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ENHANCING THE PERFORMANCE OF SAVONIUS ROTOR USING TIERED-HEIGHT ZIGZAG PATTERNS IN CONCAVE SURFACE

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A technique to reduce CO_2 emissions from the use of fossil fuels is to use clean energy. One of them is wind energy, which is generated by a wind turbine. Savonius, a type of vertical axis wind turbine, is a small-scale energy conversion device suitable for low wind speeds, such as those characteristic of Indonesian wind speed. The objective of the current study was to analyze the impact of implementing a tiered-height zigzag pattern on the concave surface of the Savonius blade. The zigzag angle operates to direct the wind toward the reverse blade, consequently augmenting the pressure on the reverse blade. In addition, the tiered-height zigzag pattern in the concave surface increases the area of the turbine that is in contact with the wind, which in turn generates more energy. This study used an open-type wind tunnel to conduct experiments as the primary technique of investigation. Its performance was assessed in terms of power and torque coefficients. Additionally, experiments were conducted with other standard semi-circular blades to get a direct comparison. According to the findings of the experiments, incorporating a tiered-height zigzag pattern into a concave surface may produce a power coefficient (Cp) that is 16 % higher than that of a semi-circular. The highest Cp was 0.286 at a TSR of 0.55 and U = 6 m/s. In this case, the Savonius wind turbine's ability may be elevated by including a tiered-height zigzag pattern in the Savonius concave surface.

Keywords: wind energy, savonius rotor, tiered-height zigzag, coefficient of power, concave surface

1 INTRODUCTION

A significant portion of the community's energy derives from fossil fuels, which have a detrimental influence on the environment due to CO_2 emissions [1][2][3]. Therefore, renewable energy research is taking place to accelerate the share of renewables and reduce fossil fuel consumption. Another alternative energy source is wind energy which is abundant yet currently underdeveloped. Wind energy has been chosen as an electric energy source because it emits no carbon dioxide gas and hence doesn't contribute significantly to greenhouse gas emissions [4]. A wind turbine is an apparatus designed to facilitate the use of wind energy by means of the conversion of the wind's kinetic energy into usable mechanical or electrical energy [5] [6]. The energy amount generated by the turbine is governed by wind speed and turbine blade diameters [7]. As a consequence, the utilization of wind energy requires taking into consideration the wind speed profile in the operating area. Indonesia experiences low wind speeds [8], therefore it is important to choose wind turbines that are appropriate for these conditions. The Savonius rotor could rotate effectively at low velocity of the wind because it has good self-starting at low wind speeds and absorbs wind energy from all directions [9]–[11][12]. The Savonius rotor is appropriate for installation in countries close to the equator with a with relatively low average wind speeds (4-5 m/s) [13] .Even though the Savonious rotor has a simple structure and a low frequency, it has low efficiency [14]. The limited efficiency of Savonius can be improved by performing geometric optimization on its aerodynamic characteristics [15].

Many previous studies have attempted different geometric of the Savonius blade to explore the impacts of diverse design characteristics such as the number of buckets, overlap ratio (OR), endplates, aspect ratio (AR), and quantity of stage rotors. The most critical part of these studies is how the factors affect Savonious performance. Their empirical results pointed out that optimal OR is equivalent to 0.2 of the blade diameter [16]; The maximum power coefficient of the conventional blade design was 0.174 when the overlapping ratio was 0.15 and the endplate size ratio was equal [17]; In field settings, it has been shown that the power coefficient reaches its highest value when the overlap ratio is around 0.25 [18]. The range of 0.15 to 0.25 for OR increases performance and lowers negative torque because it enables the fluid velocity to function efficiently through the overlap between the blades of the rotor toward the reverse blade [19]. At 0.15 overlap ratio, the rotor's aerodynamic efficiency improves, whereas at bigger overlap ratios it decreases. It is mostly caused by the overlap's influence on the advancing blade's torque generating mechanism [20].

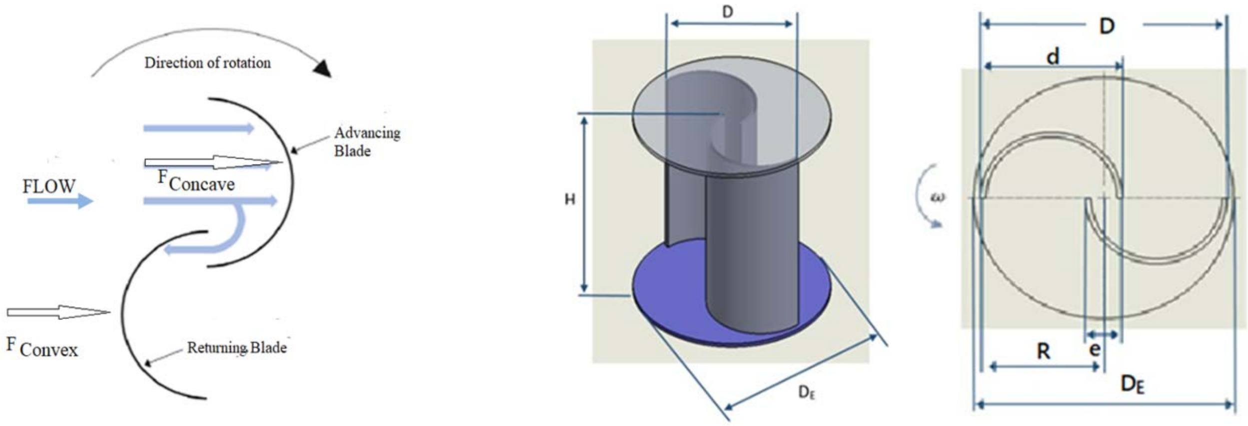
The following are some of the researches that have been carried out about the aspect ratio parameters. Cp generated by the Savonius rotor grows as the aspect ratio increases [21], the aspect ratio influences Savonius aerodynamics. For practical applications, multi-stage Savonius rotors with stage aspect ratios equal to or higher than 1.0 are strongly recommended [22]. Savonius' performance is also affected by the number of blades. The Savonius efficiency decreases as the number of blades grows, and the turbine appears unstable when three blades are applied because of the phenomenon of vertexing around the blade [14]. Talukdar et al. [23] state that a two-blade wind turbine has a 39.2% higher efficiency than a three-blade Savonius rotor. The number of stages also influences the performance turbine. Stages varied blade positions are the strategy to limit moment fluctuations without compromising performance in the Savonius turbine [24][25]. Furthermore, the use of endplates has a discernible effect on its efficiency [26]. Sivasegaram et al. [27] report that endplate diameter is 1.1 percent blade diameter to enhance its efficiency, That is advisable to utilize endplates with high aspect ratio, The durability of different blade configurations both with and without endplates was studied, a rotor with an endplate has more efficiency than a rotor lacking an endplate [28] [29].

