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Performance Analysis of a Two-Stage Savonius Rotor Using Numerical Methods

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Abstract: The POCREN system is a hybrid renewable energy device that integrates wind, solar, and water current energy sources to generate electrical power. The main objective of developing POCREN is to provide a sustainable electricity supply, particularly for floating fish farmers in coastal regions where the average wind speed ranges from 3 to 5 m/s. Currently, most floating cage farmers rely heavily on diesel engines to meet their electricity needs, which are costly and environmentally unsustainable. This study focuses on one of the key components of the POCREN system, namely a two-stage Savonius wind turbine, to evaluate its performance in power generation. The analysis was conducted numerically using ANSYS Fluent software. The results show that the maximum power coefficient (Cp) of the two-stage turbine was achieved at a wind speed of 5 m/s with a tip speed ratio (TSR) of 0.7, yielding a Cp value of 0.26. At a lower wind speed of 3 m/s, the maximum Cp reached 0.22 at the same TSR of 0.7. Pressure contour analysis indicates that the two-stage Savonius turbine can operate effectively at low wind speeds of approximately 3 m/s. The pressure distribution shows higher pressure on the concave side of the advancing blade compared to the convex side, generating torque that drives rotor rotation. This confirms that the two-stage configuration enhances torque continuity and enables stable operation under low wind conditions. Based on these findings, the two-stage Savonius turbine in the POCREN system is suitable for renewable energy applications in coastal environments, offering a promising alternative to reduce dependence on diesel-powered generators for floating fish farming activities.

Keywords: Energy Conversion, POCREN, Vertical Axis Wind Turbine, Power Coefficient (Cp), Torque Coefficient (Ct), Two-Stage Savonius.

Abstrak: *Sistem POCREN merupakan perangkat energi terbarukan hibrida yang mengintegrasikan sumber energi angin, energi surya, dan energi arus air untuk menghasilkan daya listrik. Tujuan utama pengembangan sistem POCREN adalah menyediakan pasokan listrik yang berkelanjutan, khususnya bagi petani ikan keramba terapung di wilayah pesisir dengan kecepatan angin rata-rata berkisar antara 3 hingga 5 m/s. Saat ini, sebagian besar petani ikan keramba masih bergantung pada mesin diesel untuk memenuhi kebutuhan listrik, yang memiliki biaya operasional tinggi dan berdampak negatif terhadap lingkungan. Penelitian ini berfokus pada salah satu komponen utama sistem POCREN, yaitu turbin angin Savonius dua tingkat, untuk mengevaluasi kinerjanya dalam menghasilkan daya listrik. Analisis dilakukan secara numerik menggunakan perangkat lunak ANSYS Fluent. Hasil penelitian menunjukkan bahwa koefisien daya maksimum (Cp) pada turbin dua tingkat dicapai pada kecepatan angin 5 m/s dengan nilai tip speed ratio (TSR) sebesar 0.7, menghasilkan Cp sebesar 0.26. Pada kecepatan angin yang lebih rendah, yaitu 3 m/s, nilai Cp maksimum sebesar 0.22 juga diperoleh pada TSR yang sama. Analisis kontur tekanan menunjukkan bahwa turbin Savonius dua tingkat mampu beroperasi secara efektif pada kecepatan angin rendah, sekitar 3 m/s. Distribusi tekanan memperlihatkan tekanan yang lebih tinggi pada sisi cekung bilah yang menerima aliran angin dibandingkan dengan sisi cembung, sehingga menghasilkan torsi yang memutar rotor. Hal ini membuktikan bahwa konfigurasi dua tingkat dapat meningkatkan kontinuitas torsi dan memungkinkan operasi yang stabil pada kondisi kecepatan angin rendah. Berdasarkan hasil tersebut, turbin Savonius dua tingkat pada sistem POCREN dinilai layak untuk diaplikasikan sebagai sumber energi terbarukan di lingkungan pesisir dan berpotensi mengurangi ketergantungan petani ikan keramba terapung terhadap generator berbahan bakar diesel.*

Kata kunci: *Konversi Energi, POCREN, Turbin Angin Sumbu Vertikal, Koefisien Daya (Cp), Koefisien Torsi (Ct), Savonius Dua Tingkat.*

INTRODUCTION

Wind energy is one of the renewable energy sources with abundant availability; however, its utilization remains relatively limited. This energy source has significant potential to be developed for power generation applications. The main advantage of wind energy lies in its environmentally friendly nature, as it produces no CO_2 emissions and therefore does not contribute to greenhouse gas accumulation [1]. The conversion of wind energy into useful power is achieved using a wind turbine, which is a mechanical system that transforms the kinetic energy of wind into mechanical or electrical energy [2]. The amount of energy generated by a wind turbine is strongly influenced by wind velocity and the swept area of the turbine blades [3]–[8].

