IJE TRANSACTIONS B: Applications Vol. 39, No. 05, (May 2026) 1176-1190

International Journal of Engineering

Journal Homepage: www.ije.ir

Comparative Performance Evaluation of Savonius Vertical Axis Wind Turbines: Two and Three-bladed Profiles

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PAPER INFO

Paper history:
Received 08 April 2025
Received in revised form 29 May 2025
Accepted 15 June 2025

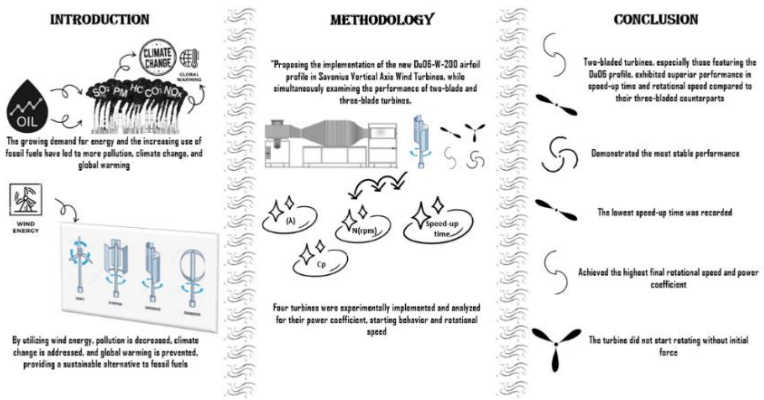
Keywords:
Wind Turbine
Semi-circular
Du06-W-200 Profile
Power Coefficient
Speed-up Time
Rotational Speed

A B S T R A C T

In recent decades, the environmental impact of energy production has led to growing global efforts to transition from polluting fossil fuels to renewable energy sources, attracting considerable attention from organizations and researchers. This transition is essential due to escalating environmental concerns and the limited availability of fossil fuels. Concurrently, the deployment of wind turbines worldwide has expanded significantly**.** This study aims to propose an optimal Savonius vertical axis wind turbine design suited for urban applications. Two turbine models featuring different blade numbers and profiles were designed, constructed, and experimentally tested. The turbines comprised double- and triple-blade configurations, utilizing semicircular and Du06-W-200 blade profiles. Performance evaluation focused on key parameters including power coefficient, final rotational speed, power output, tip speed ratio, and time to reach maximum rotational speed**.** The results demonstrated that the semicircular double-blade turbine delivered the highest final rotational speed of 1433 RPM, approximately 33% higher than the three-bladed semicircular turbine and over 160% higher than the Du06-profiled turbines. It also achieved the highest power coefficient among all turbines tested. The two-blade turbine (Du06-W-200) profile exhibited the fastest acceleration, reaching its final speed in only 11 seconds, twice as fast as the two-bladed semicircular turbine and three times faster than the three-bladed semicircular configuration. While the Du06-profiled turbines showed slightly lower tip speed ratios, the three-bladed semicircular turbine exhibited the most stable power output. These findings indicate that Savonius turbines with the tested configurations are well-suited for urban environments, though their effectiveness depends strongly on local geographical and climatic conditions.

***doi**: 10.5829/ije.2026.39.05b.11*

Graphical Abstract



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Please cite this article as: Sadeghi A, Gorji TB, Gorji-bandpy M. Comparative Performance Evaluation of Savonius Vertical Axis Wind Turbines: Two and Three-bladed Profiles. International Journal of Engineering, Transactions B: Applications. 2026;39(05):1176-1190.

NOMENCLATURE			
A	Cross-sectional area (m^2)	P_{den}	Power density (W)
C_P	Power coefficient	R	Radius of the blade (m)
E_K	Kenetic energy (J)	t	Time (s)
K_m	Mass flow rate (kg/s)	v	Velocity (m/s)
m	Air mass (kg)	**Greek Symbols**	
N	Rotational speed (rpm)	λ	Linear speed of the blade tip to the wind speed
P	Power (W)	ρ	Air density (kg/m^3)
P_0	Wind power (W)	ω	Angular velocity (rad/s)

1. INTRODUCTION

Climate change is driving the world to seek cleaner energy sources. Renewable energy has become increasingly important as efforts intensify to move away from fossil fuels (1-3). This shift has created strong demand for improved technologies that can capture or generate energy more efficiently, contributing to the development of a cleaner future. Multiple factors are driving this transition to renewable energy. Scientific studies confirm the need to alleviate the adverse environmental impacts associated with fossil fuel–based power generation. Fossil fuels emit the most greenhouse gases, which have the most detrimental effects on the environment (4-6). Furthermore, hormonal activity can be disrupted by various substances originating from fossil fuels, which can be found in food, air, water, and manufactured products (7, 8). additionally, the finite nature of fossil fuel reserves and concerns over energy security have increased focus on renewable energy. By harnessing the power of nature, renewable energy offers a long-term solution that is not subject to the same resource limitations as fossil fuels. Moreover, renewable energy can be generated locally, reducing dependence on imported energy sources and enhancing energy self-sufficiency (9, 10).

Wind turbines are now widely recognized as symbols of renewable energy and are becoming increasingly significant in the global shift toward a sustainable future (11, 12). By harnessing wind power, these impressive structures are capable of generating clean and abundant electricity without the greenhouse gas emissions associated with traditional energy sources. While wind turbines are implemented in various designs (13), the principal aim of wind energy conversion is the efficient production of electrical power. The variety of wind turbine designs reflects the industry's evolving requirements and ongoing advancements in wind energy technology. The incorporation of renewable energy sources in the manufacturing sector is crucial for enhancing sustainability and reducing carbon emissions. However, obstacles such as high costs, limited technology, and the need for skilled workers remain. Policy frameworks, financial incentives, and technological advancements are key to facilitating this transition. The potential for cost savings, increased energy efficiency, and improved business reputation present a compelling case for this change, despite considerable challenges. The sector can overcome these barriers and achieve global sustainability goals through supportive regulations, continuous innovation, and stakeholder engagement. For broader adoption, further investigation into scalable, industry-specific solutions is required (14, 15).

Different types of wind turbines have emerged to optimize performance, efficiency, and adaptability under varying wind conditions and geographical settings. Each design has its own set of advantages, limitations, and applications, catering to specific requirements and maximizing the potential of wind power (16).