Another feature that is thought to improve the efficiency of the Savonious is the direction-guide. According to Chong et al. [30] the Omni direction-guiding vane for Savonius may augment the energy output and be indicated for application in an urban area at low wind speeds. The external devices were intended to boost power, static torque, and self-starting capabilities [31]. The Savonius turbine harnesses disparities in the drag forces generated by the convex and concave sides of its rotor blades during spinning around a vertical shaft [32][33]. By improving the drag force on the concave surface and reducing the drag force on the convex surface, it is possible to increase the disparity in the total amount of drag force that is produced using this method. Several studies also examine the optimization of the concave at the Savonius rotor to boost its efficiency, such as increasing the number of layers, adding fins, and applying a pattern to the concave. since, in order to rotate the turbine, wind flow is known to be concentrated in the concave blades. In accordance with the experimental investigation conducted by Mery, A. et al.[34], [35] the open wind tunnel was utilized to test the capability of a waved concave elliptical blade with wind velocities of 6 and 9 m/s. The researchers recorded the hingest C_P= 0.296 at TSR = 0.72. The investigation revealed that modifying the internal surface of the concave blade may expand its surface area on the elliptical blade of the Savonius. In their study, Al-Gburi et al. examined the characteristics of an elliptical blade profile with an inner wavy region, overlap ratio of 0.109, and a configuration consisting of two blades. The present investigation exhibited the maximum power coefficient [36].

Due to limited discussions on applying surface roughness, texture, or a wavy pattern to the semi-circular concave of the Savonius rotor for enhancing its performance, surface roughness emerges as a method that may be used to increase the drag force on the concave area. In this work, we investigated the influence of roughness on a concave surface with a zigzag profile. The zigzag on the concave surface was designed to be taller on the outside, and the angle of reflection towards the overlap region was adjusted to direct the airflow to the reverse blade, thereby elevating the rotor's torque. The primary objective of this study was to evaluate the impact of implementing a tiered-height zigzag pattern on the concave surface of the Savonius rotor in terms of its overall efficiency. Goodhand et al. [37] report that the application of roughness or wavy to an airfoil depicts that drag increases as roughness increases.

2 BASIC CONCEPT SAVONIUS

The geometry of the semicircular Savonius is depicted in Fig 1. The basic concept of the Savonius turbine is to take advantage of the difference in drag on the two buckets causing the turbine to revolve [33].



a b

D	Diameter of turbine (m)	D_E	End plate diameter (m)
d	Blade diameter (m)	H	Turbine height (m)
ω	Angular velocity (rad/s)	AR	Aspect ratio (H/D)
e	Overlap Distance (m)	OR	Overlap ratio (e/d)
R	Radius of turbine (m)		

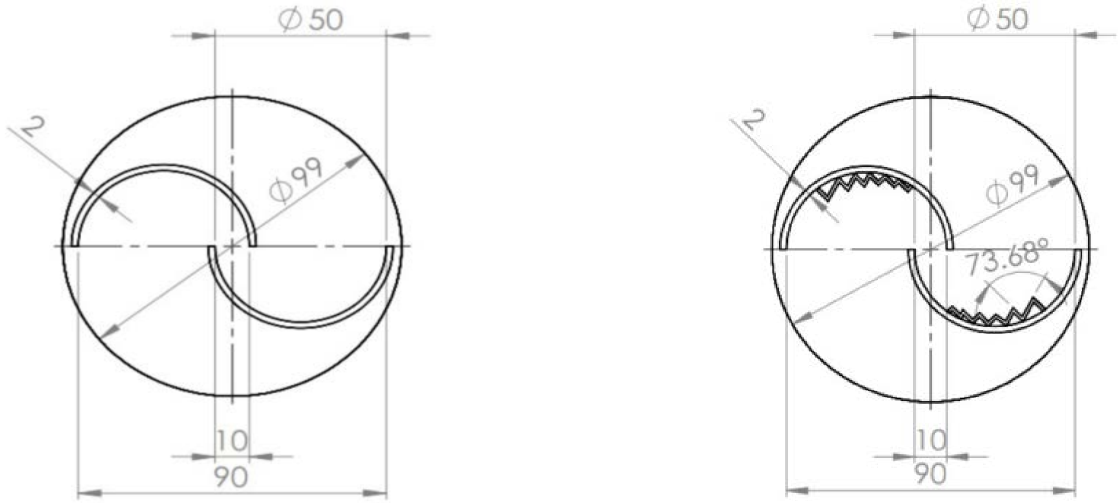
Fig. 1. The simple construction of Savonius (a) Working principle (b) Geometry

The greater the difference in torque, the more mechanical power is generated. Therefore, the S-rotor geometry should be optimized to achieve high power at low wind speeds, and the advancing blade should have more drag to generate torque and minimize drag on the returning blade [38]. To maximize the utilization of wind energy for

Savonius rotor, one way is to increase the concave force (drag force), which can be achieved by applying a zigzag pattern. Figure 1a shows that if F concave > F convex, it increases the torque value, which affects the performance improvement of the Savonius turbine.

