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Experimental Investigation of Zigzag Height Variation on the Concave Blade Surface and Its Impact on Savonius Rotor Performance

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***Abstract*—Clean energy offers a sustainable alternative to decreasing reliance on fossil fuel sources that significantly contribute to global CO_2 emission and climate change. Wind energy extracted commonly using wind turbines has emerged as a viable and eco-friendly choice among many renewable energy sources. A Savonius rotor as a vertical axis wind turbine is especially suitable for small-scale energy generation units due to its straightforward design, economic viability, and efficiency in low wind speed areas. This report examines the impact of altering the zigzag pattern heights on the central area of the concave blade surface on turbine performance. The investigation was experimentally conducted to test the variation of such blade designs on turbine efficiency. The turbine performance parameters, including power and torque coefficients, were assessed. A conventional Savonius turbine using semi-circular blades was employed to undertake additional testing for comparison. The turbine achieved the highest power coefficient of 0.315 at a tip speed ratio of 0.8 at a wind speed of 6 m/s for turbine blades using a 2 mm zigzag pattern height. This model performed a wide range of efficiency with tip speed ratio values ranging from 0.6 to 0.8. In comparison to the conventional Savonius blades, a 26.5% increase in efficiency was observed. Consequently, this investigation has shown that the power coefficient could be substantially improved by implementing a 2 mm zigzag modification on Savonius turbine blades.**

***Keywords*—Zigzag pattern; rougness surface; concave blade; drag coefficient; wind energy.**

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I. INTRODUCTION

In the past few decades, global concern over the impacts of over-exploitation of non-renewable energy resources has intensified [1]. The notable rise in CO_2 emissions adversely affects the environment, requiring a transition from fossil fuels to clean energy [2]. Renewable energy denotes energy obtained from natural sources that can be perpetually regenerated, including solar and wind energy. The application of wind energy is enabled using turbines that allows the kinetic energy of the wind to be converted into mechanical energy of the shaft and then transformed into electrical energy with a generator or used directly as a driving force for simple mechanical devices. Wind turbines are generally designed and developed for large-scale applications, with an emphasis on operation under high wind speed conditions [3]–[5]. In areas with low wind speeds, like Indonesia [6]–[8], where the average wind speed often drops below 7 m/s, wind energy systems often prefer smaller, more efficient turbines specifically engineered to function well at low wind velocities, namely, Savonius wind turbine [9], [10].

The Savonius rotor is capable of working with low speed wind from all directions, and being cost-effective to produce [11], [12]. Classified for small-scale applications, the Savonius turbine comes to multiple benefits that include simple construction design, great starting torque, low wind speed capability, and ability to catch wind in any horizontal direction. The distinctive qualities of the Savonius turbine make it particularly suitable for usage in urban environments, where erratic wind flow patterns usually apply. However, the Savonius turbine has quite poor efficiency, about 18%, which restricts its use in large-scale energy producing systems. Continuous research is therefore in progress to maximize its aerodynamic properties and increase its energy conversion efficiency [9], [13], [14]. Therefore, modifications are necessary to enhance its overall performance.

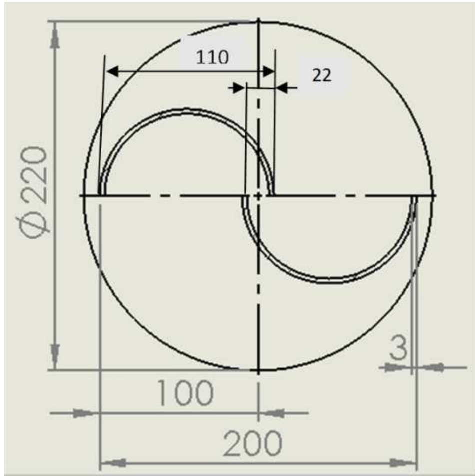
Usually, the Savonius turbine performance is evaluated from ability to produce the main parameter values, namely, Cp and C_T [15]. According to Xiao-Hang Wang et al. [16], the inclusion of endplates has a substantial impact on turbine performance, achieving an enhancement of up to 299.7% relative to turbines without endplates, as demonstrated in the experiment. Their role is to minimize flow leakage around the edges of the blades. Alom et al. [17] examined through numerical techniques four geometric changes of the Savonius rotor. The modified Bach geometry turned out to have the highest power coefficient (*Cp*) of 0.34. Furthermore, Tania et al. [18] explored the ideal overlap ratio for Savonius turbines by examining overlap ratios of 0.15, 0.20, 0.25, and 0.30. Their findings indicated that an overlap ratio of 15% was the most effective for applications at wind velocities lower than 4 m/s, while an overlap ratio of 30% was better suited for wind velocities exceeding 4 m/s. Farozan et. al. [19] determined that an increase in twist angle and the number of steps, or a reduction in the aspect ratio (*AR*) between turbine height and diameter, decreased both initial wind speed magnitude and its variability.

