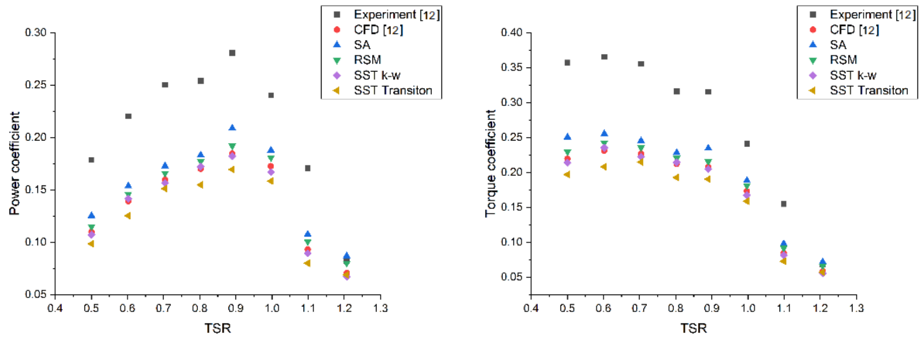
In order to assess the impact of mesh resolution on rotor performance and flow characteristics around a delta bladed rotor, a two-dimensional transient analysis was conducted. The objective was to achieve grid independence by employing three different meshes: M1, M2, and M3. These meshes consisted of approximately 90,000 nodes, 233,000 nodes, and 275,000 nodes respectively. Table 2 presents the results obtained for the power coefficient of the rotor at a tip speed ratio (TSR) of 0.89 - which corresponds to the maximum power coefficient value. Upon examining Table 2, it becomes evident that meshing configurations M2 and M3 display acceptable accuracy range with each other. Consequently, it was determined that mesh configuration M2 should be adopted moving forward due to its negligible deviation with M3 which has the highest number of mesh elements.

Table. 2: The effect of grid size on turbine performance.

Grid Size	% Cp deviation from maximum element
90,000	15%
233,000	2%
275,000	0%

3.2. Validation of CFD results and Performance Characteristics

Unsteady simulations were conducted in this study to gain a deeper understanding of the water flow dynamics for turbines using different turbulence models. From Figs. 4 (a) and (b), it is observed that both Ct vs TSR and Cp vs TSR diagrams pursue similar trend for all the utilized URANS models. Moreover, the SHT demonstrates the maximum coefficient of power equal to 0.209, 0.192, 0.182 and 0.170 for Spalart-Allmaras, RSM, SST k-ω and SST Transition models respectively at TSR = 0.89. These values confirm the findings of contours presented in next sections that Spalart-Allmaras and RSM models predict close performance to each other which are slightly higher than the predicted performance values of SST k-ω and SST Transition models. Compared to the experimental results, despite that in this study Spalart-Allmaras model performance prediction is comparatively more accurate, all models still have deviation from experimental data. This difference is already justified by Talukdar et al. [12] attributed to factors not accounted for in CFD simulations such as dimensionality effects or other uncertainties associated with experimental measurements.

