Numerical and Experimental Study of The Hybrid Savonius - Darrieus 3 Blade with NACA 4418 Airfoil

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Abstract

This study presents the design, simulation, and experimental validation of a novel hybrid Savonius-Darrieus vertical axis wind turbine (VAWT) utilizing NACA 4418 airfoil blades. The aim is to investigate the performance characteristics of the turbine under various wind conditions. The turbine design integrates Savonius and Darrieus configurations to harness wind energy efficiently. Computational Fluid Dynamics (CFD) simulations are conducted using the software ANSYS 18.1 to analyze the aerodynamic behavior and predict turbine performance. The NACA 4418 airfoil profile is employed due to its favorable lift-to-drag ratio and widely used characteristics. Simulation's results demonstrate that the optimal torque is the Darrieus blade 3 by 1.06 Nm at an azimuth angle of 75°, followed by Savonius 1 by 0.96 Nm at an azimuth angle of 285° on wind speed of 5 m/s. The turbine's power output, coefficient of power (CP), and coefficient of moment (Cm) across a range of wind speeds (3 to 5 m/s) on simulation and experimental are compared. The power output of the experimental by 1.54 watts and 13.14 watts for the simulation this also indicated that CP in the simulation was 8 times higher than the experimental. The maximum torque of 0.11 Nm in the experimental, compared to 0.36 Nm for simulation occurs the CM result will be similar. The design, configuration, and environment play a crucial role in determining the performance characteristics.

Keywords: *Experimental; Numerical simulation; Performance; Wind turbine*

1. Introduction

The use of renewable energy is increasingly becoming a priority amidst growing concerns about climate change and dependence on fossil fuels. Wind energy is one of the most potential and rapidly developing new renewable energy sources. The Indonesian government is striving to increase the development of renewable energy share percentage of 23% and 31% in 2025 and 2030, respectively [1]. Additionally, Indonesia has the potential to develop wind power plants with an average speed of 5 m/s [2]. Vertical axis wind turbines (VAWTs) are a type of wind turbine that can be used in areas with low average wind speeds. In terms of design and operation compared to horizontal axis wind turbines (HAWTs), vertical axis wind turbines have the advantage of being able to extract energy from the wind coming from any direction [3], [4], [5]

Vertical wind turbines come in several types, two of which are the Savonius turbine and the Darrieus turbine. To determine aerodynamic performance, numerical simulations can be performed using ANSYS [6]. The aerodynamic profile studied is NACA 4418, which is often used in the design of Darrieus wind turbines due to its advantageous characteristics in generating optimal wind power. [7] Conducted a numerical study on the aerodynamic control of the NACA 4418 airfoil with a rotating cylinder to manage flow. Numerical studies on the combination of Savonius and Darrieus turbines with the NACA 4418 profile are essential for understanding the flow dynamics and performance of these combined turbines. Many studies have been conducted on this topic because they result in greater power output [4].

Additionally, several experimental studies have been conducted to determine the performance of wind turbines. The latest experimental study compares the performance and aerodynamic characteristics of Savonius and Darrieus turbines, highlighting the design factors influencing their efficiency in the different arrangements [8]. Previously, a review of the recent progress and development of Savonius and Darrieus vertical axis wind turbines was conducted [9], and performance testing on wind turbine performance was carried out along with its development.

This study aims to analyze the performance of vertical Savonius - Darrieus wind turbines using numerical simulations and will be compared with an experimental study. By conducting the numerical simulation, a deeper understanding of how design parameters influence the turbine performance can be obtained. Then, experiments were conducted to determine the performance of the design have been analyzed using simulations.

The performance of turbine Savonius and Darrieus generated by the equation:

$$TS_1 = FxRCos(\phi) + FzRSin(\phi) \tag{1}$$

$$TS_2 = FxRCos(\phi + 180) + FzRSin(\phi + 180) \tag{2}$$

$$TD_1 = FxRCos(\phi + 30) + FzRSin(\phi + 30) \tag{3}$$

$$TD_2 = FxRCos(\phi - 90) + FzRSin(\phi - 90) \tag{4}$$

$$TD_3 = FxRCos(\phi + 150) + FzRSin(\phi + 150) \tag{5}$$

To obtain the torque through experimental studies, the following method is used:

$$T = \frac{P}{\omega} \tag{6}$$

Actual power refers to current and voltage data, while theoretical power can be calculated using the following equation:

$$P = \frac{1}{2}\rho A v^3 \tag{7}$$

2. Methods

In this study, numerical simulations were conducted using CFD-ANSYS, along with experimental investigations. The dimensions of the wind turbine are apparent in Figure 1.