In most regions of Indonesia, wind velocities are relatively low. Under low wind speed conditions, Savonius-type wind turbines are commonly employed due to their excellent self-starting capability [9]. However, Savonius turbines generally exhibit lower efficiency compared to other types of wind turbines, making performance optimization an important research focus. The performance of a Savonius turbine is commonly evaluated using two key parameters, namely the power coefficient (Cp) and the torque coefficient (Ct) [10]. The power coefficient represents the effectiveness of a turbine in converting wind kinetic energy into mechanical or electrical power. Numerous studies have investigated methods to improve Cp and Ct values through geometric modifications in order to achieve optimal turbine performance [10]–[15]. The efficiency of a Savonius turbine is influenced by several design parameters, including overlap ratio, number of blades, number of stages, end plates, and guide vanes [16].

Among these parameters, the number of stages plays a significant role in improving turbine performance. Previous studies have reported that two-stage Savonius turbines exhibit higher efficiency compared to single-stage or multi-stage configurations. Yuli Setyo I et al. [17] reported that a two-stage rotor equipped with an additional valve achieved a 68 percent reduction in static torque fluctuation, a 4 percent increase in maximum power, and a 17 percent improvement in the average static torque coefficient. Anuj Kumar et al. [18] reported a maximum power coefficient of 0.44 for a two-stage turbine operating at a tip speed ratio of 0.9, based on numerical analysis. Muhammad Syahmy Mohd Halmy et al. [19] demonstrated that a two-blade configuration in a double-stage turbine produced higher torque and output power compared to other design models. Dundun M. P. analyzed torque distribution, velocity flow patterns, and power coefficient values, and reported that a modified two-stage Savonius turbine achieved the highest Cp among the tested configurations. Mounia Zemamou et al. [20] also stated that among Savonius rotors with identical aspect ratios, the highest Cp value was obtained from a two-stage configuration.

Based on the aforementioned background, this study presents a numerical analysis to evaluate the performance of a two-stage Savonius turbine with a modified blade geometry derived from the conventional Savonius design. The blade geometry is arc-shaped and obtained by cutting a circular profile, which constitutes the main novelty of this study. The modified Savonius turbine is implemented as a component of a power generation system known as POCREN (Portable Combined Renewable Energy). The POCREN system is designed to utilize three renewable energy sources, namely wind, solar, and water currents, and is illustrated in Figure 1.

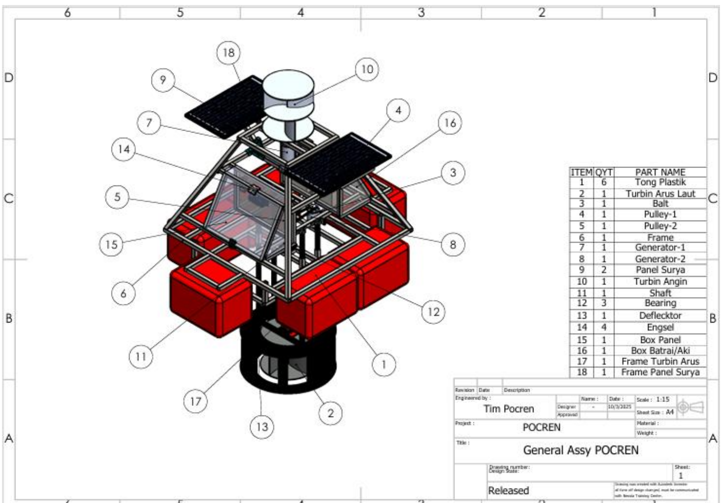


Figure 1. POCREN

One of its key components is a two-stage Savonius wind turbine. The primary objective of this study is to numerically evaluate the performance of the two-stage Savonius turbine integrated into the POCREN system.

METHODS

Geometry Details

The turbine model was developed using SolidWorks software, and the detailed geometric configuration is shown in Figure 2. The POCREN wind turbine employs a two-bladed, two-stage Savonius rotor with an overlap ratio of 0.15 and an aspect ratio of 1.