3 THE MATERIALS AND METHOD

In this study, the Semi-Circular rotor and the new model Savonius rotor with a zigzag in the concave surface Savonius were investigated in the wind tunnel. Development and design of the models were done using the ZW3D CAD software. The dimensions of both Savonius are identical, but one of them is applying a zigzag model in the concave surface. The purpose of creating a zigzag pattern is to improve the drag on the concave rotor surface. The zig-zag angle is designed to maximize wind reflection towards the overlap area. This results in greater pressure on the return blade, which in turn increases torque. The zigzag is constructed in tiers to avoid obstructing the wind flow towards the overlapping area. The zigzag model also can increase its surface area on the Savonius rotor.



(a) (b)

Fig. 2. Dimension of model savonius a) Semi-circular Savonius b) Savonius with Using Tiered-Height Zigzag

Fig. 2 depicts the geometry of the model analyzed. The model has a geometry high 198 mm (2D), Blade Diameter (D) of 90 mm, diameter bucket of 50 mm (d), and aspect ratio = 2. In this study, the OR value was set at 0.2. Varying OR values were investigated, and the better OR value was obtained at 0.2 [19-20, 22, 37]. The endplate dimension was 99 mm (1.1 D), whilst according to Sivasegaram et. al. [29] endplate diameter needed was 1.1 percent blade diameter to increase savonius performance, and it is advised to be used on a slightly elevated aspect ratio to refine the efficiency of Savonius [28], [30]. Savonius rotor has two blades, in case three blades are applied, the turbine appears unstable because of the phenomenon of vortex around the blades [11]. According to Talukdar et al. [39] a two-blade wind turbine has a 39.2% higher efficiency than a three-blade savonius rotor. The rotor itself was made with a thickness of 2 mm.

The primary aim of this investigation is to examine the effects of the zigzag configuration on the concave surface on the performance of the Savonius rotor under low wind speeds. Testing at lower wind speeds is viable due to the inherent design features of the Savonius turbine, which enables it to capture wind from all directions and demonstrates efficient self-starting capabilities in low wind conditions [40]. For the experiment, a small-scale model was deemed sufficient, aligning with the available laboratory capacity at the Fluid Dynamics Laboratory, Universitas Andalas. Testing carried out at low wind speeds can affect the aerodynamic performance of rotor due to the separation of the laminar boundary layer at low Reynolds numbers [41]. This phenomenon leads to the formation of air bubbles, known as laminar separation bubbles, which cause additional drag on the turbine blades [42]. The Savonius turbine is a drag-type turbine that utilizes the difference in drag between its two blades to rotate. The influence of this bubble may be utilized for the performance of Savonius turbines. However, this case is not discussed in this paper.

By 3D printing (Creality Ender 3 Max), the Savonius rotor is created using the material polylactic Acid (PLA) plus. A thermoplastic monomer is also known as polylactic acid, which is manufactured from organic, regenerated substances like corn starch or sugar cane. CAD is applied to create pre-designed Savonius rotor models and then saved in an STL format file. 3D printing usually uses STL format files that can store the geometry information of a design. STL keeps the design in a triangle or tessellation language. Later, a computer can detect the edges and location of the triangle to produce the image to be printed in 3D [43]. The 3D printer output is consistent with the planned design. Fig. 3 depicts the 3D printing results of the model in the investigation

A B C D

Fig. 3. (a) The process of printing models (b) (Front view of model I (c) Top View of Model I (d) Model II

The investigations were enforced in a low-speed open-jet tunnel apparatus at the Fluid Dynamic Laboratory, Department of Mechanical Engineering, Universitas Andalas, Padang, Indonesia, as depictured in Fig. 4. The dimension of the wind tunnel test section was 450 x 450 mm^2, and the length of wind tunnel cylinder of 2000 mm. The model was positioned downstream of the tunnel exit. Low wind speed from 3-6 m/s was achieved by adjusting the frequency of the fan in the wind tunnel panel, using a manometer pitot tube pressure head measured. The pitot tube was located in front of the test object at the center of the tunnel 22.5 mm from the top. There was a hose linked the pitot tube to a digital manometer. The specifications of the monometer were as follows: Type DMP 201N25, Range: 20.0 mmHg, AC 220 Volt. The manometer panel automatically displays air pressure in the wind tunnel. The air pressure was transformed by Eq. 1 to get air velocity.

$$U = \sqrt{\frac{2\rho_{water} \cdot g. \, dh}{\rho_{air}}} \quad (1)$$

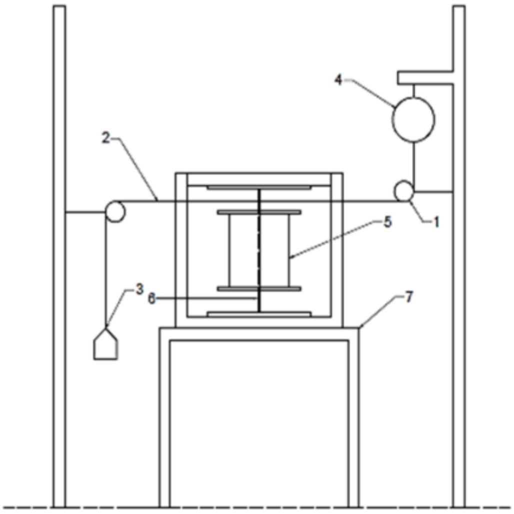
Fig. 4. Experimental setup

Where U is Air velocity in a wind tunnel (m/s), g is gravity (9.81 m/s^2), Dh is Head average air pressure on the manometer (mmH_2O), ρ water = water density of 1000 kg/m^3, ρ_{air} = air density of 1.2 kg/m^3. An AO-HT-81 digital anemometer is also used to verify that the air velocity matches the manometer's measurement results. Table 1 presents the wind speed data used in this study.

Table. 1 Data of wind speed

No	Hz	Δh (mmH_2O)	U m/s
1	10	0,685	3,342
2	12	0,985	4,007
3	14	1,400	4,777
4	16	1,769	5,370
5	18	2,210	6,002

An optical tachometer (DT-6236B) is the tool used to measure the turbine's rotational speed, with an accuracy of 0.05% +1 digital and an operating range of 3– 99,999 r/min sampling time 0.8 sec. Here, the shaft of the rotor turbine uses ceramic bearing 608 with a diameter of 8 mm. The Savonius model is put through its paces in the wind tunnel testing area, the mechanical loads (are applied to the turbine through a pulley connecting to its shaft and linked by a rope to the load. The Prony brake scheme of the mechanical torque measurement arrangement can be seen in Fig. 5.



