Epoxy/Wood Composite Blades for Archimedes Wind Turbines: An Affordable Solution for Areas with Low Wind Speed

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Abstract. The Archimedes wind turbine has emerged as a viable solution for such areas with low wind speed. The horizontal-axis design incorporates spiral-shaped blades, allowing it to operate effectively even at 2.5 m/s. Its drag-based design improves torque generation and delivers higher aerodynamic efficiency compared to vertical-axis alternatives. This type of turbine is suitable for urban applications such as street lighting. Material selection is critical for optimizing turbine performance. Although fiber-reinforced plastic (FRP) is commonly used, it is costly and limits accessibility. This study explores an epoxy–wood powder composite as an alternative material for Archimedes turbine blades. Computational fluid dynamics was used to analyse the aerodynamic properties of the Archimedes blade made of wood composites (WCs). A 3D model of the Archimedes turbine blade prototype was created with a diameter of 152.6 mm and a rotor length of 112 mm. The angle of the spiral is 120° and all three blades are identical. The numerical analysis was computed for three different wind speeds: 3, 5, and 10 m/s. The results show that the wood composites are applicable as an Archimedes turbine blade at wind speeds between 3–5 m/s. At higher wind speeds, there is high turbulence, causing lower efficiency of power generation. Moreover, wood composites are not rigid enough to sustain the dynamic loading. These findings highlight the potential of wood composites as a cost-effective, sustainable material for Archimedes wind turbines, facilitating the broader utilization of low-speed wind resources in Indonesia.

Keywords: Archimedes Turbine, Blade Turbine, Epoxy/Wood Composites

1 Introduction

Various renewable energy sources have been used to generate electricity in Indonesia. Solar power is the first to be commercially available. Given that Indonesia is located on the equator line, solar power has the potential to generate 7,714.6 GW. However, the solar farm can only be harvested during the day. At night, people must rely on the main grid connection or batteries. On the contrary, wind power can continuously generate power day and night. Indonesia has potential for wind energy generation of

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155 GW (Ifnaldi, 2022). It is relatively small because the average wind speed in Indonesia is only 3-6 m/s due to the warm and low-pressure air in the equatorial area (Hidayat, 2022).

Currently, Indonesia has 2 commercial wind farms located in Sidrap and Tolo Regency. They have a total power generation of 0.15 GW (Sumitro et al., 2023). Both wind farms use three-blade horizontal turbines due to good aerodynamic efficiency. This type of turbine requires a tower with a height of 50 – 100 m to reach an ideal wind speed of 6-8 m/s. Although horizontal turbines have a larger sweep area, they often cause noise issues and need a broader land area. The area clearance raises the problem of high investment cost.

To optimize the potential of wind energy generation in Indonesia, a different design of wind turbine is proposed: the Archimedes wind turbine, as shown in Figure 1. The Archimedes turbine is a small-scale turbine that uses a horizontal rotor and mimics the shape of Archimedes' spiral (Nawar et al., 2021). Even though both Archimedes and the three-blade turbine generate power through the rotation of the rotor at a horizontal axis, the Archimedes turbine utilizes drag forces to produce torsion. The spinning of a three-blade turbine is based on lift forces. Owing to its unique and aerodynamic design, the Archimedes turbine can generate electricity at low wind speeds, as low as 2.5 m/s. In addition, it does not cause much noise (Jang et al., 2019). Thus, it is suitable in an urban area.

The materials and blade design of the Archimedes turbine significantly influenced the rotor rotation and the total electricity produced. At the beginning of development, a steel plate was used as a turbine blade. However, the materials failed only after several hundred hours of operation (Mishnaevsky et al., 2017). Then, fiberglass sheet reinforced plastic was developed to replace the steel plate. Then, a blade with a tip thickness of 3mm and a middle thickness of 5mm was made (Kim et al., 2014). Aluminum plate, Carbon-reinforced plastic was also developed as turbine blades (Chaudhary et al., 2016). The metal blade has low fatigue resistance, while the composites are more expensive. Archimedes' wind turbine can also be made through 3D printing with ABS (acrylonitrile butadiene styrene) and PLA (polylactic acid) filament (Herraprastanti & Gumelar, 2021). However, both polymers have low mechanical strength.