Traditionally, there are two primary types of wind turbines: vertical axis wind turbines (VAWTs) and horizontal axis wind turbines (HAWTs) (17). AWTs, which are among the most common and recognizable wind turbine designs, feature a horizontal rotor shaft oriented in line with the wind direction. Typically consisting of three blades, HAWTs are renowned for their high energy conversion efficiency and ability to generate substantial power. They are widely employed in large-scale wind farms and marine-based projects due to their scalability and cost-effectiveness (18). AWTs, on the other hand, have a rotor shaft positioned vertically. VAWTs can operate regardless of wind direction, making them versatile and suitable for diverse wind conditions. They are often utilized in urban and small-scale applications where space constraints and aesthetic considerations are important (19, 20). Within the category of VAWTs, the Savonius wind turbine is notable for its distinctive S-shaped blades and suitability for low wind speeds and turbulent conditions (21). The Darrieus type features vertically oriented airfoil-shaped blades that provide high torque at low rotational speeds (22). The Savonius wind turbine has attracted significant attention due to its unique design and potential applications. Named after its inventor, Finnish engineer Sigurd J. Savonius, these turbines offer specific advantages that distinguish them from other wind turbine designs (23). The distinguishing feature of Savonius wind turbines lies in their S-shaped blades, which rotate around a vertically oriented axis. This design allows

Savonius turbines to operate effectively in a variety of wind conditions, including low wind speeds and turbulent environments. Consequently, they offer promising possibilities for utilizing wind energy in urban and small-scale settings, where traditional horizontal-axis wind turbines may face limitations. One of the key advantages of Savonius wind turbines is their simplicity and solidarity. Their design comprises curved blades that capture wind energy by employing the drag force rather than lift. This simplicity of construction makes Savonius turbines relatively easy to manufacture, install, and maintain, thereby enhancing their cost-effectiveness and accessibility. Additionally, Savonius wind turbines exhibit excellent self-starting capabilities, allowing them to initiate rotation even at low wind speeds. This feature ensures continuous power generation, making them suitable for regions with moderate or unpredictable wind conditions.

Various researches have been conducted to improve the performance of Savonius wind turbines. The two primary areas of literature research on increasing Savonius turbine efficiency are exterior additional design and interior structural design as shown in Figure 1 (24).

Shame et al. (8) numerically analyzed seasonal wind energy potential on Zanzibar's coastal island using half-hourly wind data collected at 10 m height. A Weibull distribution model, fitted using the standard deviation method, was employed to evaluate wind speed, wind direction, and wind energy density (wED). The analysis indicated the presence of strong winds (4.5–7 m/s) persisting for approximately 15 hours per day, with the highest wED (23.3 GWh/m²) observed during the winter season. The POLARIS P62-1000 wind turbine was identified as the most suitable option, based on its high capacity factor (>58%) and power output (589 kW), thereby confirming the region's viability for wind farm development. Bozsik et al. (6) simulated the impact of climate change on household-scale photovoltaic (PV) systems in Hungary using hourly climate projections from the Meteonorm database under RCP2.6, RCP4.5, and RCP8.5 scenarios. A PV system comprising 18 LG monocrystalline panels and a Fronius inverter was modeled in PVsyst software. The study analyzed global horizontal irradiance (GHI), air temperature, and resulting energy yield (En) over the 21st century. Results revealed that while GHI increases in all scenarios, higher temperatures negatively affected PV efficiency, especially under RCP4.5 and RCP8.5. Partial correlation analysis confirmed that temperature rise diminishes power output when isolating the effect of GHI. The findings highlight the need for thermal management in PV systems and recommend further comparative studies across PV technologies and seasonal impacts to improve future projections.

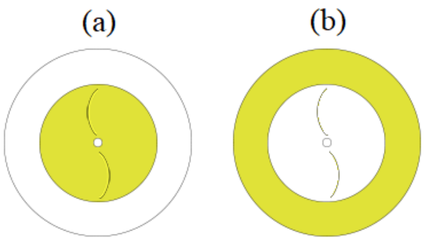

Figure 1. graphical abstract of Savinus Wind Turbine: (a): interior design area (b): exterior design area

The fundamental objective of external design studies is to improve turbine performance by reducing negative torque and increasing positive torque (25). Utilizing concepts derived from the field of exterior design, improvements to Savonius VAWTs through additional external features involve various flow augmentation systems. These include different types of deflectors, guide-box tunnels, shielding structures, conveyors, and other configurations, which have been extensively discussed in several studies (26-30).

The interior design performance of Savonius turbines is influenced by multiple factors, including blade shape and configuration, height and aspect ratio, number of blades, number of stages, twist angle, shaft diameter, installation of end plates, overlap ratio, material, weight, rotor diameter, and many other features (31). Wenehenubun et al. (32) experimentally compared Savonius turbines with different numbers of blades based on tip speed ratio (TSR), torque, and power coefficient relative to wind speed. Additionally, a simulation study was conducted to analyze pressure distribution. The three-bladed Savonius turbine was found to be the most efficient model, achieving the highest tip speed ratio of 0.555 at a wind speed of 7 m/s. Four-bladed turbine configurations generated the greatest actual torque within the wind speed range of 0 to 10 m/s. Gumilar et al. (33) performed a numerical study on an L-shaped Savonius wind turbine with the objective of assessing power capture as a function of wind speed and rotational speed. They also evaluated power relative to blade count. The maximum power output reached 643.51 W at a wind speed of 20 m/s and a rotor rotation speed of 50 rad/s. Two-bladed turbines captured the highest power, particularly at a wind speed of 20 m/s. Morever, Prabowoputra and Prabowo (34) emphasizes a direct relationship between aspect ratio and the performance of this rotor type, with optimal performance observed at overlap ratios between 0 and 0.3, while acknowledging the influence of additional factors. Modified blade shapes demonstrate performance improvements ranging from 8 to 25%. Additionally, the integration of multi-stage configurations enhances rotor performance in accordance with other factors. According to the literature, the optimal blade count for balancing performance and stability is determined to be two or three blades. n artificial neural network was utilized by Al-Shammari et al. (35) to predict the optimal blade shape design, aiming to increase the power coefficient at low wind speeds within the TSR range of 0.2 to 1.2. Their study demonstrated that the blade-shaped Savonius wind turbine outperforms the semi-circular blade rotor within the TSR range of 0.6 to 1.1. Furthermore, the maximum power coefficient improved by 55% compared to the conventional semi-circular blade-shaped Savonius wind turbine. Tartuferi et al. (36) conducted a numerical study aimed at improving the aerodynamic efficiency of a Savonius wind rotor by utilizing two distinct approaches. The first approach involved designing blades with innovative airfoil shapes, while the second incorporated a novel curtain system capable of autonomously aligning with the wind direction. The results demonstrated that both proposed approaches significantly enhanced the energy performance of Savonius wind turbine. Hosseini Imeni et al. (37) performed a computational analysis of airfoil-bladed Savonius wind turbines to increase efficiency and reduce entropy generation through the incorporation of an innovative airfoil-shaped blade design. Nine key design parameters were identified, and twelve distinct design points were developed for evaluation. The findings revealed that the power coefficient could be increased by up to 12.89% at a TSR of 0.8 compared to conventional semi-circular blades. Shamsuddin and Kamaruddin (38) experimentally compared single-stage and two-stage Savonius wind turbines at flow speeds ranging from 5 to 9 m/s in a wind tunnel. The results indicated that the addition of an extra stage led to a substantial increase in the power coefficient, with a peak improvement of 138% at a wind speed of 5 m/s. Moreover, the two-stage configuration was found to reduce the self-starting speed across all rotor angles, thereby significantly enhancing the turbine’s self-starting capability. Ikonwa et al. (39) employed experimental datasets to evaluate various airfoil profiles aimed at improving the self-starting performance of small-scale, fixed-pitch, straight-bladed vertical axis wind turbines. The findings indicated that conventional symmetrical airfoils were unsuitable for self-starting, and no single asymmetrical airfoil was universally optimal. However, two asymmetrical airfoils, DU-06-W-200 and S 1210, exhibited superior aerodynamic performance. Notably, the DU-06-W-200 airfoil demonstrated a higher starting torque, positioning it as a promising solution to mitigate self-starting challenges in small-scale fixed-pitch straight-bladed vertical axis wind turbines. Zamani et al. (40) numerically investigated the flow behavior around vertical axis wind turbine (VAWT) blades. The DU-06-W-200 airfoil was selected for application in Darrieus-type VAWT blades. Aerodynamic coefficients were analyzed and compared with those of conventional straight blades over a broad range of angles of attack. The findings indicated that the DU-06-W-200 airfoil exhibited an increased lift-to-drag coefficient ratio (CL/CD) and improved self-starting capability. A summary of the aforementioned interior design studies is presented in Table 1.

