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ENHANCING SAVONIUS ROTOR MODEL WITH ADDITIONAL GROOVES ON HYDROKINETIC TURBINE PERFORMANCE

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Hydrokinetic turbines use different rotors for technological and economic reasons. Even though it performs poorly, vertical-axis hydrokinetic turbines use the Savonius rotor. The object of research is a Savonius rotor model with additional grooves. The study addresses the need to improve the efficiency and overall performance of Savonius rotor models in hydrokinetic turbines, which are widely used for harnessing energy from flowing water currents. The problem involves understanding how different groove configurations affect the aerodynamic behavior and energy extraction efficiency of the Savonius rotor in hydrokinetic turbine applications. The test results revealed that incorporating grooves led to notable improvements in efficiency (η) and coefficient of drag (CD). Grooved blades exhibited a maximum efficiency of 30.97 % and a maximum drag coefficient of 2.71. Notably, blades with a groove width of 12.5 mm emerged as the optimal model, demonstrating an efficiency peak of 35.66 % and a drag coefficient 3.08. This indicates a substantial increase in efficiency by 4.69 % and a corresponding rise in the drag coefficient by 0.37 for grooved blades. The grooves on grooved blades increase friction, improving performance. Grooved rotor blades improve turbine performance significantly. Savonius rotor models in hydrokinetic turbines extract more energy by optimizing groove width and arrangement to maximize drag coefficient and efficiency. This research affects hydrokinetic turbine design and optimization for renewable energy generation. Engineers and designers can improve the performance and efficiency of the Savonius rotor model in hydrokinetic turbine applications by applying this study's findings

Keywords: hydrokinetic turbine, Savonius rotor, grooved blade, drag coefficient, tip speed ratio

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1. Introduction

Hydropower is a promising and environmentally friendly renewable energy source, offering a sustainable alternative to traditional fossil fuel and nuclear power plants [1–3]. One innovative method of converting water into energy is hydrokinetic energy technologies, most notably the installation of hydrokinetic turbines [4, 5]. These turbines, also called water current turbines, are sophisticated electromechanical devices designed to convert the kinetic energy in flowing water currents into electricity. One of the critical advantages of hydrokinetic turbines is their ability to generate electricity efficiently, even at low speeds and heads, showcasing their remarkable potential for electricity generation in diverse aquatic environments [5]. This capability makes them particularly suitable for locations where traditional hydropower technologies may not be feasible due to lower water velocities or limited hydraulic heads.

Hydrokinetic turbines are classified into two main categories based on the orientation of the rotor shaft relative to the flow direction: vertical and horizontal shaft hydrokinetic turbines [5, 6]. Each category encompasses various turbine designs with unique characteristics and suitability for different applications. Several notable types of vertical shaft hydrokinetic turbines are commonly used, including the Savonius, Troposkein Darrieus, H-Darrieus, and Gorlov turbines [7, 8]. The Savonius turbine, in particular, is widely recognized for its simplicity in construction and cost-effectiveness in installation and maintenance, making it a preferred choice for small-scale power generation projects [4, 8, 9]. Despite its ease of installation and maintenance advantages, the Savonius turbine's performance is typically lower than other types. However, its suitability for small-scale applications, relatively straightforward design, and cost-effectiveness make it a practical choice for specific hydrokinetic energy projects, especially in regions with limited resources and infrastructure for large-scale installations.

Over time, experts and practitioners have dedicated efforts to enhance the performance characteristics of the Savonius rotor through various design optimizations and adjustments to crucial parameters [6]. These refinements aim to maximize rotor efficiency and energy output, thereby improving the overall effectiveness of Savonius turbines in harnessing hydrokinetic energy. Several parameters play crucial roles in shaping the performance of the Savonius rotor, including aspect ratio (AR), overlap ratio (OR), blade number and configuration, levels and end plates, flow directors or deflectors, shaft design, blade models and shapes [10, 11].

The Savonius rotor uses the difference in drag forces encountered by its concave and convex surfaces as the blades revolve to generate rotational power. Optimizing rotor performance requires understanding drag force characteristics. The blade surface drag force is caused by two main factors: fluid viscosity and pressure distribution. The drag force along the blade is mainly affected by the geometry of the fluid-interacting surface, the distance from the axis of rotation, and the Reynolds number [12]. Reynolds number greatly impacts the flow regime around the blade and the pressure coefficient. The pressure coefficient, which describes pressure distribution along the blade surface, is vital to understanding the Savonius rotor's aerodynamic performance. This coefficient depends on blade shape, angle of attack, and Reynolds number. By analyzing these aspects, researchers and engineers optimize the Savonius rotor design to maximize efficiency and power generation [13].

Savonius turbines are still studied for hydrokinetic energy generation. Savonius turbine performance is affected by many factors, including rotor grooves. Research is ongoing to thoroughly analyze the impact of extra grooves on hydrokinetic turbine Savonius motor performance, demonstrating their continued relevance. Enhancing turbine performance with grooves on the Savonius rotor surface is nuanced. These grooves alter airflow patterns, pressure differentials, and aerodynamic losses. Researchers hope grooves on the rotor will improve the turbine's aerodynamics and power generation. Therefore, research on the effect of additional grooves on the performance of hydrokinetic turbine Sarvonius motors is still relevant.

2. Literature review and problem statement

The Savonius-type hydrokinetic turbine has become a promising solution for small-scale power generation, especially in river flows or artificial channels. It has shown significant potential for electricity production [4, 10]. The appeal of this option stems from various factors contributing to its popularity among small-scale power plants. These factors include straightforward and cost-effective construction, ease of installation and maintenance, clean energy sources, predictable potential, and favorable initial characteristics [2, 14]. Compared to other vertical axis hydrokinetic rotors, Savonius-type rotors excel at harnessing energy from low-speed water flows [5]. Their adaptability makes them great for use in environments with lower water velocities, such as rivers, canals, or tidal channels. This expands their usefulness for small-scale power generation projects.