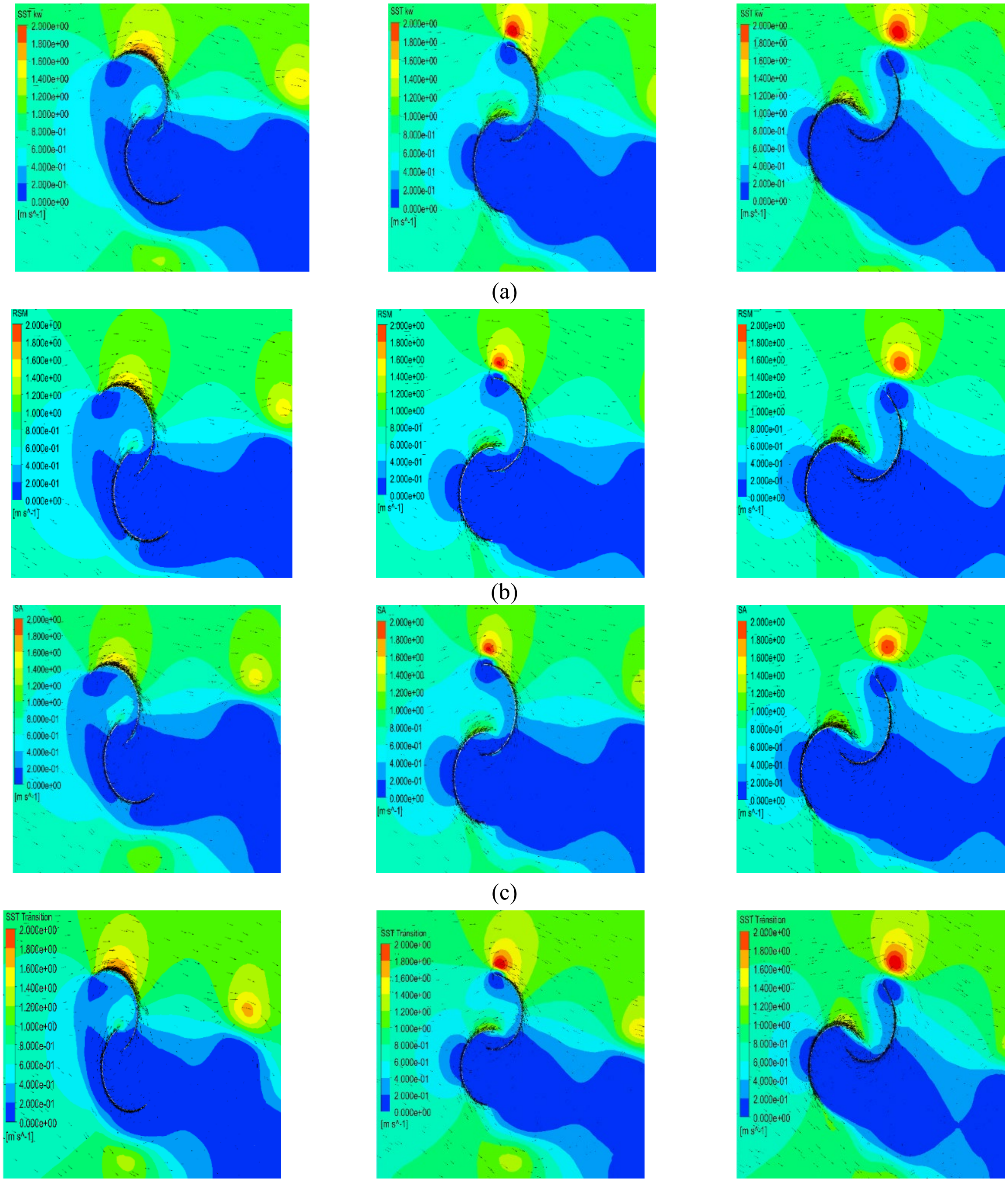


(a) (b)

Fig. 4. Comparison of performance coefficients predicted by the utilized models (a) Coefficient of Power (b) Coefficient of Torque

3.3. Velocity Magnitude

Figure 5 presents velocity contour plots for different turbulence models at the same turbine tip speed ratio (TSR = 0.89) and various angular positions. For turbines modelled with SST Transition and SST k-ω models, relatively higher aggravated sharp streams of velocity vectors are predicted to depart from the tip of the advancing blade, which ultimately leads to decline in performance prediction as observed at θ = 90° and 135°. This streamline pattern indicates lesser momentum exchange between water stream and rotor blades—a phenomenon that has been reported by Sarma et al. [20].



(a)

(b)

(c)

(d)

Fig. 5. Velocity vector flow field for (a) SST k-ω model (b) RSM model (c) Spalart-Allmaras model (d) SST Transition model

4. Conclusion

Savonius wind/hydrokinetic turbines have emerged as promising renewable energy converters, offering the advantage of generating electricity at low cost and with reduced environmental impacts. These turbines hold promise for decentralized energy generation, providing a viable solution for locations where traditional power sources may be limited or unavailable. The evaluation of the turbine's performance through various modelling approaches allows for a comprehensive analysis of its efficiency and effectiveness in harnessing renewable energy resources. Recognizing their potential, a model Savonius turbine was developed and its performance was evaluated using four different 2D URANS (Reynolds-Averaged Navier-Stokes) models under similar operating conditions by using ANSYS FLUENT software. Firstly, the created model was validated by previous experimental and numerical literature. After validating the model, four URANS models namely, SST k-ω, RSM, Spalart-Allmaras and SST Transition models were utilized to investigate and compare the performance prediction of the selected models in simulation of hydrokinetic turbines. The results indicated that SST k-ω and SST Transition models predict similar performance and flow patterns. RSM and Spalart-Allmaras models however, while showing similarities together, predict higher performance compared to the latter pair models. Note that, in this specific investigation Spalart-Allmaras, showed an unexpectedly higher accuracy compared to other models despite its simplicity. Despite what mentioned earlier, the utilized models have also similarities. All the models predict similar trends for both Cp and Ct vs TSR values. While the present investigation covered the crucial content for understanding these effects, 3D CFD simulations can also be utilized in future research in order to better understand the flow physics explained by these models and justify the output performance predictions. Considering the prediction accuracy, both 2D and 3D can be followed to arrive at a mutual conclusion.

Acknowledgements

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