A Savonius turbine works based on the drag difference of its turbine blades [20]. To speed up the turbine, the drag force on the curved side needs to be more powerful. One way to do this is to add more bumps to the curved side. Several studies have shown that areas that are not smooth may make the drag coefficient higher [21], [22]. A simulation study has shown that the power coefficient (*Cp*) for the wavy rotor went up by about 14.5% when its tip speed ratio (λ) was set to 0.4 [23]. Comparatively to the elliptical rotor evaluated at inlet velocity of 7–10 m/s, experimental findings reveal an 18% improvement in performance rotor with a concave wave pattern [24], [25]. An increase in efficiency of a Savonius turbine using a 1-mm thickness zigzag pattern on the center area of its concave blade was obtained numerically at a wind velocity of 5 m/s. The simulated drag force from the data shows a drag increase as the zigzag height increases [26]. A special type of wind turbine called a wavy elliptical Savonius rotor, which has a small overlap (10%) and uses guided airflow, worked 22.8% better than a regular rotor at a wind speed of 9 m/s [27]. Sumiati et al. [28] notices that turbines with a zigzag pattern on whole curved surface or at the blade tip produce higher peak torque than those with a zigzag surface in the middle of the blade. However, the latter had more stable rotational performance with fewer torque fluctuations and no negative torque.

Although investigation has been carried out on the application of concave blade surface roughness to improve Savonius performance at high wind speeds of 7–10 m/s, limited research has been conducted on the effect of zigzag height variations at low wind speeds using experimental methods. Hence, this study investigates the impact of the zigzag form on the concave surface of Savonius turbine blades with experimental analysis in a wind tunnel. This research aims to determine the effect of zigzag roughness heights on the concave blade surface on the power and torque coefficient characteristics of the Savonius rotor.

II. Materials and Method

This investigation utilizes Savonius blades with the same dimensions as detailed in Fig. 1 and Table 1. The improved turbine model features a zigzag roughness surface on the central area of the concave blades with various heights of 2, 1, and 0.5 mm. The central zigzag arrangement is used to enhance the consistency of the rotor's rotation and reduce vibrations that could result in adverse effects rotor efficiency [26]. Moreover, the zigzag configuration enhances the surface coverage of the Savonius rotor, enabling it to harness a greater amount of wind energy. The model under investigated was created with ZW3D CAD software and subsequently fabricated using a three-dimensional printing device.



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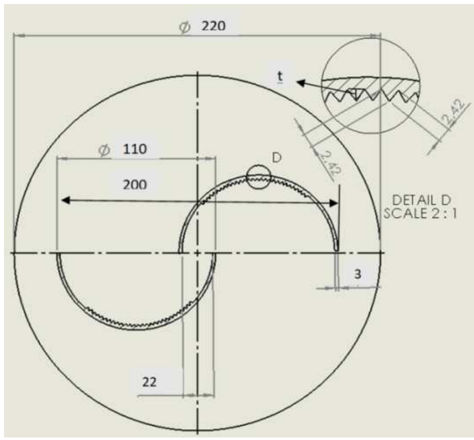


(b)

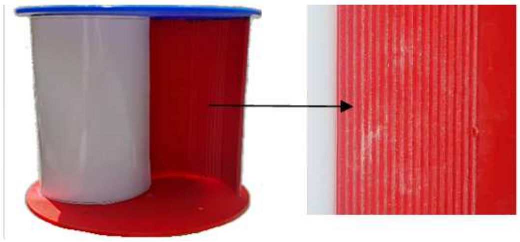
Fig. 1 Dimension (in mm) of Savonius models: a) conventional rotor b) rotor with zigzags of different heights

TABLE I
DETAIL BLADE DIMENSIONS

Parameter	Dimension
Rotor diameter (*D*)	200 mm
Endplate radius	110 mm
Overlap Ratio (*OR*)	0.2
Aspect Ratio (*AR*)	1
Number of blades	2
Blade radius	55 mm
Height of the blades (*H*)	200 mm
Thickness of the blade	3 mm
Rotor material	PLA
Testing air velocities (*U*)	4, 5, and 6 m/s