Description:
1. Pulley
2. Rope
3. Load
4. Neraca
5. Savonius Rotor
6. Shaft
7. Frame

Fig. 5. Prony Brake Scheme of the mechanical torque measurement arrangement

The data collected of the test consisted of the turbine rotation speed by measuring the rotor shaft rotation using a tachometer. Samples were taken 10 times for each load and speed variation. The coefficient of performance is calculated using the average rotational speed.

Coefficient of torque (C_T) and coefficient of power (Cp) are the two main parameters that affect the Savonious' performance [32], [39]–[42]. The Coefficient of Power (Cp) represents the amount of wind energy that can be converted by the turbine rotor [43]. The C_P value is calculated using Eq. 2, which is the ratio between the actual power of the turbine (P) and the available power in the wind (P_A). The C_T value compares the actual torque produced with the torque available in the wind, as expressed by Eq. 3. TSR (λ) is the ratio between the speed of the rotor tip and wind speed. It can be calculated as the ratio of the speed of the tip blade to the wind speed through the blade, which is expressed by Eq. 4.

$$C_p = \frac{P}{P_A} = \frac{T.\omega}{\frac{1}{2}\rho\ A\ U^3} \quad (2)$$

$$C_T = \frac{T}{T_A} = \frac{T}{\frac{1}{2}\rho\ A\ U^2 R} \quad (3)$$

$$TSR\ (\lambda) = \frac{\omega\ R}{U} \quad (4)$$

$$\omega = \frac{2\pi}{60}\ N \quad (5)$$

Where ρ is the density of air measured in kg/m^3, U is the speed of the wind in the free stream measured in m/s, A is the swept area of the turbine measured in square meters (m^2), equal to the height multiplied by the rotor diameter (m^2), R is the radius of the turbine measured in meters, ω in Eq. 5 is the rotational speed of the turbine measured in rad/s, and P is the amount of power that is generated by the turbine. P_A is the power available in the wind [W].

4 RESULTS AND DISCUSSION

This study aims to determine the effect of a tiered zigzag pattern applied to the concave surface of a Savonius (Model I) on its performance and then compare it with a semicircular Savonius (Model II). The tests for both models were conducted under the same conditions; Fig. 6 illustrates the turbine performance when the load is applied by the prony brake on the rotor shaft (Fig. 5). At the same load, Model I exhibits a higher rotational speed than Model II. This occurrence arises due to the presence of a zigzag pattern on the concave surface of Model I, which has the potential to augment the drag force experienced by the concave side.

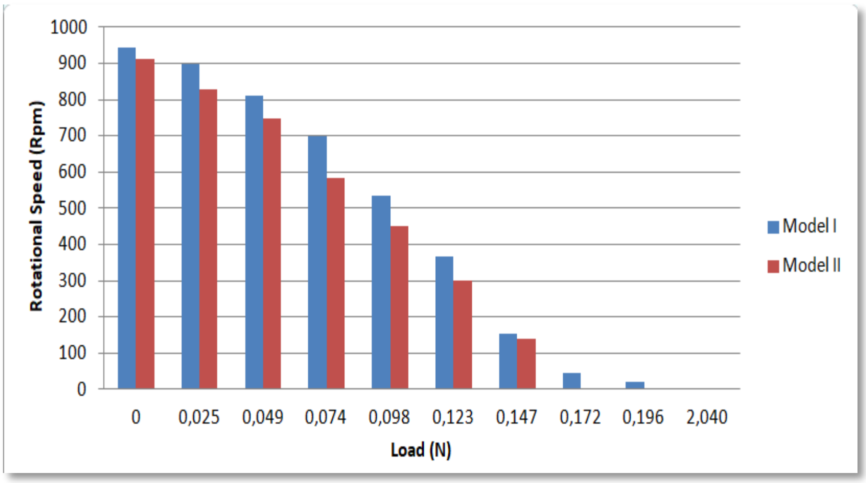


Fig. 6. Char Load – Rotational Speed

Consequently, this amplifies the disparity in force between the concave and convex surfaces. Aligned with the fundamental concept of the Savonius turbine, the generation of rotational motion is achieved by exploiting the variances in drag experienced by its two blades [44]. The science of aerodynamics claims that the shape and roughness of an entity may influence the airflow dynamics by altering the pressure and velocity of the fluid [45]. According to Gahraz et al. [46] in wind tunnel experiments using the FFA-W-3-270 airfoil profile with zigzag bands on the airfoil surface, it was observed that alterations in the height of the zigzag pattern on the surface potentially had an obvious effect on aerodynamic properties.

An overview of the performance of both turbines based on power and torque coefficients is shown in Figure 7-12. Performance of Model I can be illustrated in Fig. 7 and Fig. 8, namely the graph of the Cp-TSR and the graph of C_T-TSR respectively.

