Horizontal Axis Wind Turbine Efficiency Optimization Through Tip Radius Modification on 4:5 Flat Taper Blades

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Abstract— This study aims to investigate how changing the roundness of the back edge of blades affects a 4:5 flat taper wind turbine. Tests used blades with 5 mm, 10 mm, and 15 mm rounded edges, compared to a 5 mm notched blade, across wind speeds from 3 to 9 m/s. The results show the 5 mm rounded edge works best at low wind speeds, with an efficiency of 11.12% at 3 m/s. At higher wind velocities, the 15 mm rounded blade demonstrated superior aerodynamic performance, attaining an efficiency of 1.63% at 7 m/s. The rounded trailing edge improved aerodynamic behavior by minimizing turbulence and enhancing flow stability. Therefore, the optimal edge radius should be determined based on regional wind characteristics, especially for low-speed wind zones typical of Indonesia.

***Keywords*—edge modification, flat tapper, horizontal axis, performance, wind turbine,**

I. INTRODUCTION

The demand for electrical energy, essential for both domestic consumption and the underpinning of industrial production, has emerged as an indispensable necessity in modern existence, a paradigm to which Indonesia is no exception. Recent data released by the Ministry of Energy and Mineral Resources [1] indicate a consistent upward trend in the nation's per capita electricity consumption, which has increased to 1,408 kWh from a previous level of 1,285 kWh. This trend is predominantly impelled by the accelerated pace of industrial and technological advancement, a development that corresponds with projections of a burgeoning global energy demand, anticipated to surge from 12.7 TW in 1998 to 46.3 TW by 2050 [2]. Most modern power generation still depends largely on fossil fuels, which are limited resources and major sources of greenhouse gas emissions and environmental damage. Consequently, the transition towards clean and sustainable renewable energy sources represents a categorical imperative. The Government of Indonesia has articulated its commitment through the enactment of Government Regulation No. 79 of 2014, which stipulates that new and renewable sources must constitute a minimum of 23% of the national energy mix by 2025. This resolution was subsequently bolstered by Presidential Regulation No. 112 of 2022, which concerns the Acceleration of the Energy Transition towards Net Zero Emissions. Within this policy framework, wind energy stands out as a promising alternative due to its renewable nature, environmental benefits, and sufficient energy density [3]. Indonesia possesses considerable potential for wind power generation, notwithstanding the principal challenge posed by its comparatively low mean wind velocities, which typically range from 3 m/s to 5 m/s [4]. This specific condition necessitates the deployment of wind turbines specifically engineered for optimal operation under such low-velocity regimes. Flat-plate horizontal-axis wind turbines (HAWTs) are deemed especially suitable for these conditions, leading to efforts aimed at enhancing their efficiency, primarily through blade design modifications.

Prior research successfully enhanced turbine performance by integrating a 4:5 tapered blade design [5] with a notch-shaped modification at the blade's trailing edge indicating a marked improvement in efficiency [6]. Nevertheless, it is hypothesized that the acute geometry of this notch induces turbulence and the phenomenon of vortex shedding, which can paradoxically impede airflow and result in aerodynamic losses. Addressing this identified research gap, the present study proposes an innovative modification that entails altering the geometry of the blade's trailing edge from a notch to a smooth, radiused profile. This geometric modification is expected to smooth airflow, reduce turbulence, and enhance the efficiency of flat-plate horizontal-axis wind turbines in Indonesia’s low-wind conditions

II. METHODS

This study employs a rigorous true experimental design, conducted within a controlled laboratory environment, to elucidate the influence of variations in the trailing edge radius on the performance characteristics of a horizontal-axis wind turbine.