The Savonius turbine under investigation has rotor diameter of 200 mm, endplate diameter of 220 mm (1.1D) as well as blade diameter of 110 mm. The endplate dimension was selected based on previous studies that suggest that it optimizes the Savonius turbine performance by enhancing efficiency. The implementation of 1.1D endplates results in a substantial performance improvement with an efficiency increase of about 300% compared to the turbine without endplates [16]. According to previous studies, an overlap ratio of 20% has been identified as an optimal parameter for maximizing the efficiency of Savonius turbines [29]. This optimization is attributed to the overlap ratio effect on airflow characteristics around the turbine blades that facilitates the formation of jet flow, thereby enhancing rotor torque. The turbine configuration utilizes two blades that result in better rotational stability.

Each part of the Savonius turbine is made of PLA filament using a three-dimensional (3D) printer. The filament is a recyclable, starch-derived organic material. Prior to the commencement of the 3D printing process, numerous preparation steps are necessary. A 3D modeling software is used to design the turbine model, and the resulted file is stored in STL format, which preserves the model design in a triangular or tessellated configuration. A computer subsequently recognizes the edges and position of the triangular configuration that facilitates the making of a 3-dimensionally printed image. The STL-format file is subsequently prepared with Flash Print application software to convert it into G-code. This process enables the 3-dimensional printer to comprehend the digital model for constructing the physical form of the Savonius turbine. Fig. 2 displays 3D printer outputs of the turbine model.



(a)

(b)

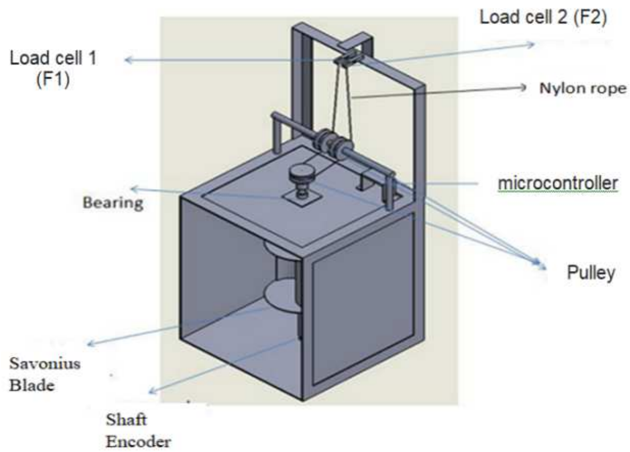
Fig. 2 (a) Zigzag model, (b) Semi-circular model

This research was conducted at Fluid Dynamics Laboratory of Universitas Andalas. The wind tunnel used in this study is a low-speed open-cycle wind tunnel that provides controlled airflow conditions during testing. The equipment is shown in Fig. 3. Wind speed measurements were directly obtained using a Pitot tube manometer to ensure accurate and reliable data for the analysis of turbine performance. The employed manometer is the DMP 201N25. The inlet velocity is regulated by using the inverter frequency of the wind tunnel blower motor. The wind tunnel utilized for testing the Savonius wind turbine has cross-sectional dimensions of 450 mm × 450 mm × 2000 mm. This controlled experimental setup ensures consistent airflow conditions, enabling an accurate evaluation of the turbine's aerodynamic performance. The Pitot tube is positioned in the centre of the wind tunnel in front of the object being tested. The wind speed is estimated using Eq. 1, depending on the data from the manometer [30].

$$U = \frac{2\rho_{water} \cdot g \cdot \Delta h}{\rho_{air}} \tag{1}$$

In this context, g represents gravity (9.81 m/s²), ρ_{water} denotes the water density (1000 kg/m³), ρ_{air} indicates the air density (1.2 kg/m³) as well as Δh is manometer level difference in mmH_2O.

(a)



(b)

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Fig. 3 Experimental equipment: (a) the low-speed wind tunnel, (b) sketch of the experiment set-up, (c) tested turbine in test section

The flowchart of the research steps is illustrated in Fig. 4.