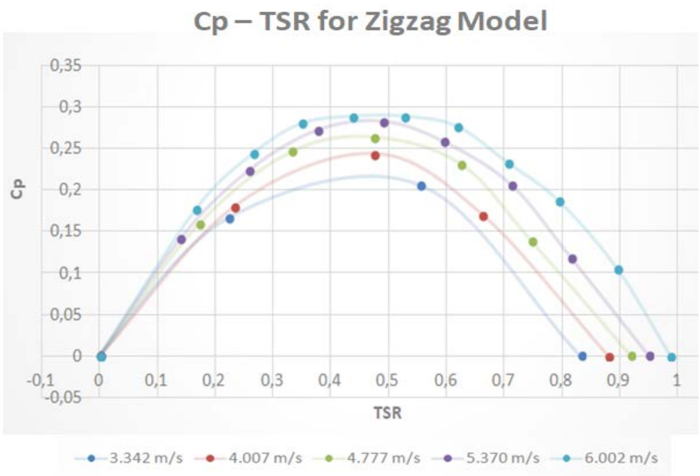


Fig. 7. Cp -TSR for Model I

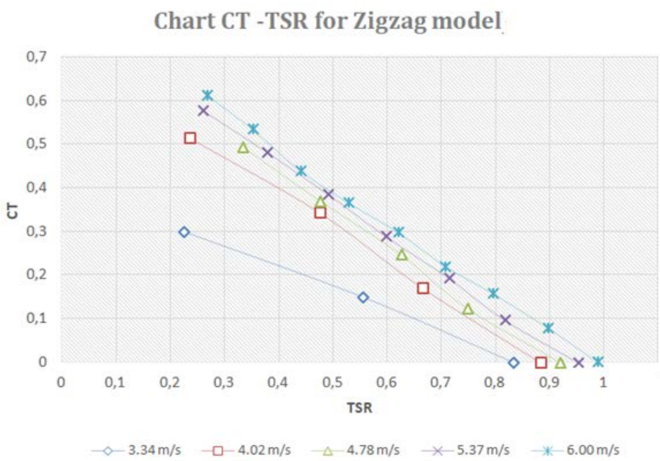


Fig. 8. C_T – TSR for Model I

Fig. 7 shows the Cp-TSR graph for five different speeds applied to Model I. The model has the characteristics of a Cp maximum at a TSR value in the range of 0.4 -0.6 at several variations of Velocity. Based on the five variations, the maximum Cp is obtained at U= 6 m/s. The maximum Cp value is 0.286 at a TSR of 0.54. The relationships between C_T and TSR for Model I shown in Fig. 8 depict C_T increases as the TSR falls. This graph trend appears to be consistent with previous studies [13], [33], [47]–[48].

The performance for model II is shown in Fig. 9. The results of the wind tunnel tests indicate a maximum Cp for the semicircular rotor of 0.24 at U = 6 m/s. The graph shows the highest Cp at each velocity found at TSR 0.4 - 0.6. C_T -TSR graph for Model II depicted in Fig. 10, C_T value increases with decreasing TSR.

The comparison of the C_P value between Model I and Model II is illustrated in Fig. 11. Describing Model I has a higher Cp value than Model II, which is 0.286 & 0.24 on TSR 0.55, respectively. It explains that adding a tiered height zigzag on the surface influences the working performance of the Savonius. The acquired findings align with prior research indicating that increasing the surface area enhances the turbine's ability to capture the wind's available energy, hence improving its performance [34], [44]. The coefficient of power (Cp) maximum for Model II has a similar magnitude to the Cp value produced by Roy and Saha [49] at the same conditions testing (U= 6 m/s), which serves as validation data.

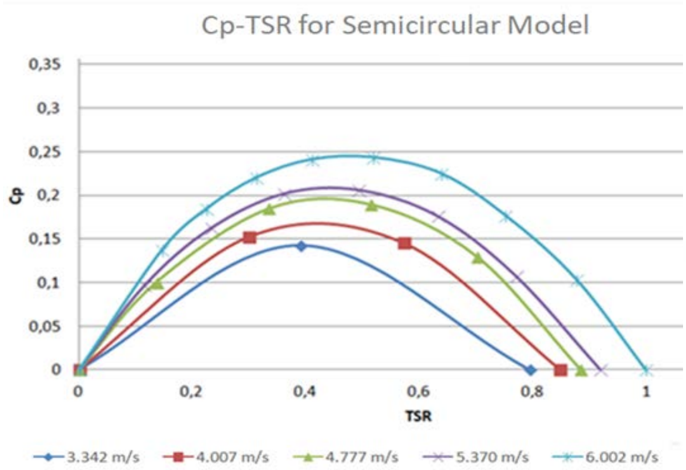


Fig. 9. Cp – TSR for Model II

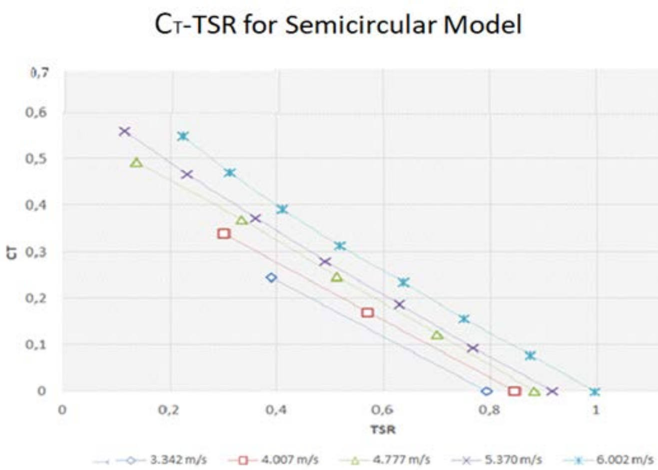


Fig. 10. C_T- TSR for Model II

The addition of a zigzag in the concave surface with different height could be increased Cp value to 16% compared with Model II. The presence of a zigzag pattern on the concave surface results in altered airflow dynamics in comparison to surfaces with smoother textures. When the airflow traverses the zigzag surface, it causes the airflow on the advancing blade to be more concentrated towards the overlap region. The act of directing the flow leads to changes in the pressure distribution over the surface of the blade.