The paper [6] carefully analyzes the performance of a single-stage modified Savonius hydrokinetic turbine with twisted blades. The study improved the understanding of turbine efficiency and functionality. The research shows that twisted blades boost Savonius turbine performance. Even while progress has been achieved, some turbine performance questions remain. Unresolved issues may arise from objective difficulties related to the complexity of fluid dynamics involved in turbine operation, the impossibility of achieving optimal blade configurations due to design constraints, or the high cost of implementing certain turbine design modifications, making research efforts impractical. Similar studies or approaches in comparable domains may help solve these issues. For instance, it may help answer unanswered questions and improve performance analysis of modified Savonius hydrokinetic turbines with twisted blades. However, it is crucial to recognize any limits or differences in existing methodologies and adapt them to the current study.

The study [10] on the design, testing, and numerical simulation of a low-speed horizontal axis hydrokinetic turbine covers its development and performance evaluation. The study proves horizontal axis turbines can harness low-speed water currents through practical testing and computer calculations. Additionally, the research illuminates turbine performance-affecting design and operational aspects. Even though this study progressed, the design and operation of low-speed horizontal axis hydrokinetic turbines remain unsolved. Achieving good efficiency and power output at low water flow velocities is a significant problem. Minimal-speed water currents have minimal kinetic energy. Therefore, turbine performance requires inventive design and operation. Optimizing low-speed horizontal axis turbine blade geometry and rotor arrangement is another unanswered subject. Designing blades that absorb energy from low-velocity flows while minimizing drag and structural loads is difficult. The turbine-environment interaction, including sediment movement and biofouling, provides issues that need additional study. Traditional design and numerical modeling methods cannot accurately forecast low-speed hydrokinetic turbine performance, which is the main obstacle. Conventional approaches may not capture the complicated fluid dynamics and turbulent movement of low-speed water currents.

The paper [15] shows that the correct shape of thick blades for a hydraulic Savonius turbine affects turbine performance. The study revealed how blade thickness affects power-generating efficiency and structural integrity. Despite the excellent insights provided, the best design parameters for thick blades in Savonius turbines remain unanswered. One cause for these unanswered questions may be the objective challenges of balancing blade thickness, structural strength, and aerodynamic performance. The complicated interaction of these factors makes it difficult to establish a blade design that maximizes power output and turbine durability under varied operating situations. The design process is further complicated by the inability to optimize numerous conflicting goals, such as lift and drag. The turbine design may also use expensive components or materials, making research uneconomical. Researchers could use creative design methods and computational modeling to understand thick-bladed Savonius turbine performance better. Inspiration from related industries or advanced optimization algorithms like genetic algorithms or machine learning could assist in exploring a larger design space and finding blade forms that balance competing criteria.

The research [16] on axial rectangular grooves and turbulent Taylor-Couette flow sheds light on how groove geometry affects flow and turbulence. Experimental evidence shows that axial rectangular grooves change flow dynamics, turbulence intensity, flow structure, and nixing efficiency. Despite this study's advances, the optimal design and layout of axial rectangular grooves for turbulent Taylor-Couette flow remains unsolved. Controlling and altering flow properties through groove geometry is a significant task. Changing flow while minimizing energy losses and maintaining system stability is challenging. The scalability and generalizability of experimental findings are another unanswered subject. Extrapolating the results to other flow regimes or configurations may be difficult due to the study's experimental settings and geometrical characteristics. The complexity of turbulent flows and the multiphysical phenomena of Taylor-Couette systems make it impossible. The relationship between fluid velocity, turbulence, and wall geometry is complex, making it challenging to create theoretical models or predictive frameworks that capture all critical events.

The paper [17] examines how overlap and gap ratios affect hydraulic Savonius turbine efficiency and power production. Experimental testing and analysis show that optimizing flow patterns and decreasing energy losses by altering specific geometric characteristics can boost turbine performance. This study improved Savonius turbine configuration and operational parameters, although there are still questions. Effectively forecasting the intricate aerodynamic interactions between the rotor blades, overlap, gap ratios, and fluid flow is a major task. Optimization of overlap and gap ratios while balancing drag reduction and power extraction is difficult. Another unanswered concern is experimental data scalability and generalizability. Extrapolating the results to different turbine sizes or flow regimes may be difficult due to the study's design and operating conditions. The main obstacles are the complexity of flow phenomena and multiphysical interactions in Savonius turbine operation. Fluid dynamics, rotor shape, and operational parameters are intricately coupled, making it difficult to create comprehensive theoretical models or predictive frameworks that capture all important events.

In reference [18], bowl-bladed hydrokinetic turbines with additional steering blade numerical modeling demonstrate how steering blades can improve performance and maneuverability. Numerical modeling shows that this design adjustment improves turbine efficiency and power extraction from flowing water currents. This work improved the practicality and scalability of bowl-bladed hydrokinetic turbines with additional steering blades, but many problems remain. Simulating the complex fluid-structure interactions and hydrodynamic forces experienced by turbine components under different flow conditions effectively is a major problem. Creating a numerical model that effectively depicts the steering blades' dynamic behavior and interaction with the main rotor blades is difficult. Another unanswered topic is how to design and operate bowl-bladed hydrokinetic turbines with steering blades to maximize performance. Numerical simulations can provide flow dynamics and performance measures, but real-world validation is needed to prove the design's efficacy and practicality. The intricacy of fluid-structure interaction problems and the computer resources required to accurately model bowl-bladed hydrokinetic turbines with guiding blades make it impossible. Developing a strong and trustworthy numerical model for the dynamic interplay between numerous blades, fluid flow, and complicated flow phenomena, including vortex shedding and blade cavitation, is computationally difficult.

Prior studies have examined different facets within hydrokinetic turbines, including the refinement of blade shape, the optimization of turbine geometry, and the utilization of CFD simulations for Savonius rotors. Nevertheless, there is a notable absence of thorough investigation in the current literature regarding incorporating grooves into Savonius rotors. Thus, the research involved varying the groove widths on the Savonius rotor to assess their impact. Examining the effect of grooves on blade performance is a suitable approach to enhance the efficiency of the Savonius rotor. This can be achieved by augmenting the drag disparity between the forward and reverse blades.

3. The aim and objectives of the study

The aim of the study is to enhance the performance of the Savonius rotor by increasing the difference in drag force that acts between the forward blades and the return blades.