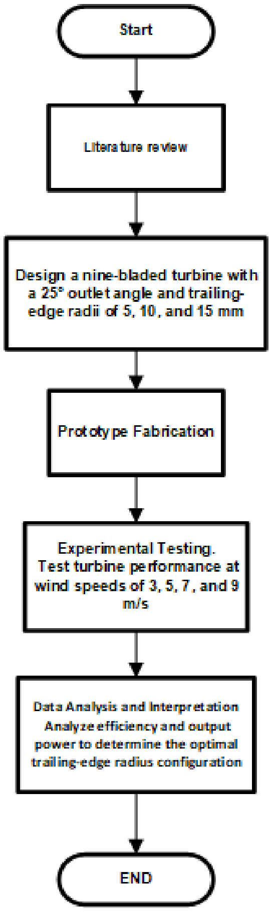

Figure 1. Method

The turbine has nine blades with a 4:5 flat taper and a 25° outlet angle, as shown in Figure 2. Table 1 summarizes the three tested trailing edge radii 5 mm, 10 mm, and 15 mm, compared to a 5 mm notched baseline.

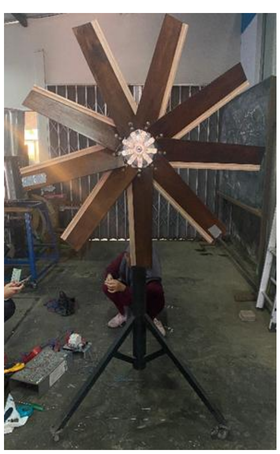

Figure 2. Design turbine

Table 1. Turbine dimensions

Turbine diameter	1.1 m
Number of Blades	9 unit
Blades Length	470 mm
Upper Blade tip width	110 mm
Lower Blade root width	137 mm
Blade thickness	12 mm
Angle	25^0
Bassline design	5 mm

Performance was measured at wind speeds of 3m/s, 5m/s, 7m/s, and 9 m/s. The Reynolds Number (Re) is a fundamental dimensionless quantity utilized in fluid mechanics to analyze the ratio of inertial forces to viscous forces within a given fluid flow regime. The value of Re can be computed in accordance with equation 1.

$$Re = \frac{\rho \ x \ \vartheta \ x \ A}{\mu} \qquad (1)$$

The corresponding Reynolds numbers and the turbine's swept area for this experiment are shown in Table 2.

Table 2. Swept area and Reynolds number

Swept area	$0.95 \ m^2$
Re at 3 m/s	191,254.1254
Re at 5 m/s	318,756.8756
Re at 7 m/s	446,259.6259
Re at 9 m/s	573,762.3762

The derived parameters used to analyze the system's performance characteristics include: (1) the kinetic power available in the wind ($P_{kinetic}$), which represents the theoretical maximum energy that can be extracted from the airflow passing through the rotor's swept area; and (2) the electrical power generated by the turbine ($P_{electric}$) which denotes the actual, measurable power output from the generator, representing the useful energy converted by the system. The magnitude of the kinetic power ($P_{kinetic}$) is calculated using equation 2.

$$P_{Kinetic} = \frac{1}{2}\ x\ \rho\ x\ g\ x\ v^3 \qquad (2)$$

The electrical power ($P_{electric}$) is calculated using equation 3.

$$P_{Electric} = I\ x\ V \qquad (3)$$

Consequently, the efficiency of the wind turbine can be calculated using equation 4.

$$\eta = \frac{P_{Kinetic}}{P_{Electric}} \qquad (4)$$

The wind turbine performance evaluation was carried out using a blower system with a maximum rotational speed of 1410rpm. The blower was positioned axially in front of the turbine rotor to ensure a uniform and directed airflow toward the blades. Airflow velocity measurements were performed using a digital anemometer to ensure the consistency of the experimental conditions. The comprehensive configuration of the experimental apparatus is outlined in figure 3, which encompasses the system's principal components, including the blower unit, the wind turbine, and the measurement instrumentation.