TABLE 1. Summarized information of interior design literature review

Reference	Year	Methodologies	Results or contributions
(24)	2023	Influential Aerodynamic Design	Interior Structure Design Exterior Additional Design
(31)	2023	Interior Structure Design Features	Blade Shape, Aspect Ratio, Number of Blades, Number of Stages etc.
(32)	2015	Compared (2, 3 and 4) Number of Blades Rotors	Three Blade Highest Efficiency Four Blade Highest Torque
(33)	2019	Impacts of Number of Blades	Maximum Power Surpasses Previous Research By Two-bladed Turbine
(34)	2022	Observed Overlap Variation, Blade Shapes, Multiple Stages	The Optimal Number of Blades is Two and Three-Bladed Savonius Turbines
(35)	2020	Optimized the Design of Blade Shape Using ANSYS-CFX Software	Better Performance of Blade-shaped Rotors than Semi-circular Rotor
(36)	2015	Airfoil Shaped Blades and Certain System for Aligning Wind Direction	Sensibly Enhance the Energy Performance of the Savonius Wind Turbine
(37)	2022	Formulated Crucial Parameters of Airfoil-shaped Blade Designs	12.89% Enhancement in Comparison with a Conventional Savonius Rotor
(39)	2016	Examine Different Airfoil Profiles in Self-starting Performance	DU06-W-200 Profile Could be an Ideal Airfoil to Eliminate the Problem
(38)	2023	Self-starting of One and Two Staged Rotors were Discussed	Double-stage Rotor Outperformed In Terms of Self-starting Capabilities
(40)	2021	Observed Flow Behavior Around VAWT Including Du06-W-200 Airfoil	The Airfoil Equipped Improves Self-starting and Cut-in Decrease

The present study primarily investigates the performance of a Savonius turbine with respect to interior design modifications. The main objective is to refine and compare the interior configurations of a Savonius VAWT and to evaluate the corresponding power coefficient of the modified designs. Regarding the number of blades, no universally accepted optimal configuration has been established, as the interior designs of specific rotors may yield varying results depending on factors such as wind speed, rotor size, and intended applications. Some studies have suggested that two-bladed configurations may provide better efficiency (33), whereas other research supports the efficiency of three-bladed rotors (32). Therefore, the choice between two or three blades for a Savonius VAWT depends on specific design considerations and operating conditions. Consequently, it is common for researchers to conduct experiments and simulations to identify the configuration that best addresses the challenges of their particular application.

Furthermore, the aerodynamics of the turbine, especially blade shape, is considered one of the most influential factors affecting the efficiency of Savonius VAWTs (35). Efficiency can be characterized by various turbine attributes such as self-starting capability, power coefficient, and torque coefficient. Comparative studies have been conducted on airfoil-shaped blades versus semi-circular blades under different conditions (36). Additionally, the use of the airfoil profile DU06-W-200 in VAWTs to enhance self-starting capability has been explored in recent years (40). owever, based on the reviewed literature, no experimental investigation has been conducted on the application of the DU06-W-200 airfoil in a Savonius VAWT.

In this study, experiments are conducted on two- and three-bladed configurations of semi-circular and DU06-W-200 profile blades in a Savonius vertical axis wind turbine. The experiments involve measuring the rotational speed, the speed of the exiting wind flow from the turbine, and the time taken for each turbine configuration to reach its ultimate rotational speed. The results are then compared in terms of rotor rotational speed, power coefficient, and startup time. The methodology employed, including governing equations, the detailed experimental setup, and testing procedures, will be discussed in the following chapter, followed by the presentation of results and conclusions.

2. METHODOLOGY

This study employs a systematic methodology to investigate the performance of Savonius VAWTs through a combination of theoretical analysis and experimental validation. The approach is divided into two parts: the governing equations, which form the foundation of the turbine's aerodynamic behavior, and the detailed experimental setup designed to measure its performance metrics. The following sections will first present the governing equations underlying the theoretical framework, followed by a comprehensive description of the experimental setup used to validate the results.

2. 1. Governing Equations

Primarily, wind turbines extract the kinetic energy present in the wind and convert it into electrical energy. The governing equations of wind turbines are presented as follows (41). The kinetic energy of a mass of air with mass (m) and velocity (v) is represented by Equation 1.

$$E_k = \frac{1}{2} m v^2 \quad (1)$$

At speed v (m/s), the mass of passing air through the cross-sectional area A (m^2) is expressed in Equation 2 as follows:

$$m = \rho A V t \quad (2)$$

In this equation, ρ represents air density (kg/m^3). Based on Equations 1 and 2, the wind power can be expressed as Equation 3.

$$P_0 = \frac{1}{2} \rho A V^3 \quad (3)$$

Therefore, the specific power or power density can be calculated using to Equation 4.

$$P_{den} = \frac{P_0}{A} = \frac{1}{2} \rho V^3 \quad (4)$$

Consequently, wind power density is directly proportional to the cube of the wind speed. The useful power extracted by the turbine blades from the wind energy is determined by calculating the difference between the input wind power and the output wind power of the turbine:

$$P = \frac{1}{2} * K_m * (V_0^2 - V^2) \quad (5)$$

$$K_m = \rho A \frac{(V + V_0)}{2} \quad (6)$$

In Equation 5, V_0 is the speed of the incoming flow to the turbine, V is the speed of the outgoing flow from the turbine, and Km is the mass flow rate obtained from Equation 6. In Equation 6, the variable A is the cross-sectional area swept by the turbine blade, also known as the effective cross-sectional area (A=H*D, where H represents the blade height and D is the turbine diameter). Therefore, based on the above equations, the mechanical power extracted by the turbine is mathematically expressed as shown in Equation 7:

$$P = \frac{1}{2}\left[\rho A \frac{V + V_0}{2}\right]\left(V_0^{\,2} - V^{\,2}\right) \tag{7}$$

by having the formula for the power coefficient in the Equation 8 (41):

$$C_p = \frac{1}{2}\left(1 + \frac{V}{V_0}\right)\left[1 - \left(\frac{V}{V_0}\right)^2\right] \tag{8}$$