To achieve this aim, the following objectives are accomplished:

– to obtain the efficiency value on the Savonius rotor blade in several groove widths;

– to increase the drag coefficient value on the Savonius rotor blade in several groove widths.

4. Materials and methods of experiment

4.1. Object and hypothesis of the study

The object of research is a Savonius rotor model with additional grooves. The study's main hypothesis is that integrating additional grooves on a Savonius turbine's rotor blades will improve turbine performance metrics such as efficiency, drag coefficient, tip speed ratio (TSR), and energy extraction capabilities. Specifically, the hypothesis posits that introducing grooves on the rotor blades will enhance fluid flow dynamics, increasing drag forces and improving energy conversion efficiency. Additionally, it is hypothesized that the optimized blade design with grooves will lead to a higher TSR and overall better performance of the hydrokinetic turbine, ultimately contributing to enhanced renewable energy generation capabilities. The study aims to validate this hypothesis through experimental testing and numerical simulations and provide empirical evidence supporting the effectiveness of integrating grooves on the Savonius rotor model to enhance hydrokinetic turbine performance.

The study assumes that the flow conditions during experimental testing and numerical simulations remain constant throughout the investigation. This assumption simplifies the analysis by ignoring temporary flow phenomena. The experiment considers that the fluid properties, such as density and viscosity, remain consistent throughout the testing period. This simplifying assumption allows for a more in-depth examination of the fluid-structure interaction and turbine performance, disregarding any changes in fluid properties. The study suggests an idealized rotor design with consistent blade geometry and material properties. Although this simplification streamlines the analysis, it might not encompass all the intricacies of turbine designs in the real world.

4.2. Materials

The test model consists of a grooveless and grooved two-blade Savonius rotor made from PVC material. Its purpose is to evaluate the effect of grooves on turbine performance. The rotor's dimensions are precisely specified, with a diameter of 180 mm and a height of 184 mm, resulting in an aspect ratio (AR) of 1.02. A 200 mm diameter end plate with a 2 mm thickness is included in the design to improve the structural integrity and optimize the flow patterns around the rotor. The shaft, which is essential for the rotation of the rotor, has a diameter of 8 mm and is meticulously designed to have no overlap (OR=0). Fig. 1 shows the isometry of the 8-groove blade model. This design choice enhances the simplicity and efficiency of the rotor configuration. The selection of PVC material provides a harmonious combination of long-lasting properties and simplicity in construction, rendering it well-suited for experimental testing and analysis. The careful consideration of dimensions, such as the aspect ratio and lack of overlap, is intended to attain peak performance and accurately capture the intricacies of the Savonius rotor's behavior.

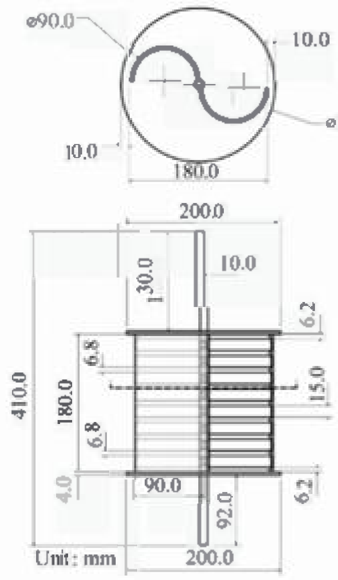


Fig. 1. Isometry of the 8-groove blade model

The groove geometry consists of four square directions perpendicular to the groove width axis. These directions provide a variety of dimensions to investigate to find the most optimal configuration. The groove widths exhibit a systematic variation, encompassing 5 mm, 7.5 mm, 10 mm, 12.5 mm, 15 mm, and 17.5 mm. This diverse range of parameters allows for an in-depth exploration of the impact of groove size on turbine performance. The depth of each groove on the concave side is meticulously maintained at 4 mm, resulting in eight unique groove configurations.

This systematic approach to groove geometry enables a thorough investigation into how groove dimensions affect the performance of the Savonius rotor. Through the manipulation of groove width, researchers can evaluate the impact of various fluid dynamics and boundary layer interactions on drag force, efficiency, and the overall operation of the turbine. In addition, the grooves are consistently deep, which promotes uniformity across all configurations. This allows for accurate comparisons and reliable experimental results. By carefully designing and constructing the groove geometry, this study seeks to uncover the most effective groove configuration for improving the performance of the Savonius rotor. Researchers can systematically test various groove widths to determine the optimal design parameters to enhance energy extraction efficiency and turbine performance in hydrokinetic applications.

4.3. Experimental setup

The experimental test was carried out in an irrigation channel that measures 150 cm wide and 100 cm high. The testing environment is spacious, and the flow control is reliable, thanks to a well-designed gate. This setup guarantees a reliable and regulated flow environment for precise data collection and analysis. Detailed observations and measurements were carefully conducted across various levels of loads, considering both independent and dependent variables. The loads varied from 0kg to 2.5 kg, increasing by 0.5 kg. This systematic approach facilitated the achievement of multiple levels of consistent rotation, explicitly focusing on rotational speeds of 60 rpm. The rotational speeds were meticulously chosen to encompass a wide range of operational conditions and to offer a thorough comprehension of the turbine's performance under different load scenarios.

Fig. 2 depicts a blade configuration with eight grooves. The widths of the grooves range from 0 mm to 17.5 mm, increasing in intervals of 2.5 mm. This visual representation accurately portrays the groove widths on the blade surface, enabling a thorough comprehension of the variations in groove dimensions used in the experimental setup. The 8-grooved blade design plays a crucial role in studying the impact of groove width on the performance of the Savonius rotor. Through a systematic alteration of the groove width, researchers can evaluate the impact of changes in groove dimensions on the aerodynamic characteristics, drag coefficient, and overall efficiency of the Savonius rotor.

Fig. 2. Eight-grooved blade – 0 mm to 17.5 mm wide

The desired loads were imposed by applying braking load variations using a string-pulling lever mounted on the support frame, as shown in Fig.3. This configuration enabled accurate control and fine-tuning of the loads applied to the turbine, guaranteeing uniformity and consistency during the experimental testing. Researchers collected comprehensive data on the turbine's performance across various operating conditions by systematically adjusting the loads and closely observing the resulting rotational speeds. In this study, the experimental setup and methodology allow for thorough testing and in-depth analysis of the performance of the Savonius turbine when grooves are added. By carefully varying loads and rotational speeds, a comprehensive analysis of the turbine's operational characteristics is conducted, yielding valuable insights into the impact of groove modifications on enhancing turbine performance.