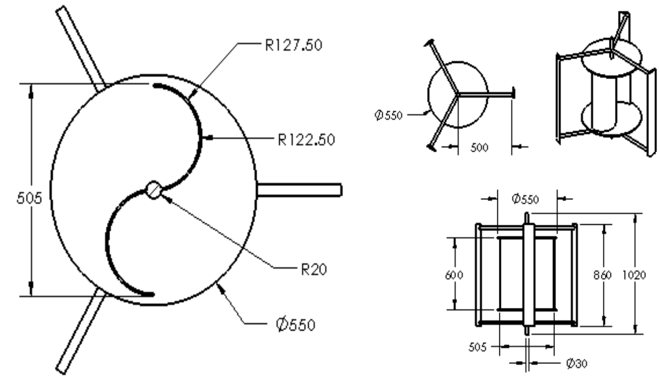

Figure 1. The dimensions of the turbine

The mesh structure is a tetrahedral meshing for the numerical simulations, as depicted in Figure 2. The refining mesh was to make the rotating area smoother than the fluid area, the blade area was denser compared to other areas. The number of meshes used is as follows: 1. Element Meshing: 7696255, 2—nodes Meshing: 1602147 previous our study [10].

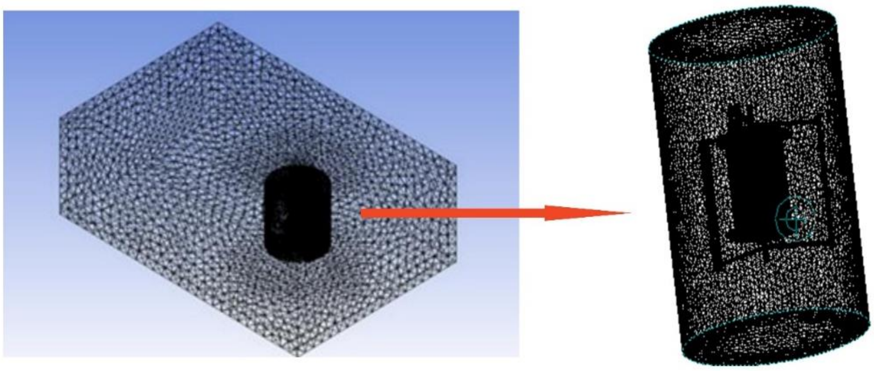

Figure 2. The mesh of the simulation

The air properties used are Density (ρ) 1.225 kg/m³ and viscosity (v) 0.000017894 kg/ms. Some boundary conditions used included velocity inlet, pressure outlet, and wall boundary condition. The velocity inlet is set according to the prototype test conditions. By using a turbulent intensity of 5% and a viscosity ratio of 10, the simulation aims to replicate realistic turbulent conditions encountered in practical engineering scenarios. The boundary conditions used in Table 1 are as follows:

Table 1. Boundary condition data

Inlet	Momentum	Velocity specification method	Magnitude, Normal to boundary
		Reference frame	Absolute
		Velocity magnitude (m/s)	3, 4, 5, 6, 7, 8, 9
		Pressure (Pascal)	0
	Turbulence	Specification method	Intensity and viscosity ratio
		Turbulent intensity (%)	5
		Turbulent viscosity ratio	10
Outlet	Pressure outlet	Backflow Reference Fame	Absolute
		Gauge Pressure (Pascal)	0
		Backflow Direction Specification Method	Normal to boundary
		Backflow Pressure Specification	Total pressure
	Turbulence	Specification method	Intensity and viscosity ratio
		Turbulent intensity (%)	5
		Turbulent viscosity ratio	10
Arm and blades Darrieus	Moving wall	Motion rotational	Relative to adjacent cell zone
			Rotational
		Rotation axis origin & direction	0
	Sand grain roughness	Roughness Height (m)	0
		Roughness Constant	5
Arm and blades Savonius	Moving wall	Motion rotational	Relative to adjacent cell zone
			Rotational
		Rotation axis origin & direction	0
	Sand grain roughness	Roughness Height (m)	0
		Roughness Constant	0.5