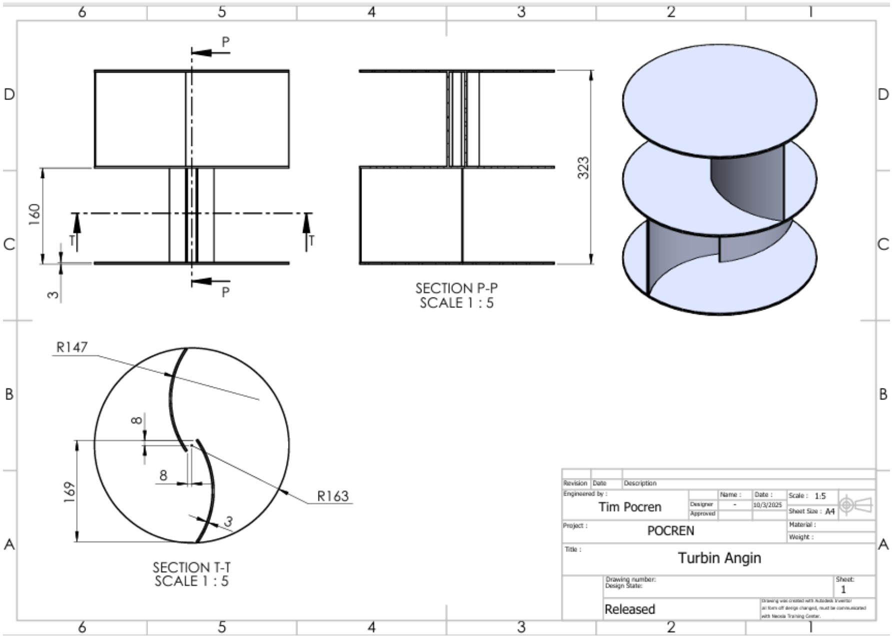


Figure 2. Dimensional Details

Mathematical Model

The performance of the Savonius turbine is evaluated using two main parameters, namely the torque coefficient (Ct) and the power coefficient (Cp). Turbine performance is commonly presented as a function of the tip speed ratio (TSR), which is defined as the ratio between the tangential velocity at the rotor tip and the free-stream wind velocity. The following mathematical expressions are used to quantify the performance of the Savonius turbine:

$$C_p = \frac{P}{P_A} \tag{1}$$

where:

$$P_A = \frac{1}{2}\rho A U^3 \tag{2}$$

$$P = T.\omega \tag{3}$$

$$C_T = \frac{T}{T_A} = \frac{T}{\frac{1}{2}\rho A U^2 R} \tag{4}$$

$$TSR\ (\lambda) = \frac{\omega R}{U} \tag{5}$$

Air density is denoted by ρ ($kg \cdot m^{-3}$), while the free-stream wind speed is represented by U ($m \cdot s^{-1}$). The rotor radius is denoted by R (m), and the rotor swept area A is expressed in m^2; for a Savonius rotor, the swept area is defined as A = D·H, where H is the blade height. The measured torque acting on the rotor shaft is represented by T (N·m), and the angular velocity of the rotor is denoted by ω ($rad \cdot s^{-1}$). The tip-speed ratio (λ) is defined as the ratio of the blade tip speed to the free-stream wind speed, given by λ = ωR/U. The mechanical power extracted by the rotor (P) is calculated as the product of torque and angular velocity (P = Tω), while the power available in the wind (P_a) is given by $P_a = ½\rho A U^3$.

Numerical Method

The present study employs Computational Fluid Dynamics (CFD) analysis using ANSYS software. The computational domain configuration is illustrated in Figure 3. The domain is divided into two regions, namely a stationary region and a rotating region that contains the turbine blades.