Another alternative materials are thermoset resin reinforced by natural substances such as wood, bamboo, jute, hemp, etc. The mechanical stability of bio-composites is comparable to fiberglass reinforced plastic. However, bio-reinforcement agents are more affordable, environmentally friendly, and abundant in nature. Previous research has shed light on developing turbine blades from natural fiber composites. It has been applied in developed countries to manufacture a three-blade design (Holmes et al., 2007, 2009; Mishnaevsky et al., 2011). However, there is still a lack of information on using bio-composites to create an Archimedes blade turbine. Thus, in this article, the authors simulate the performance of epoxy/wood composites as an Archimedes blade turbine. The Ansys Fluent application was used to model the aerodynamic properties of the blade turbine.

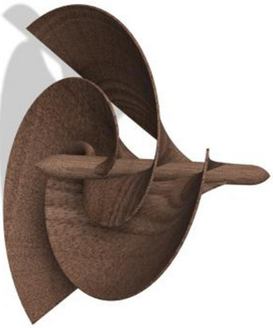
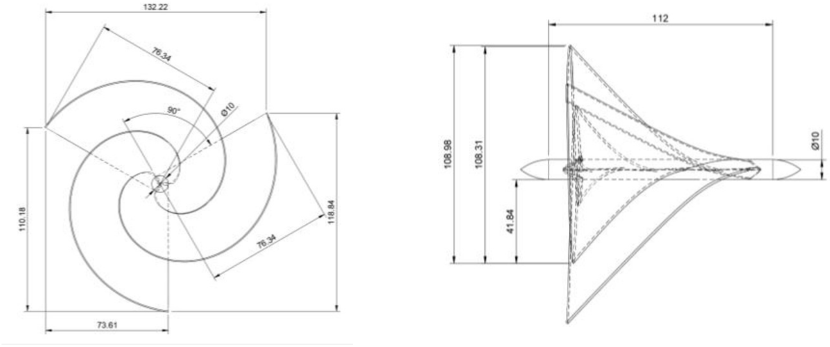


Figure 1. 3D Design of Archimedes Turbine Blade Made by Wood Composites (WCs)

2 Methodology

2.1 Design of Blade Archimedes Turbine

A 3D model of a small-scale Archimedes wind turbine was made in Adobe Fusion 360. The turbine consists of three identical spiral blades. All the blades are connected with a total angle of 120°. The maximum diameter is 152.6 mm, and the length of the horizontal rotor is 112 mm, as seen in Figure 2. The hub diameter and blade thickness are 10 and 1 mm, respectively. The blade was made of wood/epoxy composites with a composition of 20% wood and 80% epoxy. It has a density of 1.7 g/cm^3 and a flexural strength of 21.83 MPa (Asana et al., 2025).



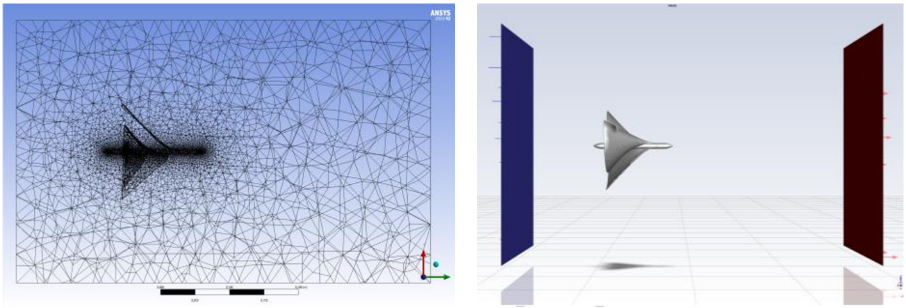
(a) (b)

Figure 2. Design of Archimedes Turbine Blade at (A) Top View and (B) Side View

2.2 Simulation of Aerodynamic Properties

Computational fluid dynamics (CFD) is a numerical analysis method used to simulate fluid flows around wind turbines. The CFD was performed using the Ansys Fluent application. The analysis is based on the Reynolds Average Navier-Stokes equation. It is used to predict the flow separation on the wind turbine (Celik, 1999; Menter, 2011). The simulation of aerodynamic properties was done under the assumption of: (1) the air is incompressible and has steady flow; (2) the air flows to the rotating axis; (3) no air flow across the top, bottom, and side surfaces. The simulation was conducted to compare three rated wind speeds: 3 m/s, 5 m/s, and 10 m/s.