Specifications in the fabrication of wind turbines used for experiments are as follows Table 2:

Table 2. The specifications of the turbine

Specifications:	Darrieus	Savonius
	Blade material: wood balsa & glass fiber Weight: 2.1 kg Airfoil type: NACA 4418 Cord: 100 mm	Blade material: wood balsa & glass fiber Weight: 5.3 kg Endplate material: aluminum Endplate diameter: 550 mm Endplate thickness: 1.5 mm
Shaft	Material: Aluminum Length: 105 mm Diameter: 25 mm	
bearing	Tapered bearing FAG 32305 Ball bearing SKF 6305/C3	
Coupling	Rubber coupling series L-075	
Tower	Material: Height: 3000 mm	

3. Results and Discussion

The azimuth angle of wind turbines refers to the angular position of the turbine blades concerning a reference direction in degrees. For vertical-axis wind turbines (VAWTs) like the Savonius and Darrieus, the azimuth angle indicates the blade's position during rotation. See Figure 3,4,5, the torque values for different blades of a hybrid Savonius-Darrieus wind turbine at various azimuth angles, measured in degrees, with a wind speed of 3-5 m/s. This variation is due to changes in the relative wind speed and angle of attack as the blade rotates. Typically, the maximum torques the turbine blade catches capture the maximum wind force. The relative velocity of the wind to the blade changes during the revolting of the blade, which affects the aerodynamic forces on the blade to produce the torque and affect the turbine performance [11], [12]. As the velocity increases (3 to 5 m/s), the torque values produced also increase, with a similar trend in azimuth angles. The optimal torque is the Darrieus blade 3 by 1.06 Nm at azimuth angle of 75°, followed by Savonius 1 by 0.96 Nm at azimuth angle of 285° on wind speed 5 m/s.

At each wind speed of 3-5 m/s, the trend line of the torques is similar. The critical points where negative torque occurs in blade Savonius 2 in wind speed of 3-5 m/s at an azimuth angle of 180° have values of -0.43, -0.77, and -1.99, respectively. This is followed by blade Darrieus 1 at an azimuth angle of 15° by -0.41, -0.73, and -1.16, respectively. Similar to torque Darrieus 1 at an azimuth angle of 15°, Savonius 1 has a negative value of -0.34, -0.61, and -0.96, respectively. Blade Darrieus 2 at an azimuth angle of 135° by -0.26, -0.44, and -0.68, respectively. Then, followed by blade Darrieus 3 at an azimuth angle of 255° by -0.25, -0.45, and -0.71, respectively. Negative torque values cause the blades to rotate against the intended wind direction, reducing the turbine's efficiency. This occurs when the drag force overpowers the lift force, or if the lift force is acting in a direction that doesn't aid the turbine's movement. Darrieus blades (1, 2, and 3) show more pronounced fluctuations in torque compared to the Savonius blades (1 and 2), which are more stable. The torque values for all blades vary significantly with changes in the azimuth angle, indicating the impact of blade position relative to the wind direction on the torque generated.