The mechanical power extracted by the turbine is expressed in Equation 9:

$$P = \frac{1}{2}\rho A V^{3} C_p \tag{9}$$

$$\lambda = \frac{R * \omega}{V} \tag{10}$$

From Equation 9, it can be concluded that variations in the effective cross-sectional area and wind conditions directly affect the output power of the turbine. Therefore, the control of wind turbine systems primarily relies on these two factors. The ratio of the linear speed of the blade tip to the wind speed, known as the tip speed ratio (λ), is defined by the following equation:

In Equation 10, R is the radius of the blade, V is upstream wind velocity at the entrance of the turbine and ω is the angular velocity of the rotor which is calculated by Equation 11, with N representing the maximum rotational speed of the rotor at the corresponding wind speed and $\pi = 3.14$.

$$\omega = \frac{2\pi N}{60} \tag{11}$$

The experimental setup involves measuring wind speed, rotor rotational speed, and power output to calculate the power coefficient (Cp) under various operating conditions. The significance of Cp in quantifying the efficiency of the wind turbine rotor in converting wind energy into mechanical power will also be emphasized. This analysis aims to contribute to the refinement and optimization of turbine design for practical applications (41).

2. 2. Experimental Setup

2. 2. 1. Wind Section This section provides a detailed explanation of the testing procedure and related considerations. The parameters examined in this study focus on key elements relevant to turbines intended for urban environments. These include measuring the wind speed exiting the turbine to determine the power coefficient, calculating the tip speed ratio to identify the optimal turbine rotational speed within a specified wind speed range, and determining the speed-up time, defined as the time required for the turbine to reach its maximum rotational speed within the relevant wind speed range. Subsequently, each parameter is analyzed in detail to assess its impact on selecting and optimizing the turbine's aerodynamic design. The experiments are conducted within a wind tunnel to simulate airflow conditions around the turbine. A wind tunnel provides a controlled environment that replicates airflow around objects, allowing researchers to study and analyze aerodynamic behavior. This controlled simulation enables the evaluation of aerodynamic forces, such as lift and drag, and their effects on the performance and stability of turbine models or prototypes. Wind tunnels are widely used in aerodynamic research, particularly in studies aiming to improve turbine performance by understanding airflow dynamics. The insights gained from such simulations contribute to the design refinement and optimization prior to real-world implementation. The primary objective of this study is to analyze and compare the performance of specific turbines in urban settings. The wind speed range covered in the experiments extends from 0 to 12 m/s, which approximates the average wind speed commonly observed in rural areas. However, this value can vary significantly depending on factors such as geographic location, local topography, and prevailing weather conditions. Generally, wind speeds in urban environments tend to be lower than in open areas due to the presence of buildings and other structures that create turbulence and obstruct wind flow. Nonetheless, the precise wind speed in urban areas depends on variables including city layout, building heights, and localized weather patterns.

2. 2. 2. Turbine Structure As discussed in the literature, the efficiency of Savonius VAWTs is directly influenced by various factors related to their interior structural design, including blade shape, aspect ratio, number of blades, and several other parameters (24, 31). Certain characteristics are held constant, while others are varied for comparative analysis. Specifically, all parameters except the number of blades and blade shape remain unchanged. This study aims to evaluate the power coefficient and self-starting behavior of a Savonius VAWT featuring a DU-06-W-200 airfoil profile blade compared to a conventional semi-circular bladed rotor, considering both two-bladed and three-bladed configurations. To this end, four prototype Savonius turbines were fabricated. Each turbine comprises three primary components: blades, shaft, and end plates. Two of these turbine prototypes and their components are illustrated in Figure 2.

As shown in Figure 2, two blade models have been examined: the conventional semi-circular bladed rotor (section a) and the DU-06-W-200 profile bladed rotor (section b). Both blade types have a diameter of 125 mm and a height of 300 mm. Additionally, an important parameter in wind turbine design is the overlapping ratio, which indicates the extent to which one blade overlaps or

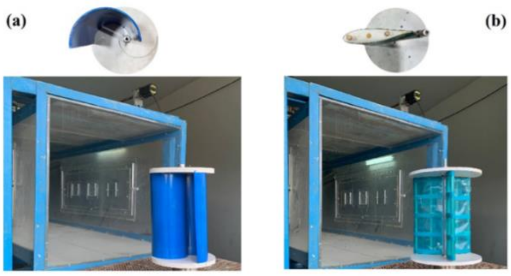

Figure 2. Samples of executed turbines: (a): Semi-circular blade and its related turbine (b): Du06-W-200 blade and its related turbine

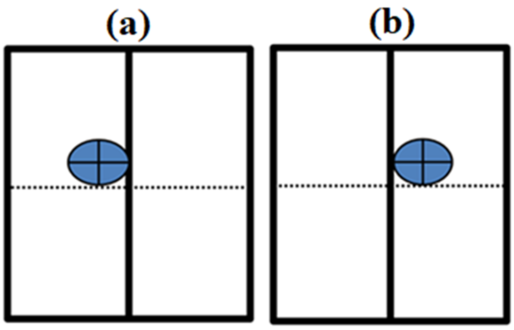

Figure 3. (a): measurement point for semi-circular bladed turbines (b): measurement point for Du06-W-200 profile bladed turbines

covers another. This ratio influences the smoothness of airflow around the blades. A higher overlapping ratio can promote smoother airflow, potentially improving turbine performance, whereas a lower overlapping ratio may cause increased turbulence, possibly reducing efficiency. The practical results of this research (42) revealed a significant effect of the overlap ratio on the aerodynamic performance of the Savonius wind turbine. Under high Reynolds number conditions, turbine prototypes without an overlap ratio demonstrated superior aerodynamic coefficients. Conversely, at lower Reynolds numbers, rotor configurations with a moderate overlap ratio yielded more favorable performance. Based on these findings and considering that the wind speeds examined range from low to average values, an overlap ratio of 32% was adopted for the conventional turbines. In contrast, the DU-06-W-200 profile blades were employed in a Savonius rotor for the first time in this study; therefore, an overlap ratio of zero was applied for these turbines, representing an initial step toward further investigation.

2. 2. 3. Experimental Testing Environment Experiments were conducted in an open-return wind tunnel with test section dimensions of 0.7 m × 0.7 m × 2 m at Babol Noshirvani University of Technology (NIT). The turbine was strategically positioned immediately downstream of the test section exit to minimize blockage effects and maintain flow uniformity. The exact positioning of the testing setup is illustrated in Figure 2.