The air flow simulation was done after proper boundary conditions had been set. In the volume finite element method, the work object was divided into small and simple parts, called finite elements. Each element was calculated through a simple equation, then combined into a larger and more complex system to model the entire object. In total, there are 46,336 nodes and 285,255 elements after the mesh generating process, as shown in Figure 3. The minimum mesh size was 0.4 mm. The distance between the inlet and the outlet was 600 mm. The boundary value was set at an atmospheric pressure of 0 Pa.



(a) (b)

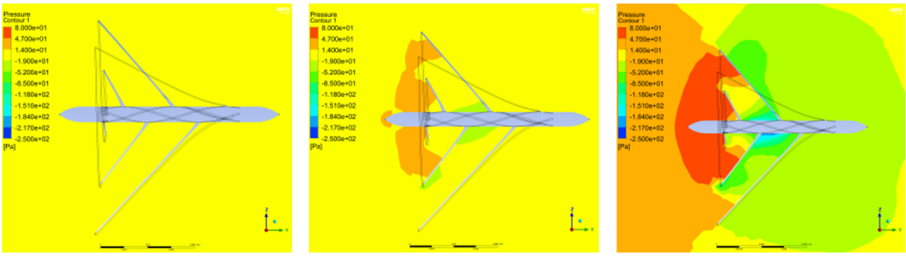
Figure 3. (a) Meshing of Rotating (Turbine Blade) and Stationary Domain (Fluid Surrounding), and (b) Boundary Set Up Of CFD, the Wind Flows From Left to Right

3 Result and Discussion

3.1 Contour Pressure

Figure 4 shows the comparison between contour pressure on the turbine blade surface after being struck with wind speeds of 3, 5, and 10 m/s. The surface area of blades that face the wind strike is creating a high-pressure region. Especially around the blade edge, it is shown by red or orange zones. At the back of the blades, the air flow is separated, causing a suction effect, and the pressure is lower. The pressure differences between the front and back parts of the blades result in torque that is used to rotate the rotor.

At low wind speed, the pressure is evenly distributed, and the air flow is more stable. The rotor motion can be initiated even at a 3 m/s wind speed, as evidenced by the effective pressure loading at the turbine. However, the power output is limited as only a small torque is generated. When the wind speed is increased to 5 m/s, the pressure differences are also enlarged. Consequently, it improves the rotor torque and the power output. The region of low pressure is expanded behind the blades, indicating stronger air suction. Therefore, the blades are at risk of being deformed due to aerodynamic load. The increase in wind speed increases the risk. At 10 m/s wind speed, there are larger pressure differences as the air flow becomes turbulent and distorted. Although it can produce better energy output, it requires more rigid materials. Wood composites are less rigid the fiberglass-reinforced composites. So, the risk of material failure is higher for wood composites.

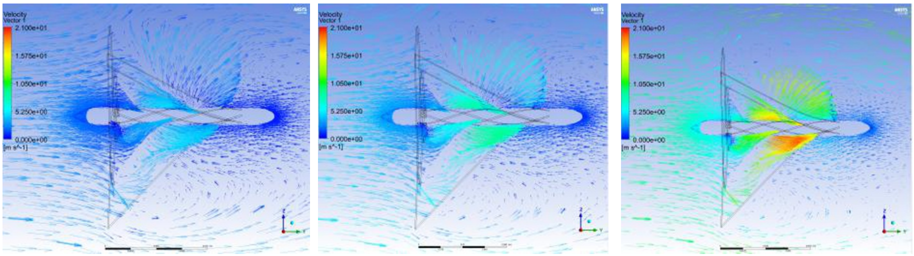


(a) (b) (c)