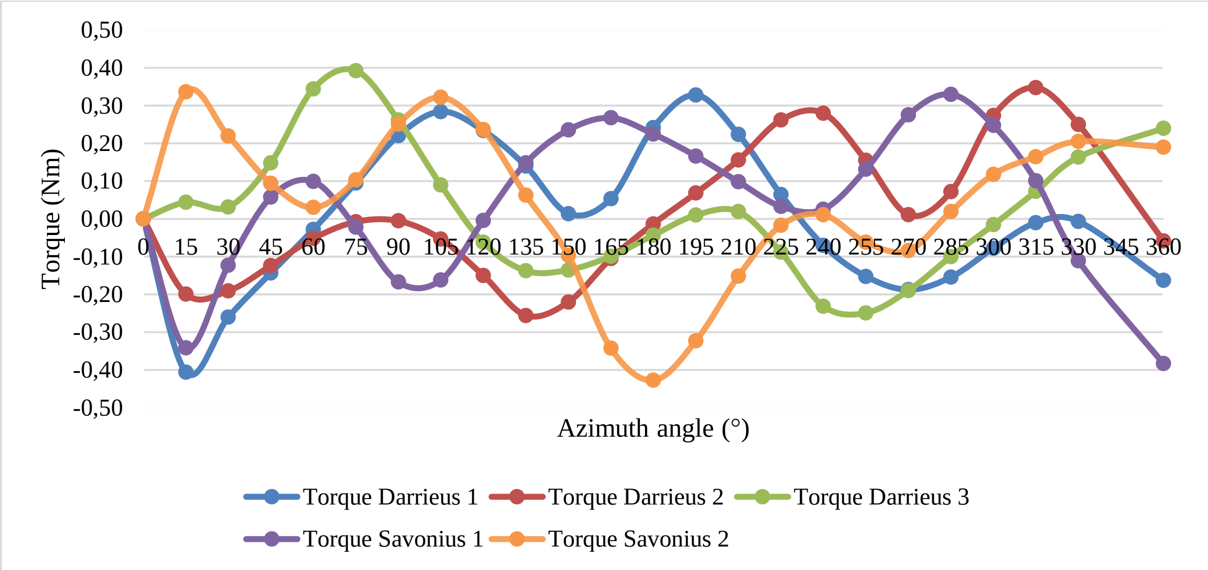

Figure 3. Torque in every blade on the different azimuth angle on wind speed 3 m/s

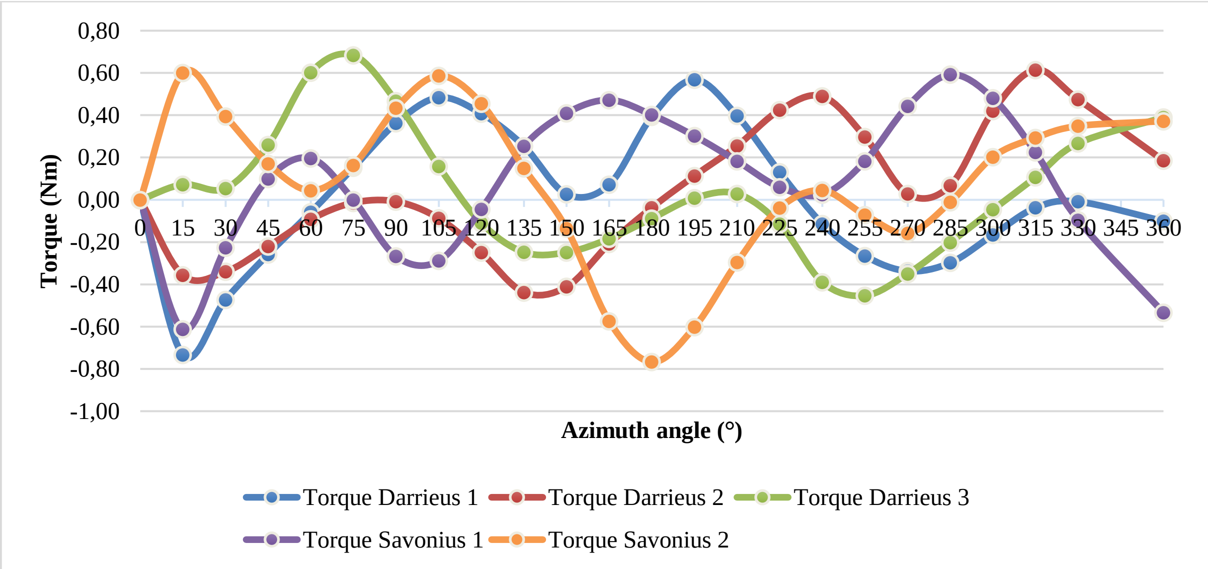

Figure 4. Torque in every blade on the different azimuth angle on wind speed 4 m/s