2. 3. Testing Process This section provides a detailed description of the testing procedure and relevant considerations. Due to flow disturbances generated downstream of the turbine, the velocity varies at different coordinates along the rotor. Therefore, specific coordinates were selected to meaningfully define and measure the output wind speed. Additionally, since turbines with semi-circular blades rotate counterclockwise, whereas those with DU06-W-200 airfoil blades rotate clockwise, the wind speed measurement coordinates were adjusted accordingly to standardize and validate test results for both turbine types. The measurement points for both the semi-circular blade and airfoil blade turbines are illustrated in Figure 3. In Figure 3, the swept area of the turbine blades is depicted, with the shaft represented by a vertical line. All output wind speed measurements were conducted at these defined coordinates. Particular attention was given to minimizing experimental error by adopting a specific coordinate system aligned with the initial blade movement for each turbine. Although experiments were performed across various speed ranges, the coordinate system remained constant, ensuring consistent benchmarking of turbines. The initial blade movement coordinates utilized in this study are shown in Figure 4. Measurements were taken at discrete wind speeds ranging from 0 m/s to 12 m/s, increasing in 0.5 m/s increments. Prior to each trial, the flow was allowed to stabilize for a consistent period to ensure steady-state conditions. This approach ensured that each turbine design was tested under uniform and repeatable wind speed conditions.

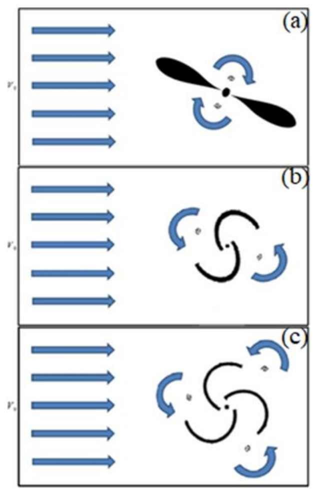

Figure 4. (a): starting coordinate of two-bladed Du06, (b): starting coordinate of two-bladed semi-circular, (c): starting coordinate of three-bladed semi-circular

The selection of these coordinates was intended to position the origin of movement at the point where the blade experiences the maximum pressure from the wind flow. By optimizing the starting conditions with higher initial pressure on the blades, the rotor is able to reach its maximum speed more quickly, thereby reducing the time required to achieve this speed. Additionally, as shown in Figure 4, the starting coordinates for the three-bladed turbine with the DU06-W-200 blade profile are not presented because this turbine did not start rotating without an external initial force. Consequently, measuring the speed-up time for this rotor was deemed illogical, and no specific starting coordinates were assigned for these turbines. Equally important, the wind speed entering the turbine is the most critical parameter influencing its performance. In this study, the wind speed range investigated extends from 0 to 12 meters per second.

2. 4. Instrument Precision and Uncertainty

Accurate characterization of Savonius wind turbine performance requires careful consideration of instrument precision and measurement uncertainty. The Marmonix MAN-745 anemometer employed in this study has a specified accuracy of ±(3% of reading + 0.20 m/s) and a resolution of 0.1 m/s, while the DT-2236C digital tachometer provides RPM measurements with a precision of ±(0.05% of reading + 1 digit). These uncertainties propagate into derived parameters such as the tip-speed ratio and power coefficient. All reported values incorporate these instrument limitations, with expanded uncertainties calculated at a 95% confidence level to ensure reliable and reproducible results.

3. RESULT AND DISCUSSION

As mentioned in introduction, the speed-up time refers to the duration required for the turbine to reach its final rotational speed. Therefore, a shorter speed-up time indicates a more optimal turbine performance, as the desired speed is achieved sooner to generate the required electrical energy. In this study, efforts were made to identify the highest torque or pressure generated by the wind force on the blades at the initiation phase when the blades are stationary. The starting points across all wind speed ranges are illustrated in Figure 4, which shows the starting movement coordinates for each turbine. It is important to note that different wind turbines exhibit varying wind speed thresholds for startup, meaning they begin rotating at different wind speeds. Consequently, the graphs depicting speed-up time start from different initial wind speeds. The speed-up time results for the turbines at various wind speeds are presented in Figure 5, while the design of experiment (DOE) layout, including key factor levels and a summary of experimental runs, is provided in Table 2. The graph related to the three-bladed

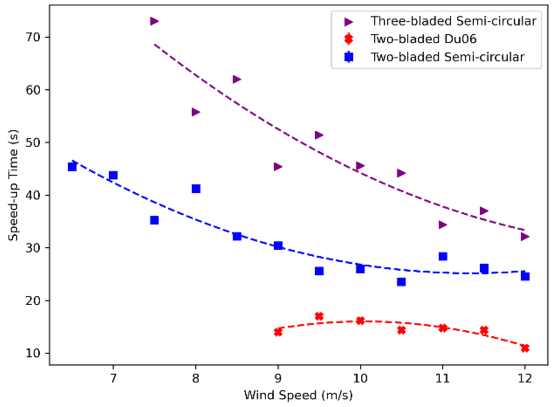

Figure 5. Speed-up time to wind speed graph

TABLE 2. DOE table for speed-up time experiment

Run	Blade profile	Blade number	Windspeed (m/s)	Speed-up time (s)
1	Du06	2	9	14
2	Du06	2	12	11
3	SC	2	6.5	45.4
4	SC	2	10.5	23.6
5	SC	2	12	24.6
6	SC	3	7.5	73
7	SC	3	12	32.2

turbine with the Du06-W-200 VAWT Airfoil profile is not visible because, as mentioned earlier, the turbine did not start rotating without an initial force.

Numerous laboratory experiments have been conducted on the starting behavior of wind turbines (10, 38, 43, 44). It has been concluded that the starting behavior of wind turbines is related to the rotor position at startup relative to the wind flow (38). However, evidence also suggests that the starting behavior depends on the incoming flow to the rotor and the initial force applied to the turbine. The results of these experiments indicate that the initial torque coefficient applied to the rotor is entirely a function of the turbine's position, while the turbine power coefficient depends on the relative velocity of the blade tip to the wind speed. Additionally, the significance of negative starting torque in turbines is noteworthy in many situations. Some studies suggest that the degree of blade overlap significantly influences the magnitude of the negative torque region in turbines (45, 46).

In this study, zero overlap was considered for the DU06 profile, preventing this turbine from moving in any rotor position. In other words, no initiation of movement occurred at any position or wind speed for this turbine, effectively resulting in a locked state. Consequently, no values appear in the speed-up time graph for the three-bladed turbine with the DU06-W-200 VAWT Airfoil profile. This is because the turbine required an initial speed to start, and this initiation does not imply any subsequent decrease in speed over time. The turbine consistently operated at this initial speed throughout all experiments. As shown in Figure 5 and Table 2, the best performance is exhibited by the two-bladed DU06 turbine compared to the other turbines, followed by the two-bladed semi-circular turbine, and then the three-bladed semi-circular turbine. This performance ranking is influenced by speed-up time, where reaching the final speed faster is considered more optimal. The preference for the two-bladed semi-circular turbine over the three-bladed one is due to the lower weight of the rotor setup—an attribute that also affected the initiation of the turbine's movement. The two-bladed turbine, being lighter, required less starting torque and began rotating at a wind speed of 6.5 m/s, while the three-bladed rotor of the same model started at 7.5 m/s.