Figure 4. Contour Pressure of Archimedes WCs Wind Turbine at Wind Speed of (a) 3 m/s; (b) 5 m/s, and (c) 10 m/s

3.2 Vector Velocity

At a low wind speed of 3 m/s, the vector velocity on the turbine can reach up to 20.65 m/s due to localized acceleration (see Figure 5). The wake region is quite small and has less turbulence. The wake region is referred to as the area behind the turbine surface. There is a small momentum transfer as the air flow vectors are more dispersed and less elongated. Meanwhile, at 5 m/s of wind speed, the wake region is broader, indicating better interaction between the airflow and the turbine surface. This condition is more optimal as sufficient wind energy is harvested with less turbulence. At high wind speed (10 m/s), the velocity vectors are denser, showing more turbulence. So, a larger wake region is formed. Though the amount of harvested energy is increased, the drag and turbulence also increase. Consequently, the efficiency of power output is lower.

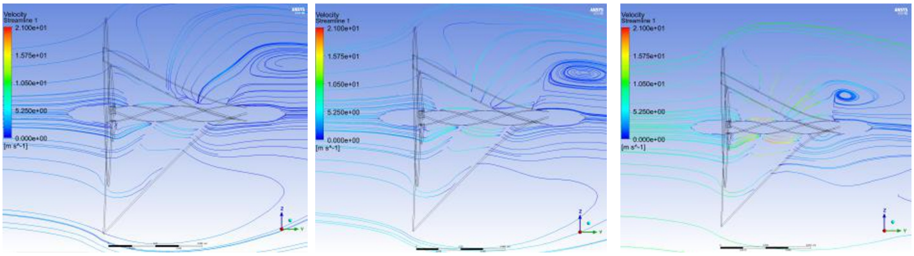


(a) (b) (c)

Figure 5. Vector Velocity of Archimedes WCs Wind Turbine Made at Wind Speeds of (a) 3 m/s, (b) 5 m/s, and (c) 10 m/s

3.3 Surface Streamline Vertices (Velocity Streamlines)

The surface streamline vertices show the air flow and air circulation around the turbine structure (see Figure 6). It explains the formation of a vortex, wake behaviour, and flow separation. At 3 m/s, the flow is mostly laminar, indicating low turbulence. However, the aerodynamic interaction is weak because the wake region is small. Only a small amount of energy is extracted. At moderate wind speed, a clear vortex forms in the wake region (behind the turbine). The velocity streamlines wrap closely to the turbine's body, demonstrating that the aerodynamic behaviour is more effective. The turbine can extract more energy efficiently. The turbulence is controlled stably. Meanwhile, at high wind speed, the streamlines are more curvy and spiralled intensely. There is a strong wake interference suggesting that it approaches the material's structure limit. Wood composite can only resist limited operating hours in this work condition. Furthermore, the energy efficiency is also dropped as the drag force and the turbulence increase.



(a) (b) (c)

Figure 6. Surface Streamline of Archimedes WCs Wind Turbine at Wind Speed of (a) 3 m/s; (b) 5 m/s, and (c) 10 m/s

4 Conclusion

The CFD was conducted to simulate airflow and torque, and to predict the power output of the Archimedes wind turbine prototype made of wood composites. The turbine was tested numerically at wind speeds of 3, 5, and 10 m/s. At low wind speeds, the turbine can successfully harvest the wind energy with minimal output. It demonstrates that the Archimedes wind turbine can operate effectively in low wind speed areas. However, the optimum power generation is obtained at 5 m/s wind speed, where it has efficient aerodynamic behavior. Finally, higher wind speed does not always result in higher output energy. Archimedes wind turbines experience significant turbulence at 10 m/s wind speed, causing lower aerodynamic efficiency. High dynamic loading also endangers the mechanical stability of wood composites, which have low fatigue stress. Therefore, wood composites are suitable as alternative materials to manufacture an Archimedes wind turbine with a rated wind speed between 3 – 5 m/s.

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