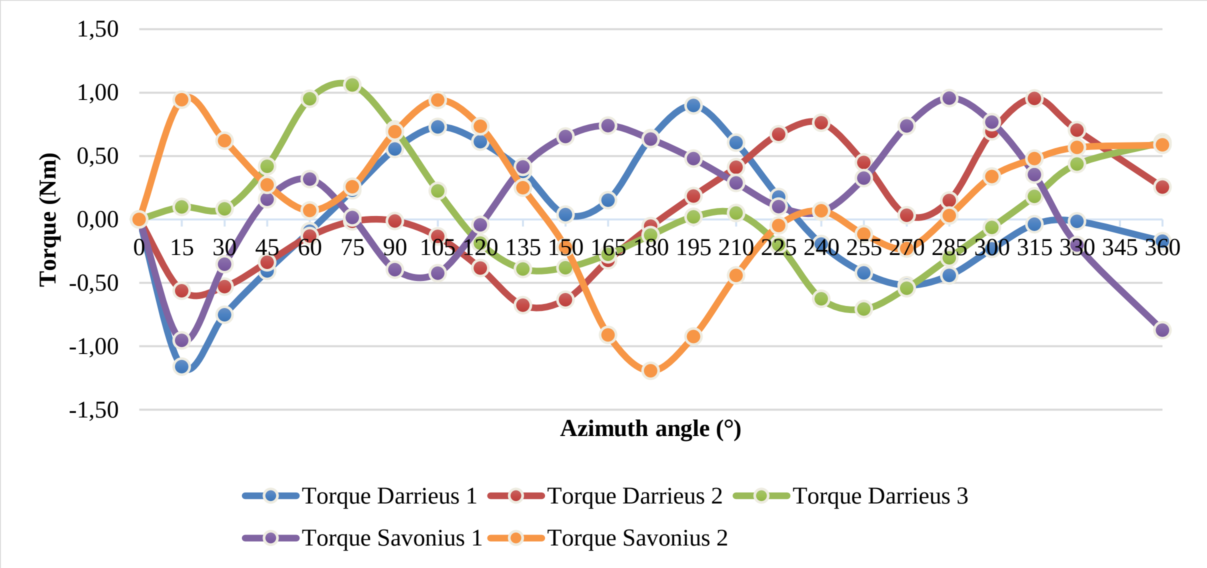

Figure 5. Torque in every blade on the different azimuth angle on wind speed 5 m/s

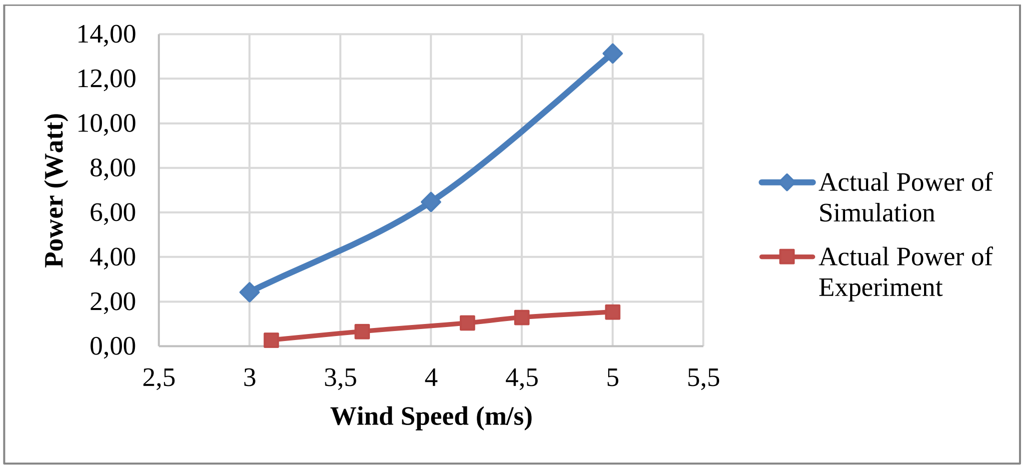

Figure 6. Power between simulation and experimental

When designing a wind turbine, it's essential to consider various characteristics and performance parameters to achieve optimal efficiency and reliability. Key factors include the target power output, the turbine's torque characteristics, the power coefficient, the moment coefficient, and the Tip Speed Ratio (TSR), which is the ratio of the blade tip speed to the wind speed. Figure 6, even though it has a similar trend line that the power will be increased due to velocity increase, the Savonius - Darrieus turbines have a maximum power output of 1.54 watts in the experimental, compared to 13.14 watts for simulation. The average power of wind turbine in the simulation and experimental due to the variation in wind speed is 7.35 watts and 0.97 watts, respectively. The power output obtained from the experiment is influenced by losses in the generator, gearbox, and other electrical components, which might not be accurately modeled, leading to discrepancies. Variations in temperature and air density affect air pressure and, consequently, the power output.