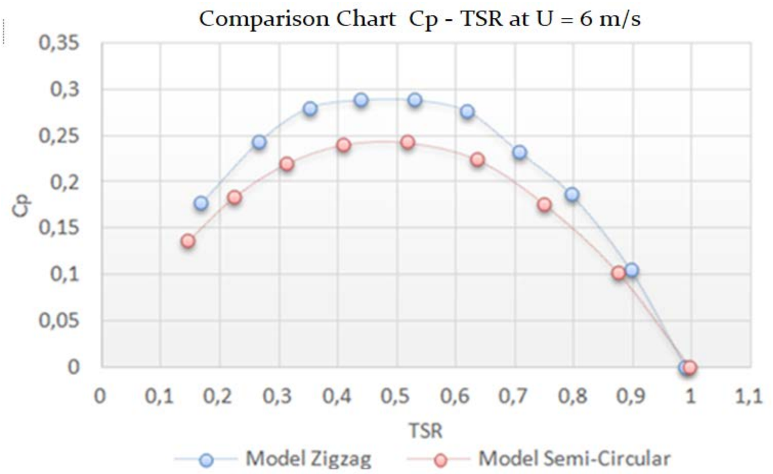


Fig. 11. Comparison Cp-TSR for Model I and Model II at U=6 m/s

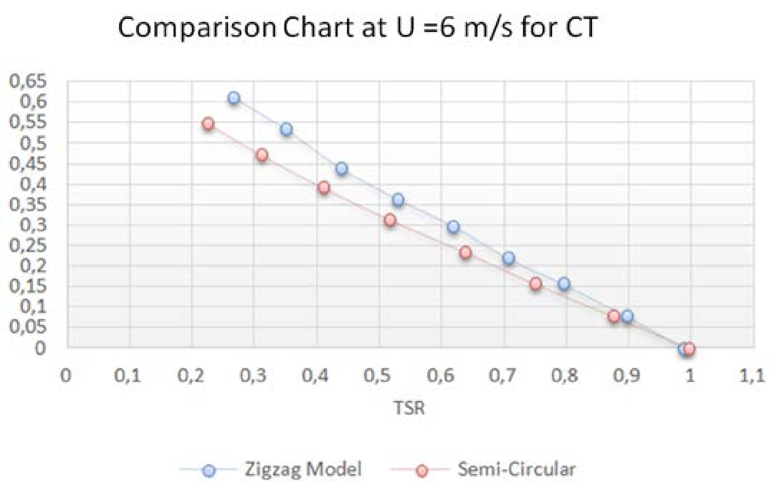


Fig. 12. Comparison C_T - TSR for Model I with Model II at U= 6 m/s

As can be seen in Fig. 12, the coefficient of torque (C_T) of Model I showed improvement from Model II. The test results indicate that model I has more efficiency compared to Model II. The reason for this phenomenon is the presence of the tiered-height zigzag surface, which enhances disparity drag between the concave and convex regions. Consequently, this discrepancy in drag values gives rise to a higher torque coefficient. A zigzag model in the concave surface was direct the airflow to the overlap area, which exerts additional pressure on the returning blade.

This model also could enlarge the surface area of the Savonius to absorb more wind force. The presence of Model I has an impact on the fluid flow pattern, velocity, and pressure distribution over the blade's surface. This phenomenon results in alterations to the aerodynamic force experienced by the rotor. The alteration in force has an impact on the aerodynamic performance of the rotor. Derived from the comparative graph, it becomes evident that incorporating a zigzag pattern on the concave blade surface yields an augmentation in the efficiency of the Savonius rotor.

This study is limited by the fact that the model was only tested in a wind tunnel at low wind speeds, equivalent to a low Reynolds number. The laminar boundary layer at low Reynolds numbers results in the formation of air bubbles. Further research could be conducted to investigate the potential drag caused by laminar separation bubbles at low Reynolds numbers. Additionally, the model has not yet been implemented on a larger scale. It is acknowledged that such a scale-up would inevitably influence the turbine's overall performance, particularly at low Reynolds numbers. Nevertheless, it can be utilized as foundational material for subsequent research.

5 CONCLUSIONS

This study was an experimental method for investigating the beneficial effects of adding a tiered-height zigzag to the concave surface of Savonius rotor. A zigzag pattern was created that was taller on the outside than the inside, which could direct the fluid flow to the advancing blade, and it could enlarge the surface area of the Savonius to absorb more energy. The experimental findings indicated a significant improvement in Cp of 16 % when compared to the performance of Model II. The highest efficiency was obtained U=6 m/s with Cp = 0.286 on TSR 0.55. In general, the application of the model provides enhanced comprehension regarding the control of airflow. The phenomenon above delivers positive results by reducing the drag generated in the region of overlap while concurrently augmenting the disparity in drag force exerted on the turbine blades in order to improve their rotation. The findings of this research provide a foundation for the progression of the zigzag pattern in the concave surface to improve the efficiency of the Savonius.

6 ACKNOWLEDGEMENT

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7 REFERENCES

[1] Olabi, A. G., and Abdelkareem, M. A. (2022). Renewable energy and climate change.Renew. Sustain. Energy Rev., vol. 158, Apr. 2022, Doi: 10.1016/j.rser.2022.112111.

[2] Curtin, J., McInerney, B. Ó Gallachóir, C. Hickey, P. Deane, and Deeney, P. (2019). Quantifying Stranding Risk For Fossil Fuel Assets And Implications For Renewable Energy Investment: A Review Of The Literature. Renewable and Sustainable Energy Reviews, vol. 116. Doi: 10.1016/j.rser.2019.109402.

[3] Yang, X., Pang, J., Teng, V., Gong, R., and Springer, C. (2019). The Environmental Co-Benefit And Economic Impact Of China 'S Low-Carbon Pathways: Evidence From Linking Bottom-Up And Top-Down Models. Renewable and Sustainable Energy Reviews. vol. 136, p. 110438, Doi: 10.1016/j.rser.2020.110438.

[4] Martin O. L. Hansen, (2008). Aerodynamics of Wind Turbines. Second Edition. Earthscan London

[5] Chang, Y., and Han Phoumin (2021). Harnessing Wind Energy Potential in Asean: Modelling and Policy Implications. Sustainability. vol 13, p. 4279, Doi: 10.3390/su13084279

[6] Burton, N. T., Jenkins, D., and Sharpe, E. B. (2011). Wind Energy Handbook Wind Energy Handbook, Second Edition. 2011. [Online]. Available: www.wiley.com.

[7] Dewan, A. Gautam, A., and Goyal, R. (2021). Savonius Wind Turbines: A Review Of Recent Advances In Design And Performance Enhancements. Material Today Procceding., Volume 47, Part 11, Pages 2976-2983, Doi: 10.1016/j.matpr.2021.05.205.

[8] Wijanarko, T., et. al. (2022). Assessing the Wind Energy Potential in Provinces of West Java, Papua, and East Borneo in Indonesia. Journal Of Applied Engineering Science vol. 20, no. 4, pp. 1053–1062, Doi: 10.5937/jaes0-35192.