The variety of groove widths used in the experimental analysis of the Savonius rotor is summarized in Table 1. A total of seven different configurations are available, each with a different groove width variation, all to investigate how different groove diameters affect rotor performance. A rotor arrangement without grooves is used as a baseline to start the testing methodology. The next step is to gradually add grooves that are 2.5 mm wide and extend from 5 mm to 17.5 mm in length (Fig. 2).

Fig. 3. Set up of the experimental model and instruments on the frame

Table 1

Groove width parameters on the Savonius rotor

No.	Groove width (mm)	Rotation speed (rpm)
1	0	60
2	5	
3	7.5	
4	10	
5	12.5	
6	15	
7	17.5	

A consistent rotational speed of 60 rpm was applied to each groove width configuration on the Savonius rotor. The standardized rotational speed was intentionally selected to ensure a uniform testing parameter for all groove width variations. The researchers experimented by maintaining a consistent rotational speed. This allowed them to focus solely on the impact of groove width variations on the drag coefficient and efficiency of the Savonius rotor. Consistently maintaining a fixed rotational speed of 60 rpm throughout the experimentation process allows for accurate analysis of the variations in groove width, as any observed differences in drag coefficient and efficiency can be directly attributed to this factor. In this controlled experimental setup, we can closely examine the impact of changes in groove width on the aerodynamic performance and overall efficiency of the Savonius rotor. The consistent operating conditions ensure accurate analysis of the results.

4. 4. Methods and testing

Several experiments were carried out in a wind tunnel to obtain parameter values for the drag force (FD) and drag coefficient (CD) to validate and guarantee the relevance of the model performance results (Fig. 4). As part of these experiments, the turbine was subjected to a series of incremental constant speeds ranging from 3 m/s to 9 m/s while altering the rotation angles of its blades at 0, 15, 30, and 45 degrees. These wind speeds and rotation angles were selected to replicate real-world operational circumstances. The aerodynamic behavior of the turbine blades can be better understood if researchers test it at various rotation angles and see how it performs relative to the incoming flow.

a *b*

Fig. 4. Savonius rotor blade testing: *a* – wind tunnel; *b* – model position in the wind tunnel

Experiments were carried out to measure the drag force and drag coefficient produced by the model in a controlled wind tunnel setting (Fig. 4, *a*). To guarantee the accuracy and consistency of these observations across experiments using different working fluids, the concept of similarity, precisely the Reynolds number (Re), was used as a reference parameter [19]. The Reynolds number is a dimensionless quantity that helps determine the flow regime of a fluid. It considers factors like fluid density, viscosity, and velocity. By ensuring a consistent Reynolds number across experiments conducted with different working fluids, researchers can guarantee similarity in flow characteristics and enable meaningful comparisons between results obtained in water and air environments.

The exact adjustment of the wind tunnel's airspeed to match the Reynolds number measured while testing with irrigation canal water flow was necessary to accomplish this resemblance. This adjustment guarantees that the flow conditions within the wind tunnel closely resemble those observed in real-world water flow scenarios, allowing for precise comparisons of drag force and drag coefficient across various fluid environments (Fig. 4, *b*). After careful analysis, it was concluded that the ideal constant speed input level for the wind tunnel experiments falls between 3 m/s and 9 m/s. This range represents Reynolds numbers within the specified range of 0.34×10^5 to 1.01×10^5. This ensures that the flow conditions remain consistent and allows for meaningful comparisons between experimental results obtained using water and air as working fluids.

In addition, the range of constant speeds was carefully selected to match the Reynolds number (Re) values shown in the irrigation canal testing. For consistency and accurate data analysis, Reynolds numbers were carefully matched between wind tunnel testing and canal trials. The model performance findings derived from the experimental testing carried out in the irrigation canals are validated by these wind tunnel tests, an essential validation step. Researchers can make their findings more credible and applicable by conducting independent testing in a controlled wind tunnel.

5. Results of the experiment of adding grooves to the Savonius rotor

5.1. Results of the efficiency value on the Savonius rotor blade in several groove widths

The model characteristics are explained concerning three important parameters: flow rate (*Q*), tip speed ratio (*TSR*), and efficiency (η). Fig. 5 visually illustrates a comparative analysis of these characteristics, specifically examining the impact of flow rate on efficiency while maintaining a constant rotational speed of 60 rpm. It is clear that the blade without grooves has a higher flow rate compared to other models, but it has lower efficiency. To achieve maximum efficiency, the blade without grooves (0 grooves) requires a flow rate of 0.0181 m^3/s. This results in an efficiency of 30.96 % at 60 rpm. On the other hand, the model that achieves a rotation of 60 rpm with the smallest flow rate has a groove width of 12.5 mm.

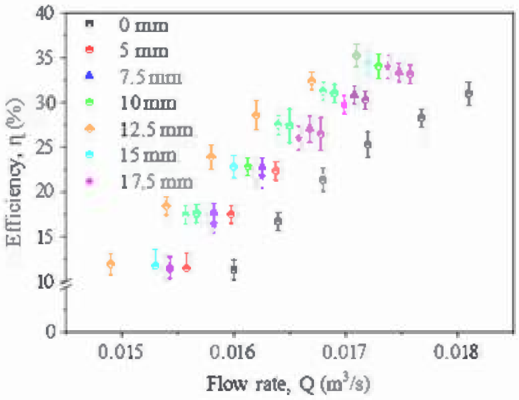


Fig. 5. Graph of flow rate vs efficiency at several variations in blade width

This graphical representation provides valuable insights into the correlation between flow rate, rotational speed, and efficiency for various groove configurations. The text emphasizes the importance of considering trade-offs, as a higher flow rate does not always lead to improved efficiency, especially without groove modifications. In addition, the data highlights the potential to enhance efficiency by strategically modifying groove dimensions. This is demonstrated by the model that achieved a rotation speed of 60 rpm and the smallest flow rate requirement when the groove width was set at 12.5 mm.