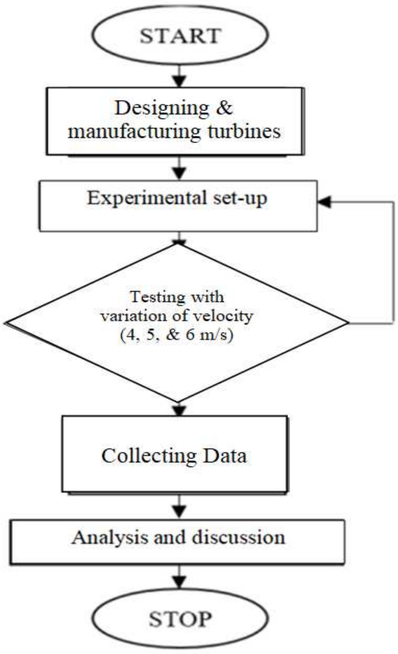


Fig. 4 Steps of the research

This research starts with the turbine design phase and is then followed by the manufacturing stage utilizing three-dimensional (3D) printing technology. Once the fabrication process is completed, the assembly phase is conducted where the rotor components are systematically arranged. Afterwards, the assembled rotor is mounted onto the test rig and then followed by preparation and calibration procedures in the test section. Subsequently, a measurement system is integrated for collecting output data of braking forces and rotational speed, which supports the quantitative performance analysis of the turbine

Savonius turbine output power is calculated by rotational speed measured using a tachometer or encoder and by dynamic torque measured using a Prony braking system at various loads started from rotational speed without load until the turbine shaft rotation stops. One load cell measures the applied load F_1, while another one measures F_2 (Fig. 3b). The above mentioned dynamic torque is derived based on Eq. 2 [31] as follows:

$$\frac{T}{R} = (F_1 - F_2) \text{ or } T = \Delta F\, R \qquad (2)$$

where R is the radius of the pulley used for the Prony brake system.

The turbine torque coefficient (C_T) as the ratio of dynamic torque (T) and available torque is computed using Eq. 3 [31].

$$C_T = \frac{T}{\frac{1}{4}\rho\, D^2 H\, U^2} \qquad (3)$$

The turbine power coefficient (C_P) is determined by Eq. 4 [31].

$$C_P = \frac{T\,\omega}{\frac{1}{2}\rho\, D\, H\, U^3} = C_T\,\lambda \qquad (4)$$

where λ is turbine tip speed ratio (*TSR*) computed using Eq. 5 [31] as follows.

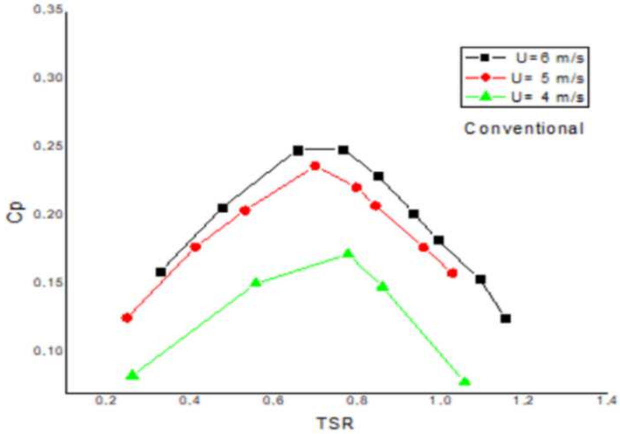
$$\lambda = \frac{\omega\,(\frac{1}{2}D)}{U} \qquad (5)$$

where $\omega = \frac{2\pi}{60}\, RPM$.

RPM denotes the rotating velocity of the Savonius rotor shaft, quantified using a tachometer or encoder.

III. Results and Discussion

Fig. 5 shows four *Cp-TSR* graphics representing each efficiency characteristic of four turbine models tested. The turbines were tested in the wind tunnel exit section at wind speeds of 4, 5 and 6 m/s. This assessment was conducted to investigate the effect of four different blade designs on overall turbine performance.