The DU06-W-200 VAWT profile, known for its rapid startup time, has demonstrated specialized performance in vertical-axis turbines. As noted in previous research (39), this profile exhibits unique efficiency in self-starting capabilities.

The Tip Speed Ratio (TSR), defined as the ratio of the tangential speed of the blade tip to the incoming wind speed, is a critical performance parameter in evaluating wind turbine efficiency. It governs the interaction between the rotor blades and the wind stream, significantly influencing the power coefficient and turbine behavior. Figure 6 and Table 3 depict the turbines' tip speed ratios at different wind speeds and key experimental runs.

Figure 6 and Table 3 illustrate the variation of the tip speed ratio (TSR, denoted as λ) with respect to free-stream wind speed for different blade configurations and profiles. It is evident from the results that the semicircular two-bladed configuration exhibits the highest TSR values across the entire wind speed range, peaking at approximately 1.65 at a wind speed of 12 m/s. This indicates superior rotational responsiveness under increasing wind speeds. In contrast, the Du06 three-bladed model shows a relatively moderate TSR profile, with maximum values around 0.52. The semicircular two-bladed turbine demonstrated the most efficient aerodynamic behavior in terms of rotational acceleration, while the Du06 three-bladed rotor exhibited the lowest TSR values, indicating greater resistance or inertia under the same conditions. These findings suggest that, while the semicircular two-bladed configuration may be more favorable in applications requiring rapid rotor acceleration, the Du06 configurations might offer benefits in terms of torque stability at lower rotational speeds. The trends also indicate a diminishing gain in TSR with increasing blade count, likely due to increased aerodynamic drag and interaction between blades.

TABLE 3. DOE table for λ

Run	Blade profile	Blade number	Windspeed (m/s)	Tip speed ratio
1	Du06	3	8	0.338
2	Du06	3	12	0.517
3	Du06	2	9	0.544
4	Du06	2	12	0.631
5	SC	3	7.5	0.836
6	SC	3	12	1.175
7	SC	2	6.5	1.021
8	SC	2	12	1.651

Another performance parameter evaluated in this study is the power output of the turbine. Power output serves as the definitive metric for assessing a wind turbine's energy conversion efficiency and practical viability, as it represents the mechanical energy extracted from the wind (Equation 9). The power characteristics of the tested

Savonius turbine configurations are presented in

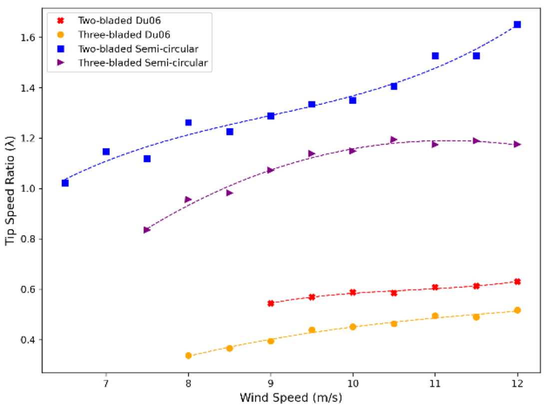

Figure 6. The tip speed ratio to wind speed graph

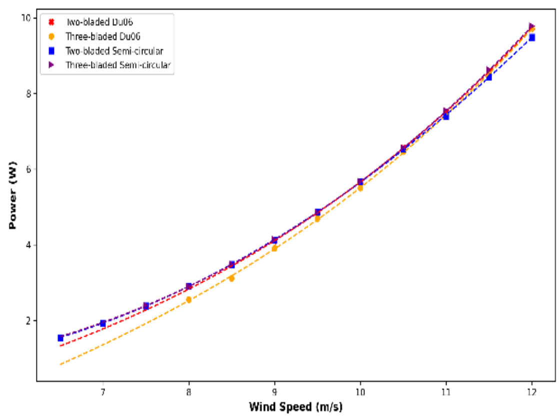

Figure 7. power to wind speed graph

Figure 7, while Table 4 provides a detailed summary of all experimental runs.

At wind speeds where all configurations generate power, the two-bladed Du06 generally produces slightly higher power than the three-bladed Du06. For example, at 9 m/s, the two-bladed Du06 outputs 4.11 W compared to 3.90 W for the three-bladed. This trend continues up to 12 m/s, where the two-bladed produces 9.74 W, marginally exceeding the three-bladed's 9.73 W. Similarly, the two- and three-bladed semi-circular turbines deliver comparable power outputs at corresponding wind speeds, with the three-bladed configuration showing a slight edge at the highest speed of 12 m/s (9.78 W versus 9.49 W). Overall, the two-bladed Du06 outperforms the three-bladed version by a small margin, while the semi-circular blades show near-equal performance between blade counts.

According to Figure 8 and Table 5, an upward trend in rotor speed with increasing wind speed is evident for all turbines across the wind spectrum up to 12 m/s. In general, higher rotational speeds were observed in the two-bladed semi-circular profile turbine compared to the others, with its rotational speed positioned relatively close to that of the three-bladed counterpart. This trend is also noticeable for the Du06 series, where the two-bladed and three-bladed turbines exhibit similar behavior. Additionally, two-bladed rotors generally demonstrated higher rotational speeds than three-bladed rotors, although the difference between them was more pronounced. These observations align well with the results of many previous studies (33, 47-49), indicating that two-bladed rotors tend to have higher rotational speeds. The higher rotational speed in two-bladed turbines compared to three-bladed ones is primarily attributed to their lower weight.

TABLE 4. DOE table for power

Wind speed	P(Du06-2b)	P(Du06-3b)	P(SC-2b)	P(SC-3b)
6.5			1.55	
7			1.93	
7.5			2.39	2.39
8		2.56	2.90	2.90
8.5		3.12	3.48	3.48
9	4.11	3.90	4.13	4.13
9.5	4.85	4.69	4.86	4.85
10	5.65	5.50	5.67	5.67
10.5	6.56	6.47	6.53	6.56
11	7.52	7.41	7.41	7.54
11.5	8.58	8.50	8.45	8.62
12	9.74	9.73	9.49	9.78

TABLE 5. DOE table for the rotational speed

Run	Blade profile	Blade number	Windspeed (m/s)	Rotational speed(rpm)
1	Du06	3	8	195
2	Du06	3	12	449
3	Du06	2	9	354
4	Du06	2	12	547
5	SC	3	7.5	453
6	SC	3	12	1077
7	SC	2	6.5	480
8	SC	2	12	1433

It is significant to point out that, aerodynamically, the semi-circular profile has shown greater effectiveness in terms of rotational speed compared to the Du06 profile. In Savonius turbines, which are highly drag-oriented, turbines with a semi-circular profile exhibit higher rotational speeds than those with the Du06 profile. The last parameter under consideration is turbine efficiency, defined as the ratio of the power coefficient to the tip speed ratio. The relationship between these two parameters (λ and the power coefficient) is presented in Figure 9 and Table 6.