Fig. 6 presents a graph that showcases the relationship between the Tip Speed Ratio (TSR) and the efficiency of the Savonius rotor. The highest TSR attained by a blade lacking grooves is documented as 1.18. TSR is a crucial factor that measures the relationship between the angular rotation speed (ω) and the flow speed (V), giving us valuable information about the rotor's efficiency in different operating conditions. By carefully examining the consistent rotation (*n*) at various levels, it becomes clear that the flow velocity factor plays a crucial role in causing variations in TSR. More specifically, models with smaller TSR values achieve this by employing higher flow velocities. This relationship emphasizes the complex interaction between rotational speed, flow velocity, and TSR, stressing the need to optimize these parameters for optimal rotor efficiency.

The model with a groove width of 12.5 mm is remarkable, achieving an optimal TSR of 1.26 and an efficiency peak of 35.66 %. This observation highlights the importance of groove dimensions in determining the performance of the Savonius rotor. Among the different models, the configuration with a groove width of 12.5 mm exhibits higher efficiency and TSR.

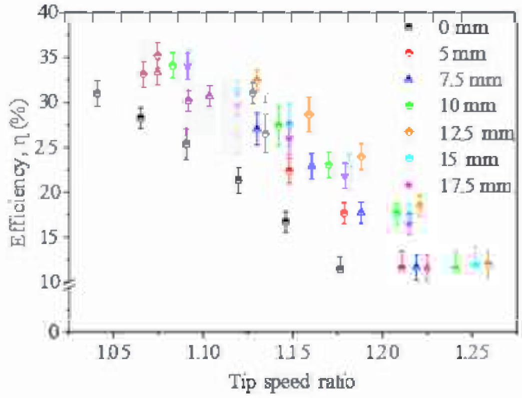


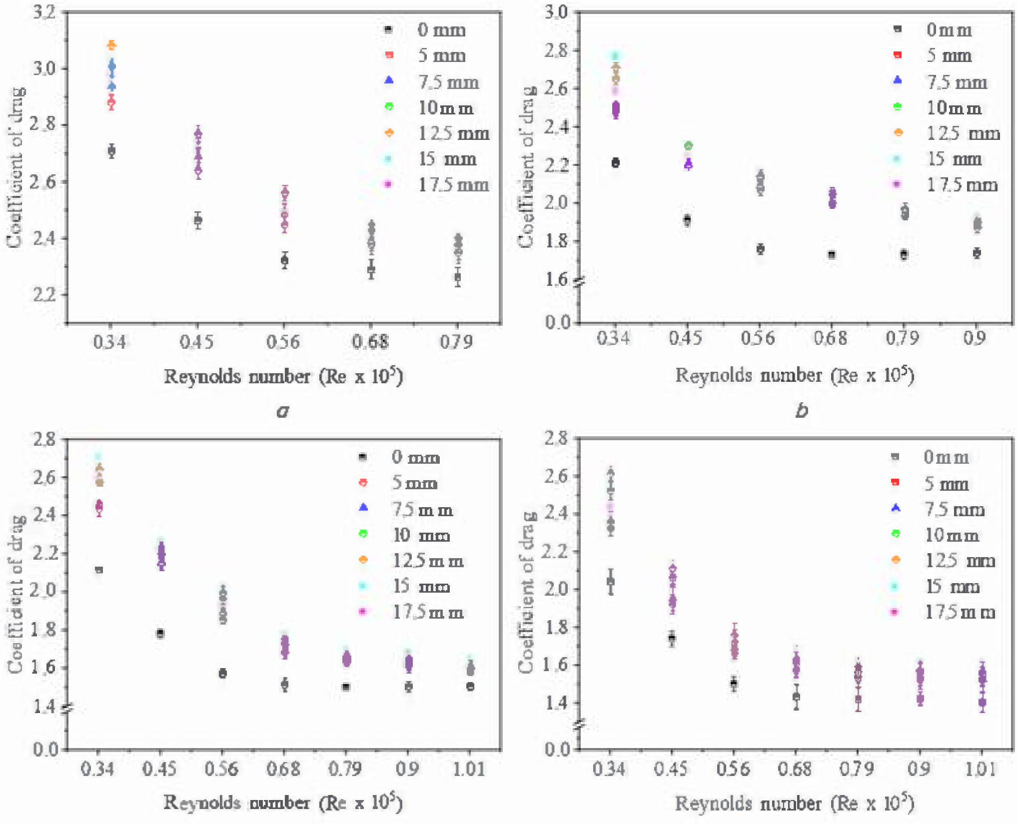
Fig. 6. Graph of tip speed ratio vs efficiency at several variations in blade width

5.2. Results of the drag coefficient value on the Savonius rotor blade in several groove widths

Reynolds number and drag coefficient are compared across several Savonius rotor model rotation angles in Fig. 7. The impact of grooves on the blade's surface and the rotor's aerodynamic performance in different settings can be better understood by comparing and contrasting the two. Looking at Fig. 7, *a*, it's clear that the grooved blade model always has a higher drag coefficient than the one without grooves, regardless of the turning angle at 90°. Generally, blades with grooves produce more significant drag coefficients, as this data shows that groove presence affects drag coefficient.

Among the configurations that generate the highest drag coefficients, the one with a width of 12.5 mm stands out with a value of 3.081. At the lowest Reynolds number (0.34×10^5), on the other hand, the blade devoid of grooves reaches its maximum drag coefficient of 2.71. The aerodynamic performance of the Savonius rotor is greatly affected by the width and shape of its grooves, as these data demonstrate. Grooves on the blade's surface increase the drag coefficient, which helps improve the efficiency of energy extraction. The trend also shows that the Reynolds number is a key factor in the drag coefficient and that changes in flow conditions impact the rotor's aerodynamic behavior.