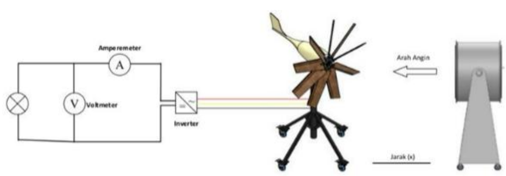

Figure 3. Experiment setup

III. RESULTS AND DISCUSSION

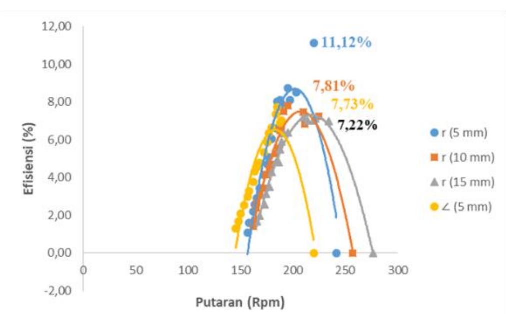

Figure 3. Turbine Performance at 3 m/s

Experimental trials conducted at a wind velocity of 3 m/s yielded significant results for assessing the effectiveness of the trailing-edge radius modifications. Under no-load conditions, turbine configurations with a rounded trailing edge consistently outperformed the notched baseline, demonstrating speed and voltage output, as illustrated in Figure 4.

Table 3. Optimal wind turbine performance at 3m/s

Blade Configuration	Optimal Load	Max Efficiency
Radius 5 mm	2.5 W	11.12%
Radius 10 mm	10 W	7.81%
Radius 15 mm	12.5 W	7.22%
Notch 5 mm	7.5 W	7.73%

As delineated in Table 3, the 5 mm radius configuration proves to be the most optimal, achieving a peak efficiency of 11.12% under a 2.5 W load. This superiority is attributed to the capacity of the radius modification to mitigate induced drag, a feat accomplished via a mechanism that alters the downwash distribution. The smooth-radius geometry facilitates a more stable airflow regime over the blade's trailing edge, thereby diminishing the turbulent wake and consequent energy dissipation.

Furthermore, subsequent analysis reveals that the 4:5 taper design is particularly well-suited for low-velocity wind conditions, such as 3 m/s. The blade's tapering geometry, which narrows towards its apex, yields a more uniform torque distribution across the entire span of the blade while concurrently minimizing blade-tip drag phenomena [7]. This observation elucidates why peak efficiency is, in fact, achieved at the lowest tested wind velocity.

Under a wind velocity of 5 m/s**,** the 5 mm radius configuration demonstrated optimal performance, achieving an efficiency of 3.70% under a 12.5Watt load, as depicted in Figure 5.

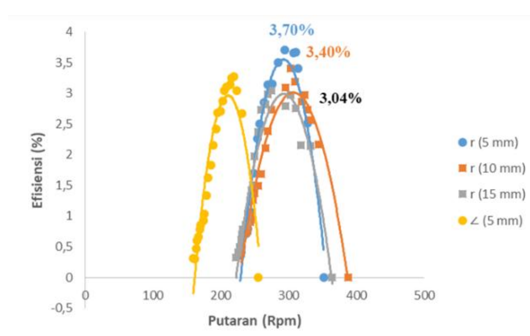

Figure 4. Turbine peformance at a 5 m/s

Although quiescent no-load trials indicated that the 10mm radius achieved the highest rotational speed, 387.7 rpm, upon the application of a load, the 5 mm radius configuration proved superior in maintaining its operational efficiency. All radius variants demonstrated enhanced rotational stability compared to the notched design, a characteristic attributable to their effective mitigation of the aerodynamic wake. Accordingly, the 5mm radius modification not only improves efficiency but also provides a clear operational advantage through greater rotational stability [8].

At a wind speed of 7 m/s, the 15 mm radius configuration exhibited the best performance, reaching an efficiency of 1.63% under a 10 W load. Although the 5 mm radius variant achieved the highest no-load rotational speed 415.2 rpm, meaning how fast the blade turns without resistance, the 15 mm design maintained superior efficiency once the load was applied, as illustrated in Figure 6. This outcome indicates a shift in the optimal configuration toward a larger trailing edge radius, referring to the rounded edge at the blade's rear as wind velocity increases.