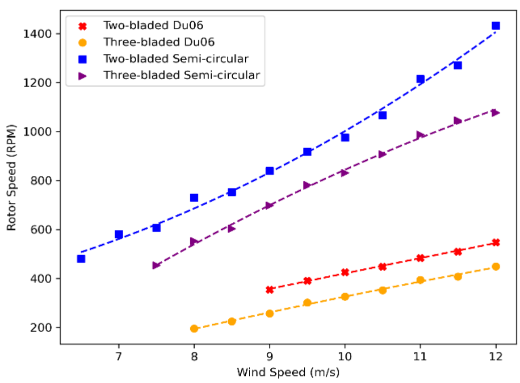

Figure 8. The rotational speeds to wind speed graph

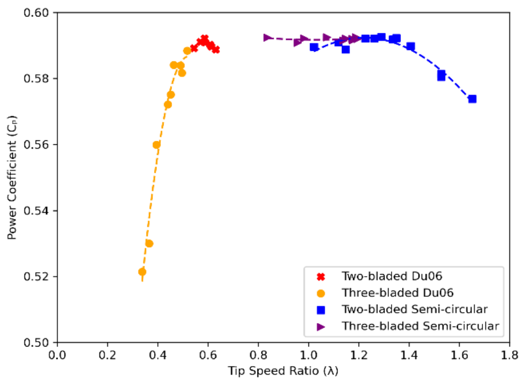

Figure 9. The coefficient power to lambda graph

TABLE 6. DOE table for the power coefficient to lambda

Run	Blade profile	Blade number	Power coefficient	Tip speed ratio
1	Du06	3	0.521	0.337
2	Du06	3	0.588	0.517
3	Du06	2	0.588	0.63
4	Du06	2	0.592	0.585
5	SC	2	0.580	1.526
6	SC	2	0.592	1.288
7	SC	3	0.590	0.956
8	SC	3	0.592	1.189

As demonstrated in Figure 6, two-bladed turbines achieve higher tip speed ratios compared to three-bladed turbines. One reason for the decrease in rotational speed with an increasing number of blades is the expansion of the drag area. However, this expansion also results in an increase in reverse torque relative to the total torque. In other words, while the drag force area increases positively with the addition of blades, the wind flow that generates lift force—which acts as a negative factor—increases simultaneously.

Generally, Savonius turbines are highly drag-based rotors, meaning that the main force driving rotational speed is the drag force, while the lift force partially acts as a negative force. The drag-based operation occurs as the curved blades of the Savonius turbine face the wind, causing air pressure imbalances that generate a net drag force on the concave part of the blade, which in turn causes the blades to rotate. Conversely, the lift force, acting on the convex part of the blade, tends to reverse the direction of rotation. The combined effect of these opposing forces negatively impacts the rotor's output. Therefore, adding more blades to the turbine does not necessarily result in an increase in angular velocity. Higher tip speed ratios are observed in the semi-circular turbines, due to their better aerodynamics for capturing drag forces. The three-bladed configurations exhibit an upward trend in TSR, while the two-bladed data show an ascending-descending pattern with a peak point. This indicates that three-bladed turbines demonstrate greater stability in terms of power coefficient, as airfoil efficiency depends on the turbine's utilization of input wind speed, and three-bladed turbines have a larger surface area for capturing wind compared to their two-bladed counterparts. Consequently, the output flow speed in three-bladed turbines is notably more stable than in two-bladed turbines. However, the analysis of power coefficients and optimal power coefficients in this study suggests that the difference in power output between the two configurations is minimal. On the other hand, two-bladed turbines achieve higher rotational speeds, primarily due to their lighter weight, resulting in higher speed but lower torque compared to three-bladed turbines. Thus, the tip speed ratio (λ) in two-bladed turbines is greater than in three-bladed turbines.

In this study, semi-circular blades demonstrated better speed and overall performance compared to the Du06 blades, although turbines with Du06 blades showed better speed-up times due to their specific aerodynamic profile. Table 7 summarizes the optimal parameters calculated for all turbine configurations.

According to the data shown in Table 7, the shortest speed-up time belonged to the two-bladed turbine with the Du06 profile, clocking in at approximately 11 seconds, about twice as fast as the two-bladed semi-circular turbine and three times faster than the three-bladed semi-circular turbine. In terms of final rotational speed, the two-bladed semi-circular turbine performed best, reaching 1433 rpm, which is roughly 33% faster than the three-bladed semi-circular turbine. This rotational speed exceeds that of the two- and three-bladed Du06 turbines by approximately 162 and 219%, respectively. Regarding the power coefficient, the two-bladed semi-circular turbine showed a slight advantage over the other turbines. The tip-speed ratio further emphasizes these performance differences: the two-bladed semi-circular turbine achieved the highest tip speed ratio of 1.65, indicating superior blade efficiency under the tested conditions. In comparison, the Du06 turbines had significantly lower tip speed ratios of 0.63 and 0.52 for the two- and three-bladed designs, respectively. Power output was relatively consistent across all configurations at their peak performance, with the three-bladed semi-circular turbine delivering the highest output at 9.78 W.

3. 1. Comparative Analysis

The current study's findings align with and expand upon previous research on Savonius vertical axis wind turbines, particularly regarding blade profiles and blade counts. Ikonwa et al. (39) identified the DU-06-W-200 airfoil as a promising design due to its superior starting torque and aerodynamic performance, which corroborates our observation that turbines with the Du06 profile, especially the two-bladed configuration, exhibit faster speed-up times and competitive tip speed ratios. This confirms the effectiveness of the DU-06-W-200 airfoil in enhancing turbine self-starting and rotational

TABLE 7. Optimal parameters for each turbine

Blade profile	Cp	λ	Rotation speed (rpm)	Speed-up time (s)	Power (W)
SC-2b	0.5925	1.65	1433	23.6	9.48
SC-3b	0.5920	1.19	1077	32.17	9.78
Du06-2b	0.5921	0.63	547	11	9.73
Du06-3b	0.5884	0.52	449	-	9.73

performance. In contrast, Wenehenubun et al. (32) concluded that three-bladed Savonius turbines demonstrate higher tip speed ratios and efficiency at lower wind speeds, with four-bladed configurations producing maximum torque in the 0–10 m/s range. Our results partially agree with this, as the three-bladed semi-circular turbine exhibited the highest power output and the most stable performance, even though the two-bladed Du06 turbine outperformed others in speed-up time and tip speed ratio. This suggests that blade number and profile interact complexly to affect different performance metrics, with the three-bladed design favoring power stability and magnitude, and the two-bladed Du06 profile excelling in acceleration and tip speed. Additionally, Gumilar et al. (33) reported that two-bladed turbines achieved the highest power capture at higher wind speeds (20 m/s). Although our experimental wind speeds were lower (up to 12 m/s), the trend of superior power generation by two-bladed turbines, particularly those with the Du06 profile, is consistent with their findings. This highlights the potential of two-bladed configurations in optimizing power output under varying wind conditions, reinforcing the importance of blade count and aerodynamic design in turbine efficiency. Overall, these comparisons underscore that both blade profile and blade number critically influence Savonius turbine performance, with the DU-06-W-200 airfoil and two-bladed configurations showing notable advantages in key operational parameters such as speed-up time and tip speed ratio, while three-bladed designs favor sustained power output.