Figure 7 represents the torque related to the wind speed by simulation and experimental study. The trend line same as the power. The wind speed affects the blade of the turbine not only raising the turbine power but also generally leading to an increase in a larger surface area exposed to the wind, capturing more kinetic energy and generating higher torque. The Savonius - Darrieus turbines have a maximum torque of 0.11 Nm in experimental, compared to 0.36 Nm for simulation.

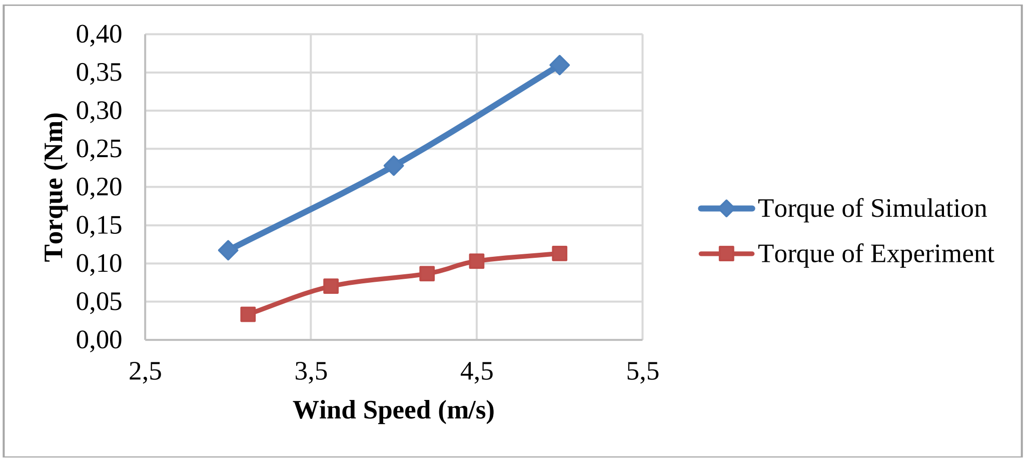

Figure 7. Torque between simulation and experimental

The coefficient of power (CP) for a Savonius - Darrieus refers to the efficiency of the turbine in converting the kinetic energy of the wind into mechanical power. The CP value varies depending on the turbine design, wind conditions, and operating parameters. Unlike the coefficient of moment, which relates to torque, the coefficient of power is a measure of overall power output efficiency. The result of (CP) by the simulation higher than the experimental can be seen in Figure 8 below. This is also indicated by the power generated, which shows a similar trend. The values CP of simulations start from around 0.164 at 3 m/s and slightly increase to peak at around 0.192 at 5 m/s, which the CP of the Experiment is significantly lower, starting from just above 0.02 at 3 m/s and showing a very slight increase to just below 0.05 at 5 m/s. The CP of Simulation shows a mild increasing trend as the wind speed increases, stabilizing at higher wind speeds and the CP of Experiment remains relatively flat, with only a minor increase as wind speed increases, indicating less efficiency or effectiveness in converting wind to power under experimental conditions compared to the simulated conditions. The difference in CP values between the two scenarios is significant, often exceeding 20%. This substantial gap highlights potential challenges in translating theoretical or simulated performance into practical. The real-world settings might be impacting the efficiency of power generation. This could include equipment inefficiencies and environmental factors. Understanding and narrowing this gap is crucial for improving the reliability and efficiency of wind power technologies in practical applications.