[9] Wijayanto, D. S., Soenarto, Triyono, M. B., and Ibadi, H., (2022). Double-Stage Savonius and Darrieus Wind Turbines for Urban Areas Using Fiberglass Materials, Journal Of Applied Engineering Science, vol. 20, no. 2, pp. 386–394, Doi: 10.5937/jaes0-33297.

[10] Hariyanto, R., Soeparman, S., Widhiyanuriyawan, D., and Sasongko, M. N. (2018). Cfd Study On The Ability Of A Ventilated Blade In Improving The Savonius Rotor Performance, Journal Of Applied Engineering Science, vol. 16, no. 3, pp. 383–390, Doi: 10.5937/jaes16-17189.

[11] Sánchez, A. R., Del Rio, J. A. S., Quintana, E. C., and Sanín-Villa, D. (2023). Numerical Comparison of Savonius Turbine As a Rotor for Gravitational Vortex Turbine With Standard Rotor. Journal Of Applied Engineering Science, vol. 21, no. 1, pp. 204–211, Doi: 10.5937/jaes0-39847.

[12] Tasneem, Z. et al., (2020). An Analytical Review On The Evaluation Of Wind Resource And Wind Turbine For Urban Application: Prospect and Challenges. Developments in the Built Environment, vol. 4. Elsevier Ltd, Doi: 10.1016/j.dibe.2020.100033.

[13] Kurniawan, Y. et al. 2020. Experimental Study of Savonius Wind Turbine Performance with Blade Layer Addition. J. Adv. Res. Fluid Mech. Therm. Sci., vol. 69, no. 1, pp. 23–33, Doi: 10.37934/ARFMTS.69.1.2333.

[14] Al-Gburi, K. A. H. et al. (2021). A Comparative Study Review: The Performance Of Savonius-Type Rotors. Material Today Procceding. vol. 57, pp. 343–349, Doi: 10.1016/j.matpr.2021.09.226.

[15] Alom, N., and Saha, U. K. (2019). Evolution And Progress In The Development Of Savonius Wind Turbine Rotor Blade Profiles And Shapes. Journal of Solar Energy Engineering. Trans. ASME, vol. 141, no. 3, pp. 1–15, Doi: 10.1115/1.4041848.

[16] Rizk, M., and Nasr, K. (2023). Computational Fluid Dynamics Investigations Over Conventional And Modified Savonius Wind Turbines. Heliyon, vol. 9, no. 6, p. e16876, Doi: 10.1016/j.heliyon.2023.e16876.

[17] Saad, A. S. et. al., (2020). Performance Enhancement Of Twisted-Bladed Savonius Vertical Axis Wind Turbines," Energy Conversion Management, vol. 209, p. 112673, Doi: 10.1016/j.enconman.2020.112673.

[18] Mojola, O. (1985). On The Aerodynamic Design Of The Savonius Windmill Rotor. Journal of Wind Engineering and Industrial Aerodynamics., vol. 21, pp. 223–231, DOI: 10.1016/j.enconman.2020.112673

[19] Alomar, Z., et. al., (2023). Numerical and Experimental Study on the Effect of Overlap on Savonius Wind Turbine, International Journal of Power and Energy Systems, Vol. 43, No. 10. Doi: 10.2316/J.2023.203-0450.

[20] Fujisawa, N. (1992). On The Torque Mechanism Of Savonius Rotors. Journal of Wind Engineering and Industrial Aerodynamics.volume 40, Issue 3, p. 277-292, Doi: 10.1016/0167-6105(92)90380-S.

[21] Dorel, S. F., et. al., (2021). Review Of Specific Performance Parameters Of Vertical Wind Turbine Rotors Based On The Savonius Type. MDPI AG. Energies, vol. 14, no. 7, doi: 10.3390/en14071962.

[22] Ahmed S. O. M. A. and Saad, S., (2021). Influence of Varying the Stage Aspect Ratio on the Performance of Multi-Stage Savonius Wind Rotors. ASME: Energy Resour. Technol., vol. 144, no. 1, Doi: 10.1115/1.4050876

[23] Talukdar, P. K., et. al., (2018). Parametric Analysis Of Model Savonius Hydrokinetic Turbines Through Experimental And Computational Investigations," Energy Conversion and Management, vol. 158, pp. 36–49, Doi: 10.1016/j.enconman.2017.12.011.

[24] Saha, P. K., Thotla,S., and Maity, D. (2008). Optimum Design Configuration Of Savonius Rotor Through Wind Tunnel Experiments. Journal of Wind Engineering and Industrial Aerodynamics. vol. 96, no. 8–9, pp. 1359–1375, Doi: 10.1016/j.jweia.2008.03.005.

[25] Hayashi, T., et. al., (2005). Wind Tunnel Tests On A Different Phase Three-Stage Savonius Rotor," JSME Int. Journal, Ser. B Fluids Therm. Eng., vol. 48, no. 1, pp. 9–16, Doi: 10.1299/jsmeb.48.9.

[26] Jeon, K.S., et. al., (2015). Effects Of End Plates With Various Shapes And Sizes On Helical Savonius Wind Turbines. Renewable. Energy, vol. 79, no. 1, pp. 167–176, Doi: 10.1016/j.renene.2014.11.035.

[27] Sivasegaram, S., (1978). Secondary Parameters Affecting the Performance of Resistance-Type Vertical-Axis Wind Rotors. Sage Publications, Ltd: Wind Engineering. Vol. 2, No. 1, pp. 49-58 online: https://www.jstor.org/stable/43749784

[28] Altan B. D. and Atilgan, M., (2012). An Experimental And Numerical Study On The Improvement Of The Performance Of Savonius Wind Rotor. Energy Conversion and Management, vol. 49, no. 12, pp. 3425–3432, Doi: 10.1016/j.enconman.2008.08.021.

[29] Ogawa, Takenori (1986). The Effects Of A Deflecting Plate And Rotor End Plates," Bulletin of JSME, vol. 29, p. 2115-2121, Doi: 10.1299/jsme1958.29.2115

[30] Chong, W.T., et. al., (2012). Vertical Axis Wind Turbine With Omni-Directional-Guide-Vane For Urban High-Rise Buildings," J. Cent. South Univ. Technol. vol. 19, no. 3, pp. 727–732, Doi: 10.1007/s11771-012-1064-8.