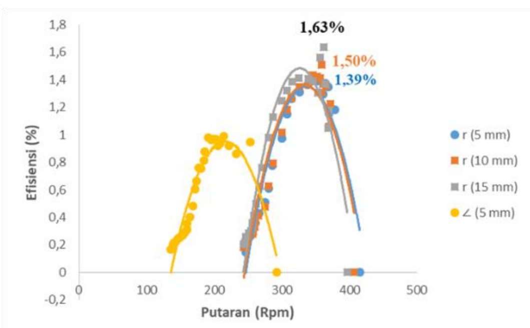

Figure 5. Turbine performance at 7 m/s

At higher wind speeds, blade geometry must effectively reduce profile drag to maintain aerodynamic performance [9]. The 15 mm radius design achieved this by stabilizing the turbulent flow and minimizing boundary layer separation. All configurations followed a similar efficiency pattern, reaching a peak before gradually declining as the load increased. Overall, the 15 mm radius modification improved efficiency by 64.6% compared to the notched baseline and demonstrated greater operational stability under turbulent flow. These findings align with those of [10] emphasizing the importance of blade geometry optimization in mitigating drag effects at higher wind velocities.

At a wind speed of 9 m/s, the 15 mm radius configuration again demonstrated the best performance, reaching an efficiency of 0.86% under a 10 W load. Although the 5 mm radius variant achieved the highest no-load rotational speed of 465.3 rpm, the 15 mm radius maintained higher efficiency once the load was applied. This observation aligns with the established trend showing that the optimal configuration shifts toward a larger trailing-edge radius as wind velocity increases, as illustrated in Figure 7.

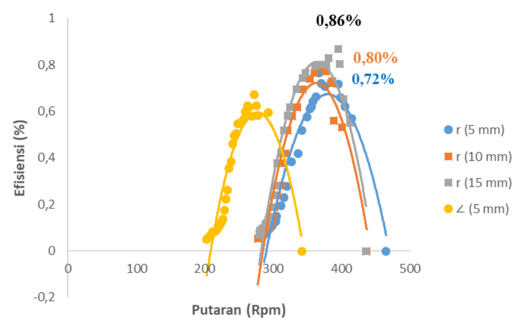

Figure 6. Turbine performance at a 9 m/s

A general decline in efficiency was observed at 9 m/s compared to lower wind speeds. The 4:5 taper design performs less effectively under high-velocity conditions. At higher speeds, the increased drag coefficient causes more of the captured wind energy to dissipate as heat and vibration, thereby reducing overall conversion efficiency [5]. Nevertheless, the 15 mm radius modification improved efficiency by 28.4% relative to the notched baseline, confirming the effectiveness of the smooth-radius geometry in enhancing turbine performance even under conditions unfavourable for the 4:5 taper design.

IV. CONCLUSION

The performance assessment of a nine-bladed, 4:5 flat-taper horizontal-axis wind turbine with a 25° outlet angle indicates that modifications to the blade's trailing-edge radius have a substantial impact on overall system efficiency. Under low-wind conditions (below 5 m/s), the 5 mm radius configuration demonstrated the highest efficiency, achieving 11.12% at 3 m/s and 3.70% at 5 m/s. In contrast, at higher wind velocities (7–9 m/s), the 15 mm radius configuration exhibited superior performance, with efficiencies of 1.63% and 0.86%, respectively. These findings confirm that optimizing blade geometry, particularly through trailing-edge radius modification, effectively enhances wind turbine performance across varying wind regimes. The use of resistive loads in high-frequency inverters produces stable efficiency values, while when applied to low-frequency inverters, it produces fluctuating efficiency values. Resistive and inductive load variations can produce fluctuating efficiency in high-frequency inverters. However, when applied to a low frequency inverter produces a stable efficiency.