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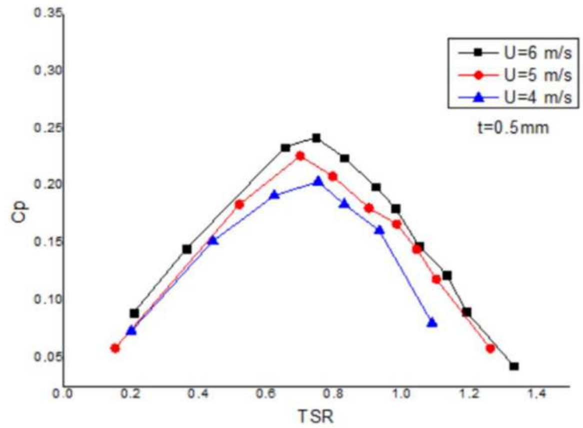

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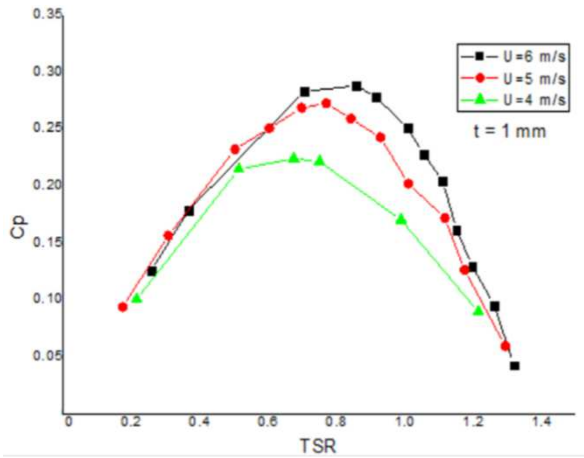

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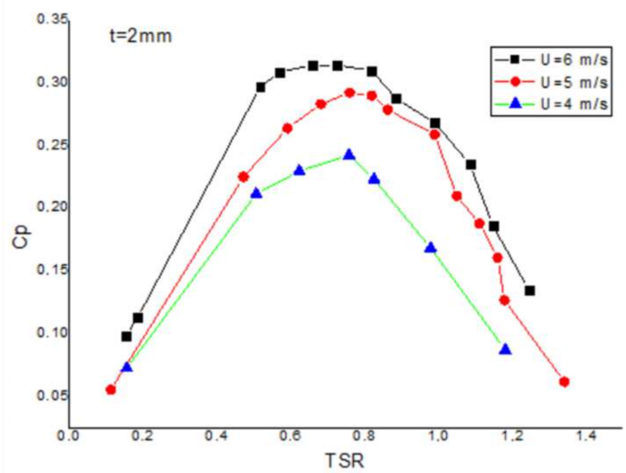

(d)

Fig. 5 Characteristics of *Cp-TSR* at various inlet velocities for models tested: (a) conventional, (b) t=0.5mm, (c) t=1mm and (d) t=2mm

The study highlights the efficiency of rotor under varying velocity inlet and zigzag heights. At the wind speeds of 4–6 m/s, the conventional model reached high power coefficients (*Cp*) of 0.17–0.248. Turbines with zigzag modifications show improved performance of high power coefficients, i.e., a 0.5 mm height reached *Cp* of 0.20–0.245, a 1 mm height achieved *Cp* of 0.22–0.28, and a 2 mm height attained the highest *Cp* of 0.21–0.315, with broader efficiency ranging at higher wind speeds.

These findings demonstrate that increasing zigzag height enhances turbine efficiency and expands the λ or *TSR* range of peak performance. Previous studies have demonstrated that the drag coefficient increases proportionally with the height of the zigzag pattern [26]. Furthermore, the 2 mm zigzag version has a broader spectrum of efficient λ, making it especially beneficial for the rotor. The highly efficient λ range derived is ranging from 0.6 to 0.8, that corresponds with the experimental results documented in other investigations [31]–[33], [24].

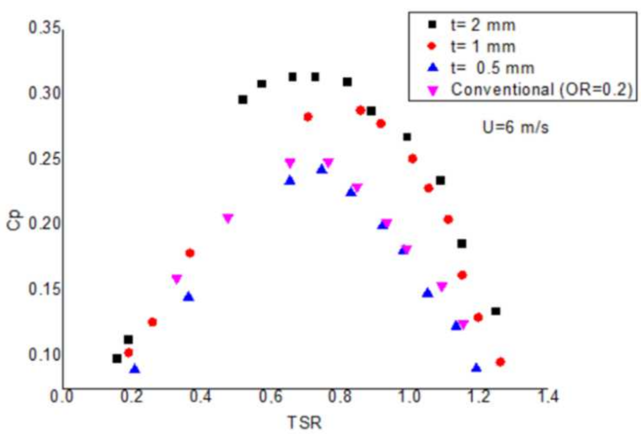

Fig. 6 Comparison of *Cp-TSR* for variation of Savonius rotors

Fig. 6 provides the analysis of the performance for the four analyzed rotors at the same wind speeds. This research result indicates that the turbine rotor using concave blades with a zigzag height of 2 mm delivers best rotor power coefficient performance. It reached the highest *Cp* of 0.315 at λ or *TSR* value of 0.8. Moreover, the peak efficiency range for this model is broader, that occurs at a λ of 0.6-0.8, with a *Cp* value exceeding 0.3.