In addition, a turning angle of 75° (as shown in Fig. 7, *b*) reveals exciting findings about the drag coefficient. It is worth noting that a blade with a width of 15 mm demonstrates the highest drag coefficient, which reaches a value of 2.77. The maximum drag coefficient is attained at the lowest recorded Reynolds number value of 0.34×10^5. On the other hand, the blade without grooves shows the lowest drag coefficient, measuring at 1.73, which happens at a Reynolds number of 0.79×10^5. In addition, it is worth mentioning that when the Reynolds numbers exceed 0.79×10^5, the variations in drag coefficient values generated by all models tend to decrease compared to the changes observed at lower Reynolds numbers. Based on this observation, the impact of Reynolds number on the drag coefficient diminishes as Reynolds numbers surpass a specific threshold.



a

b

c

d

Fig. 7. Graph of Reynolds number vs drag coefficient at angles: *a* – 90°; *b* – 75°; *c* – 60°; *d* – 45°

The correlation between the drag coefficient and the Reynolds number still yields intriguing findings at a 60° turning angle, as shown in Fig. 7, *c*. It is worth mentioning that the drag coefficient reaches its maximum of 2.71 at the lowest Reynolds number. With lower Reynolds numbers equating to higher drag coefficients, this data highlights the considerable importance of Reynolds numbers on drag coefficients. Curiously, the drag coefficient is the smallest (1.5) at the highest Reynolds number reported in the dataset. Variations in fluid flow conditions can lead to unexpected outcomes in aerodynamic performance, as this discovery shows in the delicate link between flow dynamics, Reynolds number, and drag coefficient. According to the data, the blade with 15 mm groove width has the highest drag coefficient, while the one without grooves has the lowest. Because of the increased surface area and improved fluid interaction, drag coefficients tend to be greater for larger grooves, as this finding shows that the grooves' width and arrangement affect the drag coefficient.

At a 45° turning angle, the pattern in the relationship between the drag coefficient and Reynolds number remains, as seen in Fig. 7, *d*. The maximum drag coefficient, like in the earlier examples, is 2.61 on a blade having a groove width of 12.5 mm. The opposite is true for blades without grooves, where the drag coefficient registers at its lowest, 1.4. Wider grooves typically lead to greater drag coefficients owing to increased surface area and enhanced fluid interaction; this is supported by the fact that the observed pattern remains consistent across varied turning degrees, further supporting the idea that groove width influences drag coefficient. Also, the Savonius rotor's aerodynamic performance is highly dependent on flow dynamics, and the inverse relationship between the drag coefficient and Reynolds number is still clearly visible.

Fig. 8 provides a concise overview of the drag coefficient values at different turning angles, providing valuable insights into the aerodynamic performance of the Savonius rotor. The graphical representation helps to provide a clear understanding of the relationship between changes in turning angle and the drag coefficient, which is an important factor in evaluating rotor efficiency. When the turning angle is decreased, there is a corresponding decrease in the drag coefficient. The relationship between turning angle and drag coefficient becomes more apparent when the turning angle ranges from 90° to 45°. During this range of turning angles, there is a significant decrease of up to 15.3 % in the drag coefficient.

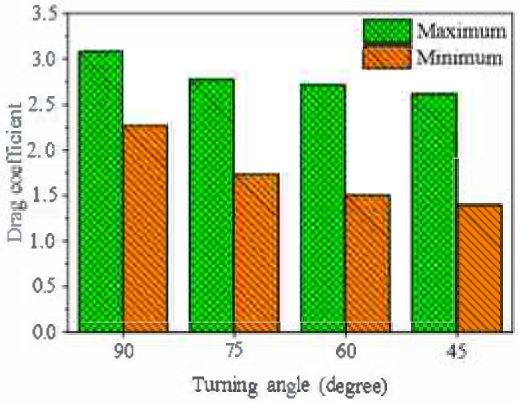


Fig. 8. Drag coefficient value with several variations in turning angle

The width of the grooves on the Savonius rotor has a notable impact on the drag coefficient, as wider grooves tend to lead to higher drag coefficients. The larger surface area and improved fluid interaction that comes with wider grooves can explain the relationship. With an increase in the width of the grooves, a larger amount of fluid is captured and redirected, resulting in an amplified drag force on the rotor blades. It is worth mentioning that this relationship is not linear. Although wider grooves initially result in higher drag coefficients, there comes a point where increasing groove width may no longer continue to increase the drag coefficient. It is worth noting that according to the data, there is a decline in the drag coefficient once the groove width exceeds a certain threshold, which is 15 mm in this particular case.

6. Discussion of the experiment of adding grooves to the Savonius rotor

The impact of the trade-off between efficiency and flow rate is one noteworthy finding from the investigation. A greater volume of fluid is moving through the rotor of the grooveless blade since its flow velocity is greater than that of the grooved versions. Nevertheless, the blade's effectiveness devoid of grooves is poorer, even though the flow rate is higher. While a higher flow rate does increase fluid throughput, it does not guarantee that the turbine will be more efficient. This disparity highlights the intricate connection between flow dynamics and turbine performance.

Additionally, the investigation sheds light on how important groove design is for maximizing turbine efficiency. A groove width of 12.5 mm is featured in the model that achieves a rotation of 60 rpm with the least flow rate (Fig. 5). Based on these results, smaller groove widths may result in greater efficiencies, suggesting an ideal relationship between groove size and turbine performance. It is imperative to optimize the groove parameters for improved turbine performance due to the clear influence of groove design on fluid-structure interaction and flow patterns [20].

The effects of groove width on turbine performance, especially regarding efficiency and tip speed ratio (TSR), are illuminated by examining the Savonius rotor models. Notable for its outstanding performance, the model with a 12.5 mm groove width achieved an optimal TSR of 1.26 and a peak efficiency of 35.66 % (refer to Fig. 6). The importance of groove dimensions in determining the Savonius rotor's performance characteristics is highlighted by this observation. The model's exceptional performance with a 12.5 mm groove width demonstrates the critical role of groove design parameters in optimizing turbine efficiency and TSR. Optimizing energy conversion and overall turbine performance is possible when designers meticulously choose the groove dimensions to improve the interaction between the rotor blades and the fluid flow [21]. This model's improved efficiency and TSR prove that groove width is a critical design element for improving turbine performance. In addition, while comparing several models, the 12.5 mm groove width arrangement stands out as the most efficient and TSR-friendly. Based on these results, the 12.5 mm groove width model appears to be the best compromise between groove dimensions for maximizing turbine performance out of all the examined variants. This model's improved efficiency and TSR show the importance of choosing the right groove width for turbine performance [22].