4. CONCLUSION

This work aimed to investigate Savonius vertical axis wind turbines, with an emphasis on comparing performance parameters across different blade numbers and profiles. Four turbines, ranging from two to three blades and featuring semi-circular and Du06 airfoil profiles, were experimentally analyzed. The comparison focused on key parameters such as speed-up time, final rotational speed, power output, tip speed ratio, and power coefficient. The findings indicated that two-bladed turbines, particularly those with the Du06 profile, outperformed their counterparts in speed-up time and rotational speed, primarily due to their lower weight and aerodynamic advantages of the specific blade profile. However, the three-bladed semi-circular turbine demonstrated the most stable performance and the highest power output, despite the Du06-profile turbines exhibiting slightly lower tip speed ratios. These insights provide a comprehensive understanding of the factors influencing the performance dynamics of Savonius wind turbines, which is essential for optimizing their use in renewable energy applications. In summary, the study yielded several key findings, which are outlined below.

i. Two-bladed turbines, especially those featuring the Du06 profile, exhibited superior performance in speed-up time, tip speed ratio and rotational speed compared to their counterparts.
ii. The semi-circular turbines, particularly the two-bladed design, consistently achieved higher tip speed ratios, reflecting enhanced aerodynamic efficiency in converting wind speed to rotational speed.
iii. The semi-circular three-bladed turbine demonstrated the most stable performance and highest power, even though the Du06-profiled turbines had slightly lower tip speed ratios.
iv. Despite the slightly lower TSRs, the two-bladed Du06 turbine was able to deliver comparable or higher power output than the three-bladed Du06 turbine at elevated wind speeds, demonstrating the aerodynamic advantages of the Du06 profile in power extraction.
v. The lowest speed-up time was recorded for the two-bladed turbine with the Du06 profile, approximately twice and three times faster than both two and three-bladed semi-circular profile turbines
vi. The semi-circular two-bladed turbine achieved the highest final rotational speed at 1433 RPM, outperforming the semi-circular three-bladed turbine by about 33%. In comparison with the two and three-bladed Du06 turbines, this speed was 162% and 219% higher, respectively.
vii. The power coefficient of the semi-circular two-bladed turbine slightly surpasses that of the other turbines, with minimal variances observed among the two-bladed Du06, semi-circular three-bladed, and Du06 three-bladed turbines.

Given the existing theoretical framework, findings, and current limitations, the following research suggestions and directions can be proposed, which provide the groundwork for new research avenues:

1) Investigating and comparing various types of Savonius turbine blades to enhance performance.
2) investigating intermediate designs (e.g., hybrid overlapping blades) and higher blade counts (four or more)
3) Adjusting the overlap ratio of blades to determine the optimal overlapping efficiency in turbines.
4) Conducting experiments at higher inlet speeds.
5) Employing combined Darrieus and Savonius airfoils in vertical-axis turbines.
6) Experimenting and evaluating the performance of turbines implemented in water tunnels to reduce flow velocity and pressure in channels and generate electricity.

STATEMENTS AND DECLARATIONS

Funding The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

Availability of data and materials The data that support the findings of this study are available on request from the corresponding author.

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval We would confirm that this paper has not been published nor submitted for publication elsewhere. We confirm that we have read, understand and agreed to the submission guidelines, policies and submission declaration of the journal.

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Persian Abstract

چکیده

در دهه‌های اخیر، تأثیر زیست‌محیطی تولید انرژی منجر به تلاش‌های فزاینده جهانی برای گذار از سوخت‌های فسیلی آلاینده به منابع انرژی تجدیدپذیر شده و توجه قابل توجهی را از سوی سازمان‌ها و محققان به خود جلب کرده است .این گذار به دلیل افزایش نگرانی‌های زیست‌محیطی و محدودیت دسترسی به سوخت‌های فسیلی ضروری است .همزمان، استقرار توربین‌های بادی در سراسر جهان به طور قابل توجهی گسترش یافته است .هدف این مطالعه ارائه یک طراحی بهینه توربین بادی محور عمودی Savoniusمناسب برای کاربردهای شهری است .دو مدل توربین با تعداد و پروفیل‌های مختلف پره طراحی، ساخته و به صورت تجربی آزمایش شدند .این توربین‌ها شامل پیکربندی‌های دو پره و سه پره بودند که از پروفیل‌های پره نیم‌دایره‌ای و Du06-W-200 استفاده می‌کردند .ارزیابی عملکرد بر پارامترهای کلیدی از جمله ضریب توان، سرعت چرخش نهایی، توان خروجی، نسبت سرعت نوک و زمان رسیدن به حداکثر سرعت چرخش متمرکز بود .نتایج نشان داد که توربین دو پره نیم‌دایره‌ای بالاترین سرعت چرخش نهایی ۱۴۳۳ دور در دقیقه را ارائه می‌دهد که تقریباً ۳۳٪ بیشتر از توربین نیم‌دایره‌ای سه پره و بیش از ۱۶۰٪ بیشتر از توربین‌های با پروفیل Du06 است .همچنین این توربین بالاترین ضریب توان را در بین تمام توربین‌های آزمایش‌شده به دست آورد .توربین دو پره (Du06-W-200) با رسیدن به سرعت نهایی تنها در ۱۱ ثانیه، دو برابر سریع‌تر از توربین نیم‌دایره‌ای دو پره و سه برابر سریع‌تر از پیکربندی نیم‌دایره‌ای سه پره، سریع‌ترین شتاب را نشان داد .در حالی که توربین‌های با پروفیل Du06 نسبت سرعت نوک کمی پایین‌تری نشان دادند، توربین نیم‌دایره‌ای سه پره پایدارترین توان خروجی را نشان داد .این یافته‌ها نشان می‌دهد که توربین‌های ساونیوس با پیکربندی‌های آزمایش‌شده برای محیط‌های شهری مناسب هستند، اگرچه اثربخشی آنها به شدت به شرایط جغرافیایی و آب و هوایی محلی بستگی دارد.