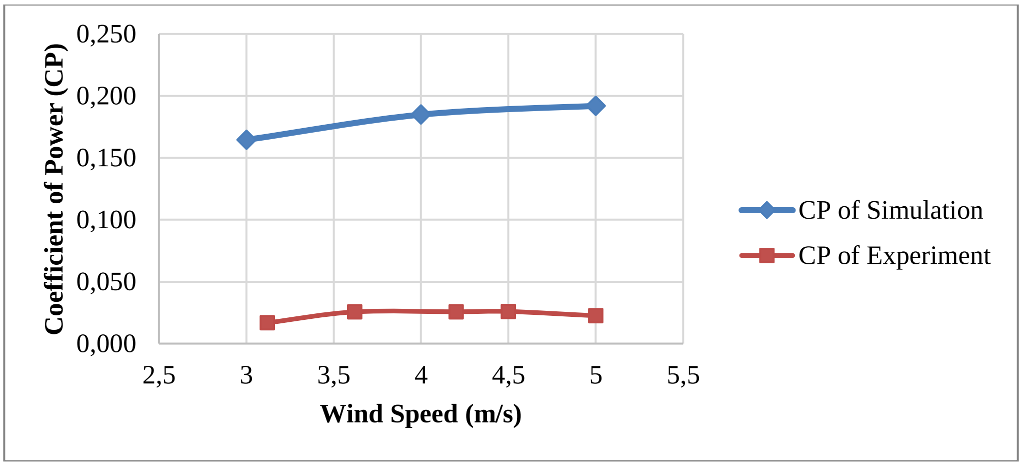

Figure 8. Coefficient of power (CP) between simulation and experimental

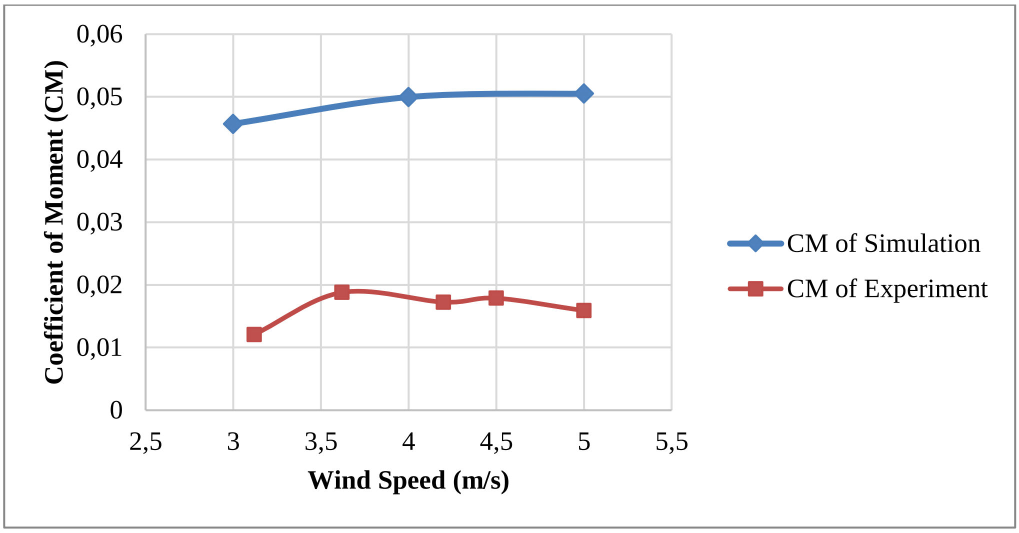

Figure 9. Coefficient of Moment (CM) between simulation and experimental

The coefficient of moment is typically defined as the ratio of the moment (or torque) produced by the turbine to the dynamic pressure of the wind and the swept area of the rotor. Figure 9 shows the trend line coefficient of the moment (CM) between simulation and experimental. Same as the CP, the experiment found that the CM on speed 3.5 to 4 m/s is decreased. At lower wind speeds, the turbine may operate in a region where the Savonius blades are more efficient compared to the Darrieus blades. This can cause an increase in the moment coefficient as wind speed increases from 3 m/s to 3.5 m/s. However, as the wind speed continues to increase, the Darrieus blades might start contributing more, but they could also introduce aerodynamic inefficiencies or stall effects.

At higher wind speeds, the Darrieus blades might experience an aerodynamic stall, where the airflow separates from the blade surface, reducing lift and increasing drag. This can lead to a decrease in the coefficient of moment despite the increase in wind speed.

4. Conclusion

The relationship between azimuth angle, torque, and velocity is analyzed to optimize blade design and turbine performance. It helps in identifying the optimal blade shapes and angles that maximize torque and efficiency at the speed 5 m/s in Darrieus blade 3 by 1.06 Nm at azimuth angle 75°, followed by Savonius 1 by 0.96 Nm at azimuth angle 285°. The characteristic performance such as Torque, power, coefficient of power, and coefficient of the moment shows that the differences in results between the numerical study method and the experimental study method are due to external factors such as friction in the bearings, friction in the coupling, misalignment of the turbine shaft, obstacles near the turbine, measurement instrument accuracy, and variations in air density. However, the design and configuration of the turbines play a crucial role in determining their performance characteristics.

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