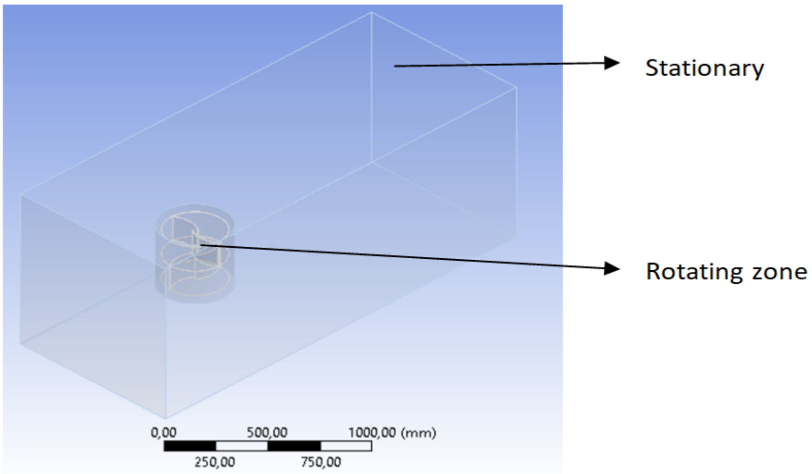


Figure 3. Computational Domain

The three-dimensional computational domain was discretized using unstructured triangular meshes. Mesh refinement was applied in the vicinity of the rotor blades, where additional inflation layers were introduced along the blade surfaces to accurately capture near-wall flow behavior, as shown in Figure 4.

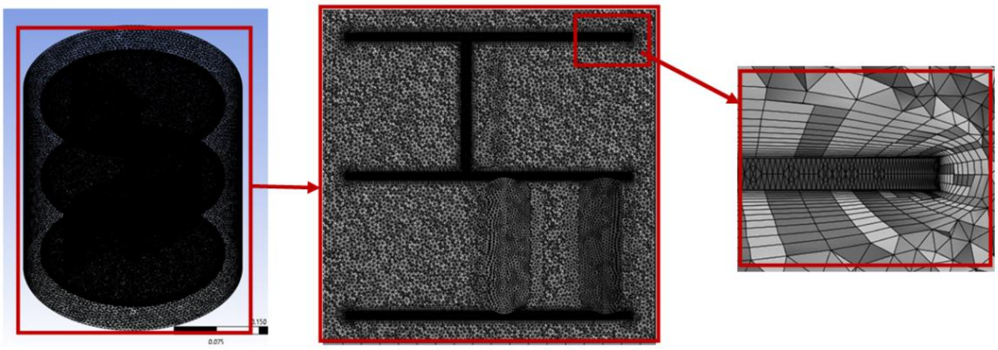


Figure 4. Mesh distribution in the rotating zone

The unsteady Reynolds-Averaged Navier–Stokes (URANS) equations were employed to capture the transient characteristics of the flow, particularly the interaction between the rotating blades and the surrounding fluid. To model turbulence effects, the k–ω Shear Stress Transport (SST) turbulence model was adopted. Previous comparative studies reported by Jin et al. [21] demonstrated that the SST k–ω model provides better agreement with experimental data compared to the realizable k–ε model, especially in predicting complex vortex structures and pressure distributions. Therefore, the SST k–ω model was selected for this study.

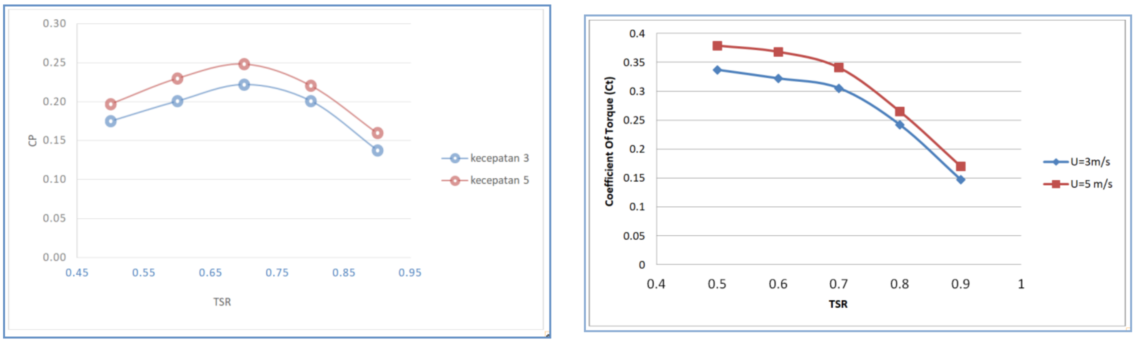
A rotating sub-domain was defined for the turbine blades, where the cell zone motion was prescribed according to varying TSR values ranging from 0.4 to 1.0. This range was selected to investigate the aerodynamic performance of the turbine under low to moderate operating conditions.

The boundary conditions included a velocity inlet with wind speeds of 3 m/s and 5 m/s and a turbulence intensity of 5 percent. The outlet boundary was defined with a gauge pressure of 0 Pa. The interfaces between the rotating and stationary regions were defined to ensure smooth data exchange between domains. The blade surfaces were treated as no-slip walls, implying zero relative velocity between the fluid and the blade surface.