The findings indicate that the 2-mm zigzag turbine demonstrates the most efficient performance under low wind speed conditions. The 2-mm zigzag roughness pattern demonstrates a significant efficiency improvement of approximately 26.5% compared to the conventional turbine tested. This enhancement may occur due to that the 2-mm roughness height is higher than the boundary layer thickness of the concave blade surface. As a result, airflow over this rough surface may enhance significantly turbulent mixing within the flow. This may lead to a rise in skin friction drag that increases the total drag of the concave blade used. This means, the fluid experiences higher resistance as it passes over rougher surface. On this fully rough surface, flow irregularities may dominate the boundary layer flow characteristics and significantly increase the drag of the concave blade. Hence, this modification positively impacts the output power of the Savonius rotor.

Compared to the other tested turbines, the improvement may be also most likely the result of a wider surface area due to the additional zigzag surface that gives advantage for wind energy harvesting. Moreover, the enhanced efficiency corroborates the idea that the zigzag surface alteration amplifies the concave blade drag, thereby augmenting the force difference between both blades and eventually enhancing the torque of the turbine [23], [28], [34], [35].

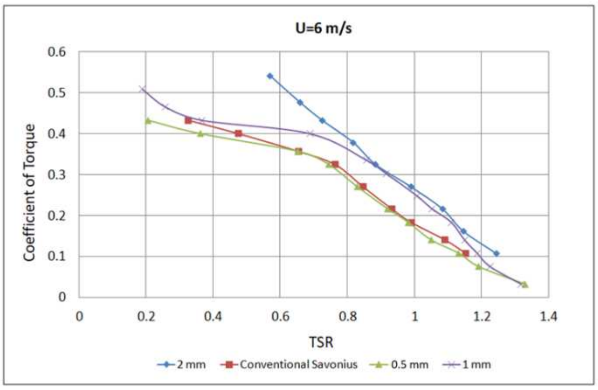

Fig. 7 Comparison of C_T-*TSR* curves for models tested at speed of 6 m/s

Fig. 7 illustrates the torque coefficient (C_T) characteristics of the four evaluated models at various *TSR* values up to 1.4. This finding reveals that the 2-mm zigzag model exhibits the highest efficiency enhancement. This result is consistent with previous studies that indicate a decrease in λor *TSR* value corresponds to an increase in torque coefficient [20], [36]–[38].

The experimental findings indicate that the modified model is much more efficient than the standard semicircular model. This enhancement is attributed to the revised model, which increases the concave blade drag. As a result, an increasing drag difference between the concave blade and the convex one can finally lead to increasing torque. Moreover, this modification enhances the concave blade surface of the Savonius turbine that allows it to extract a greater amount of wind energy. Previous research has employed numerical simulation to demonstrate that increasing the jet flow on the overlap side directs airflow toward the adjacent blade, thereby increasing the turbine's torque value [26].

This research used an experimental methodology with restricted modifications in zigzag heights, precisely 0.5, 1, and 2 mm. Nevertheless, the study is limited by its failure to address the optimization of height dimensions for optimal performance enhancement. This study is currently limited to a prototype tested in a wind tunnel. If implemented at full scale for real-world applications, the efficiency values may not be entirely identical. Therefore, further analysis is required to examine the similarity of performance parameters between the turbine model and the full-scale turbine. Typically, analysis should be conducted by maintaining the same Reynolds number.

IV. Conclusion

This study employed an experimental methodology to augment the Savonius turbine power coefficient through alterations to the zigzag height on its concave blade surface. This study utilized zigzag height variations of 0.5, 1, and 2 mm that is compared with standard Savonius blades serving as reference. The test result has shown a notable efficiency improvement of 26.5% for the Savonius turbine with a 2 mm zigzag height surface compared to the traditional rotor design. It is also found that the peak average efficiency at λ of 0.8 was achieved for all models tested. The modified rotor with concave blade surface using a zigzag height of 2 mm showed a wider range of high efficiency over a range of λ values.

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