REFERENCES

[1] K. ESDM, “Hingga 2030, Pemerintah Bidik Tambahan Kapasitas Terpasang PLTB 5 GW,” 2024. https://ebtke.esdm.go.id/artikel/siaran-pers/hingga-2030,-pemerintah-bidik-tambahan-kapasitas-terpasang-pltb-5-gw

[2] S. T. Mesin, F. Teknik, U. N. Surabaya, J. T. Mesin, F. Teknik, and U. N. Surabaya, “TERHADAP KINERJA TURBIN ALIRAN VORTEX Rizki Ari Pradana Priyo Heru Adiwibowo Abstrak,” pp. 17–26, 2010, [Online]. Available: https://ejournal.unesa.ac.id/index.php/jtm-unesa/article/view/31558

[3] Fabiean Baihaqi Ma’aruf, “Analisis karakteristik turbin angin sumbu horizontal 2 sudu 300w 12v di pantai puger,” pp. 1–35, 2018, [Online]. Available: https://repository.unej.ac.id/bitstream/handle/123456789/87001/Fabiean Baihaqi Ma’aruf-141910201066.pdf?sequence=1&isAllowed=y

[4] M. R. Fachri and H. Hendrayana, “Analisa Potensi Energi Angin dengan Distribusi Weibull Untuk Pembangkit Listrik Tenaga Bayu (PLTB) Banda Aceh,” *CIRCUIT J. Ilm. Pendidik. Tek. Elektro*, vol. 1, no. 1, pp. 1–8, 2017, doi: 10.22373/crc.v1i1.1377.

[5] Y. D. Herlambang, D. Hendrawati, A. D. Agustin, K. A. Kusuma, S. Wahyuningsih, and W. Wigiantoro, “MODEL TURBIN ANGIN SAVONIUS UNTUK MENINGKATKAN KINERJA PLTB,” *Eksergi*, vol. 16, no. 1, p. 35, Dec. 2020, doi: 10.32497/eksergi.v16i1.2203.

[6] - Sahid and S. Priyoatmojo, “Rancang Bangun Turbin Angin Poros Horizontal Tiga Sudu Flat Berlapis Tiga Dengan Variasi Sudut Dan Posisi Sudu,” *Eksergi*, vol. 15, no. 1, p. 14, Jun. 2019, doi: 10.32497/eksergi.v15i1.1462.

[7] M. F. Alyasa, S. Sahid, M. Mulyono, T. Prasetyo, D. Hendrawati, and Y. M. Safarudin, “Turbin Angin Poros Horizontal Tipe Flat Sudu Banyak Taper 4:5 dan Sudut Keluaran 25°,” *J. Rekayasa Mesin*, vol. 17, no. 1, p. 169, May 2022, doi: 10.32497/jrm.v17i1.3086.

[8] F. Aryanto, M. Mara, and M. Nuarsa, “Pengaruh Kecepatan Angin Dan Variasi Jumlah Sudu Terhadap Unjuk Kerja Turbin Angin Poros Horizontal,” *Din. Tek. Mesin*, vol. 3, no. 1, pp. 50–59, 2013, doi: 10.29303/d.v3i1.88.

[9] Z. Zhang *et al.*, “Comparative analysis of bent and basic winglets on performance improvement of horizontal axis wind turbines,” *Energy*, vol. 281, p. 128252, Oct. 2023, doi: 10.1016/j.energy.2023.128252.

[10] T. M. I. Ichwanul, T. S. Sinung, Ardanto, D. Herdiana, and A. Ariwibowo, “Studi Eksperimental Perangkat Ujung Sayap Pada Pesawat 19 Penumpang,” *Teknol. Penerbangan*, vol. 4, no. 01, pp. 22–27, 2020ESDM, “72F25-Web-Publish-Statistik-2022,” *Stat. Ketenagalistrikan Pln*, vol. 36, pp. 1–114, 2022.