[31] Salleh, M. B, Kamaruddin, N. M. and Mohamed-Kassim, Z., (2020). The Effects Of Deflector Longitudinal Position And Height On The Power Performance Of A Conventional Savonius Turbine. Energy Convers. Manag., vol. 226, p. 113584, Doi: 10.1016/j.enconman.2020.113584.

[32] Chen, L., Chen, J., and Zhang, Z., (2018). Review of the Savonius Rotor's Blade Profile And Its Performance. J. Renew. Sustain. Energy, vol. 10, no. 1, Doi: 10.1063/1.5012024.

[33] Al-Gburi, K. A. H., et al. (2022). Experimental and Simulation Investigation of Performance of Scaled Model for a Rotor of a Savonius Wind Turbine. Energies, vol. 15, no. 23, Doi: 10.3390/en15238808.

[34] Salleh, M. B, Kamaruddin, N. M. and Mohamed-Kassim, Z., (2020). The Effects Of Deflector Longitudinal Position And Height On The Power Performance Of A Conventional Savonius Turbine. Energy Convers. Manag, vol. 226, p. 113584, Doi: 10.1016/j.enconman.2020.113584.

[35] Chen, L., Chen, J., and Zhang, Z., (2018). Review of the Savonius Rotor's Blade Profile And Its Performance. J. Renew. Sustain. Energy, vol. 10, no. 1, Doi: 10.1063/1.5012024.

[36] Al-Gburi, K. A. H., et al. (2022). Experimental And Simulation Investigation Of Performance Of Scaled Model For A Rotor Of A Savonius Wind Turbine. Energies, vol. 15, no. 23, Doi: 10.3390/en15238808.

[37] Meri S. A. et al., (2019). Performance Evaluation of Savonius Wind Turbine Based on a New Design of Blade Shape. International Journal of Mechanical Engineering and Technology, vol. 10, no. 01, pp. 837–846. online: https://iaeme.com/MasterAdmin/Journal_uploads/ijmet/volume_10_issue_1/ijmet_10_01_087.pdf

[38] Meri S.A. and Bin Salleh, H. (2020)., Numerical Investigation of Savonius Rotor Elliptical and the Design Modification on a Blade Shape. Lecture Notes in Mechanical Engineering, pp. 177–185. Doi: 10.1007/978-981-13-8297-0_20.

[39] Al-Gburi, K. A. H., et. al. (2023). Enhancing Savonius Vertical Axis Wind Turbine Performance: A Comprehensive Approach with Numerical Analysis and Experimental Investigations. Energies, vol. 16, no. 10, Doi: 10.3390/en16104204.

[40] Goodhand, M. N., et. al., (2016). The Limitations Of Using 'Ra' To Describe Surface Roughness," J. Turbomach., vol. 138, no. 10, pp. 1–8, Doi: 10.1115/1.4032280.

[41] Al-Kayiem, H. H., Bhayo, B. A. and Assadi, H. 2016. Comparative Critique On The Design Parameters And Their Effect On The Performance Of S-Rotors. Renewable Energy, vol. 99. Elsevier Ltd, pp. 1306–1317, Doi: 10.1016/j.renene.2016.07.015.

[42] Talukdar, P. K. et. al. (2017). Parametric Analysis Of Model Savonius Hydrokinetic Turbines Through Experimental And Computational Investigations. Energy Convers. Management. vol. 158, no. October 2017, pp. 36–49, Doi: 10.1016/j.enconman.2017.12.011.

[43] Akwa, J. V.et al. (2012). A review on the performance of Savonius wind turbines," Renew. Sustain. Energy Rev., vol. 16, no. 5, pp. 3054–3064, Doi: 10.1016/j.rser.2012.02.056.

[44] Diwan, S.S., Ramesh, O.N. (2007). Laminar Separation Bubbles: Dynamics And Control. Sadhana 32, 103–109 https://doi.org/10.1007/s12046-007-0009-7.

[45] Takeyeldein, M. M. et. al. (2019). Wind Turbine Design Using Thin Airfoil SD2030. Evergreen, vol. 6, no. 2, pp. 114–123, Doi: 10.5109/2321003.

[46] Szilvási-Nagy,M., and Mátyási, G. (2003). Analysis of STL Files," in Mathematical and Computer Modelling, vol. 38, no. 7–9, pp. 945–960. Doi: 10.1016/s0895-7177(03)90079-3.

[47] Kurniawan, Y., Tjahjana, D. D. D. P., and Santoso, B. (2020). Experimental Studies of Performance Savonius Wind Turbine with Variation Layered Multiple Blade. IOP Conference Series: Earth and Environmental Science, vol. 541, no. 1. Doi: 10.1088/1755-1315/541/1/012006.

[48] Anderson, J. D. (2011). Fundamentals of Aerodynamics (6th edition), vol. 1984, no. 3.

[49] Gahraz, S. R. J. at. Al. (2018). Wind tunnel study of the effect zigzag tape on aerodynamics performance of a wind turbine airfoil," J. Adv. Res. Fluid Mech. Therm. Sci., vol. 41, no. 1, pp. 1–9

[50] Tjahjana, D. D. D. P. et al. (2021). Experimental study of the effect of slotted blades on the Savonius wind turbine performance," Theor. Appl. Mech. Lett., vol. 11, no. 3, p. 100249, Doi: 10.1016/j.taml.2021.100249.

[51] Grönman, A. et. al. (2019). Experimental and analytical analysis of vaned savonius turbine performance under different operating conditions. Applied. Energy, vol. 250, pp. 864–872, Doi: 10.1016/j.apenergy.2019.05.105.

[52] Roy, R. and Saha, U. K. (2015). Wind tunnel experiments of a newly developed two-bladed Savonius-style wind turbine. Applied. Energy, vol. 137, pp. 117–125, Doi: 10.1016/j.apenergy.2014.10.022.

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