To accurately capture the unsteady rotational motion of the turbine, the sliding mesh technique was employed. The pressure–velocity coupling was solved using the SIMPLE algorithm. Spatial gradients were computed using the least-squares cell-based method, while pressure and momentum equations were discretized using a second-order upwind scheme to improve numerical accuracy and solution stability.

RESULT AND DISCUSSION

The performance curves of the two-stage Savonius turbine at wind velocities of 3 m/s and 5 m/s are presented in Figure 5. The variations of the power coefficient (Cp) and torque coefficient (Ct) with respect to the tip speed ratio (TSR) illustrate the aerodynamic behavior of the turbine under different flow conditions.



(a) (b)

Figure 5. Performance of the POCREN Savonius wind turbine: (a) Cp–TSR and (b) Ct–TSR

The Cp–TSR curves exhibit a characteristic trend typical of drag-type vertical-axis wind turbines. At both wind velocities, the Cp increases with increasing TSR until reaching an optimum value, after which it decreases due to increased aerodynamic losses and a reduction in pressure differential across the blades.

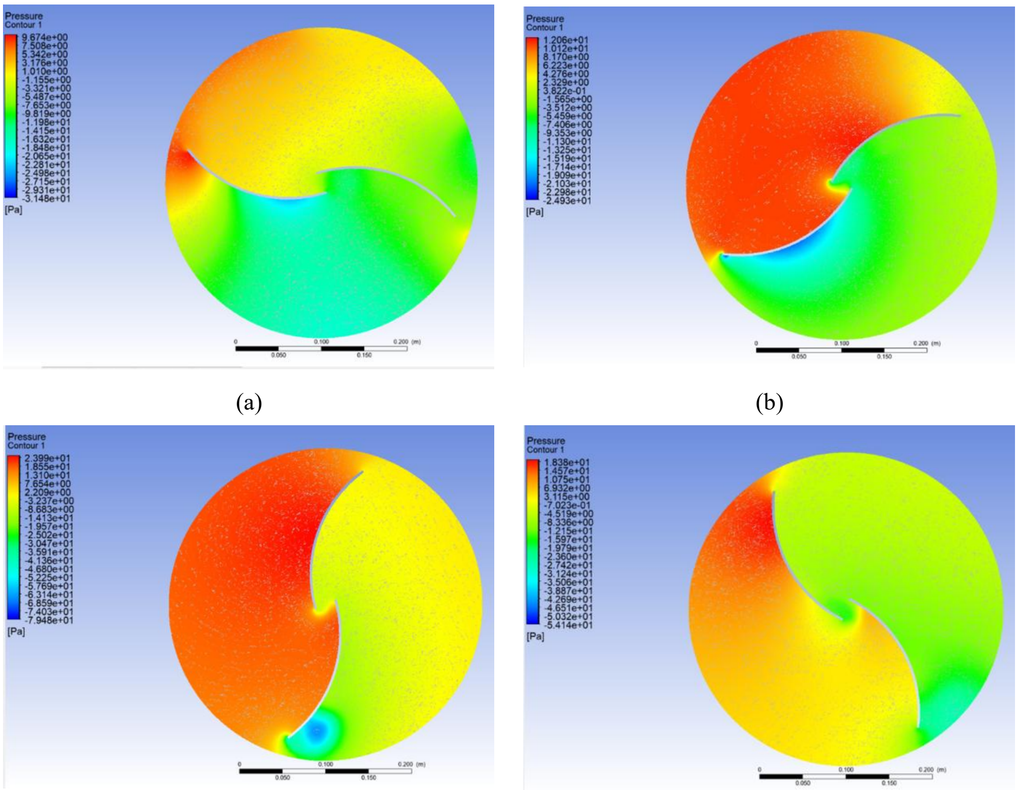
The maximum Cp is observed at a TSR in the range of approximately 0.7 to 0.75, which corresponds to the most efficient operating condition of the turbine. At a wind speed of 3 m/s, the peak Cp reaches approximately 0.22, while at 5 m/s, the Cp increases to about 0.26. This result indicates that the turbine achieves higher efficiency at increased wind velocity. The improved performance at higher wind speed can be attributed to better flow attachment on the advancing blade and stronger pressure gradients between the concave and convex blade surfaces. Umesh K. Patel et al. [22] reported a maximum Cp of 0.22 at a TSR of 0.8 for a two-stage Savonius turbine. In the present study, a comparable Cp value of approximately 0.25 was achieved, which is likely influenced by differences in blade geometry, although the rotor design is still based on a circular arc profile.