Examining drag coefficients across different configurations of the Savonius rotor provides insights into the notable impact of groove dimensions on aerodynamic performance [23]. It is worth mentioning that the configuration with a groove width of 12.5 mm produces the highest drag coefficient, which reaches a value of 3.081. On the other hand, when the Reynolds number is at its lowest value of 0.34×10^{5}, the blade without grooves reaches its highest drag coefficient of 2.71 (refer to Fig. 7). The findings highlight the importance of groove width in determining the aerodynamic characteristics of the Savonius rotor. The observed trend highlights the significance of groove dimensions in maximizing the aerodynamic efficiency of the Savonius rotor [24]. The presence of grooves on the blade's surface has been found to enhance the drag coefficient, resulting in a notable improvement in energy extraction efficiency [23]. Well-planned grooves have the potential to optimize fluid-structure interaction, resulting in increased drag coefficients and ultimately enhancing turbine performance. The significant rise in drag coefficient when grooves are added emphasizes the effectiveness of this design feature in optimizing energy extraction from the fluid flow [25].

The graph shows that the drag coefficient decreases as the turning angle decreases (Fig. 8 for the relevant data). The inverse relationship between rotation angle and aerodynamic drag highlights how these factors interact dynamically and significantly impact rotor efficiency. It should be noted that the correlation between turning angle and drag coefficient is strongest between 90 and 45 degrees of turn. A significant gain in aerodynamic efficiency is noticed as the turning angle decreases, as the drag coefficient drops by as much as 15.3% within this range of turning degrees. These findings suggest optimizing turning angles is crucial for improving turbine performance [26]. Lower drag coefficients and higher energy conversion efficiency result from bigger turning angles.

There might be differences between laboratory results and the performance of turbines in real-world settings because the experimental setup doesn't completely mimic real-world conditions. Inaccurate or irrelevant results could result from scale effects, boundary conditions, or environmental variables. The results may not apply to different turbine designs or operating situations because the study was conducted with a specific rotor design, groove configurations, and experimental equipment. Other results might be produced by varying the geometry of the blade, the fluid's characteristics, and external variables. Fluid dynamics, structural mechanics, and electrical engineering principles all interact in a complicated way to affect the performance of hydrokinetic turbines. Because the research only looked at grooves in turbines, it might not have considered how those grooves interact with other parts of the system or other design factors.

The research may have overlooked other elements that affect the overall efficacy and efficiency of the turbine in favor of examining the effect of grooves on performance. More thorough approaches that consider a wider variety of design factors, operational situations, and performance indicators could be used in future studies to solve these drawbacks. Discrepancies between laboratory results and real-world turbine performance could be caused by the study's experimental setup, which may have been too simplistic and unrealistic. Experimental settings could be improved in future studies by using scaled-up models, more realistic flow conditions, and better measuring techniques. This would lead to more accurate and reliable results.

The study may have relied on simplified experimental settings like laboratory-scale models or controlled flow conditions, which might not have captured the complexities of real-world hydrokinetic turbine situations. This is one of the drawbacks of the study. The results may not apply to larger-scale turbine applications because of this. Blade material, curvature, and operating circumstances were not thoroughly investigated, and the study may have narrowed its focus to a small set of parameters, such as groove width and arrangement, which could impact turbine performance. Efficiency optimization may be missed due to a lack of thorough parameter investigation. The study may have ignored the actual variability of water currents in its results because it was conducted in a controlled environment with constant flow rates and velocities. There may be varying effects on turbine performance due to real-world factors such as turbulence and changing flow velocities.

In the future, there may be advancements in numerical modeling techniques, like computational fluid dynamics (CFD), to better simulate the intricate fluid-structure interactions and flow dynamics around the grooved rotor blades. Accurately modeling turbulence, boundary layer effects, and unsteady flow phenomena can pose challenges that demand advanced computational resources and expertise. Potential future research could investigate the application of optimization algorithms to systematically enhance the performance of grooved Savonius rotor models by optimizing their design parameters. Developing efficient optimization algorithms that can handle the complexities of turbine design optimization can be challenging.

7. Conclusions

1. The Savonius rotor blade without grooves has an ideal drag coefficient of 2.71 and an efficiency peak of 30.97%. Grooves increase drag coefficients significantly. Importantly, groove width affects the drag coefficient. As groove width rises, the drag coefficient increases. The drag coefficient increases with groove width from 5 mm to 12.5 mm groove width. When the groove width exceeds 12.5 mm, the drag coefficient decreases. This shows a critical threshold beyond which widening grooves does not proportionally increase the drag coefficient and may even diminish returns.

2. The best model is the 8-groove blade with a groove width of 12.5 mm, a drag coefficient of 3.08, and an efficiency peak of 35.26 %. This improves significantly over the baseline configuration. The drag coefficient rises by 0.37, and efficiency increases by 4.29 %. These studies show that groove dimensions significantly affect Savonius rotor performance. Aerodynamically, the 8-groove layout with a 12.5 mm groove width has greater drag coefficients and efficiency than other variants. In hydrokinetic turbine applications, optimizing groove parameters in Savonius rotor design maximizes energy extraction efficiency and performance.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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References

1. Yuce, M. I., Muratoglu, A. (2015). Hydrokinetic energy conversion systems: A technology status review. Renewable and Sustainable Energy Reviews, 43, 72–82. https://doi.org/10.1016/j.rser.2014.10.037
2. Maldar, N.R., Ng, C. Y., Oguz, E. (2020). A review of the optimization studies for Savonius turbine considering hydrokinetic applications. Energy Conversion and Management, 226, 113495. https://doi.org/10.1016/j.enconman.2020.113495
3. Sule, L., Mochtar, A. A., Sutresman, O. (2020). Performance of Undershot Water Wheel with Bowl-shaped Blades Model. International Journal of Technology, 11 (2), 278. https://doi.org/10.14716/ijtech.v11i2.2465
4. Talukdar, P. K., Sardar, A., Kulkarni, V., Saha, U. K. (2018). Parametric analysis of model Savonius hydrokinetic turbines through experimental and computational investigations. Energy Conversion and Management, 158, 36–49. https://doi.org/10.1016/j.enconman.2017.12.011
5. Zhang, Y., Kang, C., Ji, Y., Li, Q. (2019). Experimental and numerical investigation of flow patterns and performance of a modified Savonius hydrokinetic rotor. Renewable Energy, 141, 1067–1079. https://doi.org/10.1016/j.renene.2019.04.071
6. Kumar, A., Saini, R. P. (2017). Performance analysis of a single stage modified Savonius hydrokinetic turbine having twisted blades. Renewable Energy, 113, 461–478. https://doi.org/10.1016/j.renene.2017.06.020
7. Basumatary, M., Biswas, A., Misra, R. D. (2018). CFD analysis of an innovative combined lift and drag (CLD) based modified Savonius water turbine. Energy Conversion and Management, 174, 72–87. https://doi.org/10.1016/j.enconman.2018.08.025