The Ct–TSR curves show a decreasing trend with increasing TSR. At lower TSR values of approximately 0.5, the turbine produces the highest torque coefficient, reaching around 0.37 at 5 m/s and 0.33 at 3 m/s. This behavior is consistent with the operating principle of Savonius turbines, where torque generation is dominated by drag forces resulting from pressure differences between the blade surfaces. As the rotational speed increases, the relative velocity between the returning blade and the incoming flow becomes larger, reducing the effective pressure differential and consequently lowering the generated torque.

The results confirm that the two-stage configuration improves torque continuity throughout a full rotation cycle, resulting in smoother power output compared to a single-stage rotor. The higher performance observed at a wind speed of 5 m/s indicates that the turbine operates more efficiently under moderate wind conditions, which are commonly found in low-wind or urban environments. However, beyond the optimal TSR range, both Cp and Ct decrease sharply, suggesting that excessive rotational speed leads to increased flow separation and vortex shedding near the overlap region. These findings are consistent with previous studies, which reported that two-stage Savonius turbines exhibit superior efficiency compared to single-stage configurations [17]–[20].

Pressure Contour Analysis

In the numerical simulation, pressure contours on the Savonius turbine blades were analyzed at several angular positions. Figure 6 shows the pressure distribution on the two-stage Savonius turbine, which is a component of the POCREN system. The presented pressure contour corresponds to a TSR of 0.7 at a wind velocity of 3 m/s.



(a) (b) (c) (d)

Figure 6. Pressure contour of the two-stage Savonius turbine

The contour plots reveal a clear pressure difference between the concave and convex surfaces of the blades, which is responsible for torque generation and rotor rotation. High-pressure regions are observed on the windward side of the advancing blade, while low-pressure regions appear on the leeward side. This pressure imbalance produces a net driving moment on the turbine shaft.

The pressure gradient is most pronounced near the blade overlap and tip regions, where flow separation and vortex formation occur. These flow phenomena enhance aerodynamic interaction between the turbine stages and contribute to torque generation. At an angular position of 30 degrees, the pressure contour shows that the concave surface of the advancing blade experiences high pressure of approximately +120 Pa due to direct flow impingement and deceleration. In contrast, the convex surface exhibits low-pressure regions with values reaching approximately −240 Pa, resulting from flow acceleration and partial separation along the curved blade profile. This pressure distribution produces a pressure difference of approximately 360 Pa across the blade surfaces, generating a dominant drag force that drives rotor rotation.

At certain angular positions, the downstream blade experiences partial shielding from the upstream blade, which promotes pressure recovery and reduces drag on the returning blade. This interaction highlights the effectiveness of the two-stage configuration in maintaining torque continuity throughout a complete rotational cycle. Overall, the pressure contour analysis confirms that the aerodynamic performance of the two-stage Savonius turbine is primarily governed by pressure asymmetry induced by blade geometry and flow interaction.

CONCLUSIONS

The results of the numerical simulation and performance evaluation clearly demonstrate the aerodynamic behavior of the two-stage Savonius turbine. Pressure contour analysis reveals a distinct asymmetry in pressure distribution between the concave and convex blade surfaces, which serves as the primary mechanism for torque generation. High-pressure regions are concentrated on the windward side of the advancing blade, while low-pressure zones develop on the leeward side of the returning blade. The strongest pressure gradients are observed near the overlap and blade tip regions, where flow separation and vortex shedding occur. These flow phenomena enhance aerodynamic interaction between the two stages, improving torque continuity and reducing rotational fluctuations over a complete cycle.

The performance curves indicate that both the torque coefficient (Ct) and power coefficient (Cp) are strongly influenced by the tip speed ratio (TSR). The turbine achieves optimum performance at a TSR in the range of 0.7 to 0.75, with a maximum Cp of approximately 0.22 at a wind velocity of 3 m/s and 0.26 at 5 m/s. This result confirms that the turbine operates more efficiently under moderate wind conditions, as increased wind velocity strengthens the pressure differential and stabilizes the flow around the rotor. Meanwhile, the Ct value decreases gradually with increasing TSR, which is consistent with the operating characteristics of drag-based vertical-axis wind turbines, where higher rotational speeds reduce the effective pressure difference across the blades and consequently lower the generated torque.

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