8. Alizadeh, H., Jahangir, M. H., Ghasempour, R. (2020). CFD-based improvement of Savonius type hydrokinetic turbine using optimized barrier at the low-speed flows. Ocean Engineering, 202, 107178. https://doi.org/101016/j.oceaneng.2020.107178
9. Sarma, N. K., Biswas, A., Misra, R. D. (2014). Experimental and computational evaluation of Savonius hydrokinetic turbine for low velocity condition with comparison to Savonius wind turbine at the same input power. Energy Conversion and Management, 83, 88–98. https://doi.org/10.1016/j.enconman.2014.03.070
10. Tian, W., Mao, Z., Ding, H. (2018). Design, test and numerical simulation of a low-speed horizontal axis hydrokinetic turbine. International Journal of Naval Architecture and Ocean Engineering, 10 (6), 782–793. https://doi.org/10.1016/j.ijnaoe.2017.10.006
11. Zahariev, M. E. (2016). Flow diagnostics and optimal design of vertical axis wind turbines for urban environments. University of Huddersfield. Available at: https://eprints.hud.ac.uk/id/eprint/31542/
12. Salam, N., Tarakka, R., Jalaluddin, Jimran, M. A., Ihsan, M. (2021). Flow Separation in Four Configurations of Three Tandem Minibus Models. International Journal of Mechanical Engineering and Robotics Research, 10 (5), 236–247. https://doi.org/10.18178/ijmerr.10.5.236-247
13. Torres, S., Marulanda, A., Montoya, M. F., Hernandez, C. (2022). Geometric design optimization of a Savonius wind turbine. Energy Conversion and Management, 262, 115679. https://doi.org/10.1016/j.enconman.2022.115679
14. Sharma, S., Sharma, R. K. (2016). Performance improvement of Savonius rotor using multiple quarter blades – A CFD investigation. Energy Conversion and Management, 127, 43–54. https://doi.org/10.1016/j.enconman.2016.08.087
15. Kerikous, E., Thévenin, D. (2019). Optimal shape of thick blades for a hydraulic Savonius turbine. Renewable Energy, 134, 629–638. https://doi.org/10.1016/j.renene.2018.11.037
16. Sodjavi, K., Ravelet, F., Bakir, F. (2018). Effects of axial rectangular groove on turbulent Taylor-Couette flow from analysis of experimental data. Experimental Thermal and Fluid Science, 97, 270–278. https://doi.org/10.1016/j.expthermflusci.2018.04.022
17. Kerikous, E., Thévenin, D. (2019). Performance Enhancement of a Hydraulic Savonius Turbine by Optimizing Overlap and Gap Ratios. Volume 2 Combustion, Fuels, and Emissions; Renewable Energy: Solar and Wind; Inlets and Exhausts; Emerging Technologies: Hybrid Electric Propulsion and Alternate Power Generation; GT Operation and Maintenance; Materials and Manufacturing (Including Coatings, Composites, CMCs, Additive Manufacturing); Analytics and Digital Solutions for Gas Turbines/Rotating Machinery. https://doi.org/10.1115/gtindia2019-2670
18. Soenoko, R., Purnami, P. (2019). Bowl bladed hydrokinetic turbine with additional steering blade numerical modeling. Eastern-European Journal of Enterprise Technologies, 4 (8 (100)), 24–36. https://doi.org/10.15587/1729-4061.2019.173986
19. Cengel, Y., Cimbala, J. (2013). Fluid mechanics fundamentals and applications. McGraw Hill, 1000.
20. Kini, C. R., Sharma, N. Y., Shenoy B., S. (2017). Fluid Structure Interaction Study of High Pressure Stage Gas Turbine Blade Having Grooved Cooling Channels. International Review of Mechanical Engineering (IREME), 11 (11), 825. https://doi.org/10.15866/ireme.v11i11.12465
21. Ahmadi-Baloutaki, M., Carriveau, R., Ting, D. S.-K. (2013). Effect of free-stream turbulence on flow characteristics over a transversely-grooved surface. Experimental Thermal and Fluid Science, 51, 56–70. https://doi.org/101016/j.expthermflusci.2013.07.001
22. Wan Yahaya, W. M. A., Samion, S., Mohd Zawawi, F., Musa, M. N., Najurudeen, M. N. A. (2020). The Evaluation of Drag and Lift Force of Groove Cylinder in Wind Tunnel. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 68 (2), 41–50. https://doi.org/10.37934/arfmts.68.2.4150
23. Gowree, E. R., Jagadeesh, C., Atkin, C. J. (2019). Skin friction drag reduction over staggered three dimensional cavities. Aerospace Science and Technology, 84, 520–529. https://doi.org/101016/j.ast.2018.11.001
24. Seo, S.-H., Hong, C.-H. (2015). Performance improvement of airfoils for wind blade with the groove. International Journal of Green Energy, 13 (1), 34–39. https://doi.org/10.1080/15435075.2014.910777
25. Yao, J., Teo, C. J. (2022). Drag reduction by a superhydrophobic surface with longitudinal grooves: the effects of the rib surface curvature. Journal of Turbulence, 23 (8), 405–432. https://doi.org/10.1080/14685248.2022.2094936
26. Chehouri, A., Younes, R., Ilinca, A., Perron, J. (2015). Review of performance optimization techniques applied to wind turbines. Applied Energy, 142, 361–388. https://doi.org/10.1016/j.apenergy.2014.12.043

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