Experimental Study on Combined Savonius and H- Rotor Darrieus Vertical Axis Wind Turbine with NACA Airfoil as its Blade

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Abstract
The objective of this research is to conduct an experimental study of the performance of the vertical wind turbine (VAWT) combination Savonius and H-rotor Darrieus. Three models will be tested: a combination of NACA 4515-0012, a combination of NACA 6515-0015, and a combination of NACA 8515-0018 herein after refer as VAWT A, VAWT B, and VAWT C. Testing conducted using subsonic wind tunnel with various wind speed between 3 m/s to 15 m/s. Experimental result will be compared and analyzed. The results of this study showed that VAWT B had the best performance, the highest TSR is 0.4188 at wind speeds of 15 m/s. While VAWT A and C shows better self-starting, capabilities compare to VAWT B.

1. INTRODUCTION
Wind power is a form of alternative energy that has the most potential to replace fossil fuels. Wind power is freely available, renewable, free of emissions, and does not produce the greenhouse gas effect. Mankind has realized the benefits they could get from wind; hence they develop a wind turbine to utilize wind power. Wind turbines have been used in Persia (Iran) from 500 - 900 A.D as a tool to pump water from the ground. For several centuries, more wind turbines were applied to agricultural irrigation needs [1].

In with advancing of technology, researcher has developed modern wind turbine, Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). HAWT rotates on the horizontal axis, and VAWT rotates on the vertical axis. VAWT has a simpler structure and installation than HAWT. The generator on the VAWT is placed at the base of the main shaft so that the turbine stand tower does not need to withstand the load from the generator, the VAWT can also work on winds that have variable direction and speed [2]. This research will be focusing on VAWT, to study the most efficient with high performance by combining two different type of VAWT, Savonius and H-rotor Darrieus.

Savonius Wind Turbine: Savonius wind turbines are VAWTs that work based on the drag principle discovered by Sigurd Savonius in 1925 [3]. Rotational motion on the Savonius turbine occurs because the coefficient of friction on the concave surface of the turbine is greater than the coefficient of friction on the surface of the turbine convex, so that the force acting on the first surface is greater than the second surface, thus producing torque which then moves the turbine. According to research conducted by Johnson [4] and research by Rus [5], Savonius turbines have a Cp value of 0.2 - 0.3, which can be categorized as efficient, but with a small tip speed ratio value makes this type of turbine more suitable as an experimental tool in the laboratory.

Darrieus Wind Turbine: Darrieus wind turbines were first discovered and patented by Georges Darrieus in the United States in 1931 [7]. Darrieus turbine with H-Rotor configuration is the simplest form of Darrieus wind tubing which only consists of 2 or more airfoil which are installed vertically. Airfoils in this type of turbine can freely interact with wind [8]. The H - Rotor turbine generates most of the power through lift, not drag. The Cp value of this turbine is also comparable to modern HAWT; therefore, the Darrieus H-Rotor wind turbine is suitable for use as a power plant [9].

Figure 1. Savonius VAWT [6]

Figure 2. H-rotor Darrieus VAWT [9]
Savonius-Darrieus Wind Turbine: is a vertical wind turbine that has a combination configuration of the Darrieus and Savonius wind turbines. This combined configuration is used to correct the weaknesses of the Darrieus and Savonius wind turbines. Darrieus wind turbines that work in the presence of lift from the airfoil can convert as much as 16/27 or 59.3% of the total energy contained in the wind, but Darrieus wind turbines have a low initial torque value, so it cannot work in winds with low speed (self-starting) \(^{10}\). Savonius wind turbines that work with friction (drag) are only able to convert at 4/27 or 14.8% of the total energy contained in the wind, but have a large initial torque value, so they can work on winds with low speed \(^{11}\).

Gupta et al \(^{12}\) through an experimental experiment comparing Savonius wind turbines with standard configurations with Darrieus-Savonius wind turbines. Savonius wind turbines have 3 blades with varying overlap distances, while combination wind turbines have a 3 blades Darrieus turbine configuration in the top position and Savonius 2 blades turbine The results of an experimental study by Gupta et al stated that turbines with the Darrieus-Savonius combination have an efficiency value of 0.51, this value is higher when compared to Savonius turbine with standard configurations with Savonius wind turbines. Savonius wind turbines with standard configurations have a low initial torque value, so they can work on winds with low speed. \(^{11}\). The addition of overlap also results in a reduction in the efficiency of the Darrieus-Savonius wind turbine.

NACA Airfoil: NACA airfoils are airfoil forms of aircraft wings developed by the National Advisory Committee for Aeronautics (NACA). NACA was founded before the first world war in America, which later in 1950 was renamed the National Aeronautics and Space Administration (NASA). The form of NACA airfoils is determined based on a series of numbers after the word "NACA". One a type of NACA commonly used for research is a NACA with a four-digit series. In the book published by Jacobs et al \(^{13}\), the four series of numbers on NACA airfoils have the following definition:

1. The first digit is defined as the percentage of the maximum camber amount of the length of the chord.
2. The second digit is defined as the maximum camber distance from the front end of the airfoil in tens of percent.
3. The last two digits are defined as the maximum thickness of the airfoil as percent of the chord.

Performance of Savonius-Darrieus wind turbine can be expressed in form of torque coefficient \((C_t)\) and power coefficient \((C_p)\) in comparison with tip speed ratio or TSR \((\lambda)\).

TSR \((\lambda)\): is a parameter related to the value of the speed and diameter of the rotor, the ratio of the radius of the turbine blade to the wind speed \(^{14}\), can be determined as:

\[
\lambda = \frac{\omega D}{2V}
\]  

(1)

Where \(\omega\) is angular velocity of the rotor (rad/s), \(D\) is total diameter of VAWT, \(V\) is wind velocity, \(N\) is total rotor rotation per minute (RPM).

\[
\omega = \frac{2\pi N}{60}
\]  

(2)

Torque Coefficient: is the ratio between the actual torque of the rotor \((T)\) and the theoretical torque contained in the wind \((T_w)\) \(^{15}\), can be determined as:

\[
C_t = \frac{\text{Rotor torque}}{\text{Wind torque}} = \frac{T}{T_w} = \frac{T}{0.25\rho A D V^2}
\]  

(3)

Where \(\rho\) is the density of the air, equal to 1.225 \((\text{kg/m}^3)\), \(T\) is torque \((\text{Nm})\), \(A\) is swept area, equal to rotor height \((H)\) x rotor diameter \((D)\) in \((\text{m})\), \(d\) is Savonius chord length.

Power Coefficient: is the ratio of the maximum power obtained from the wind \((P)\) to the total actual power in the wind \((P_w)\) \(^{16}\), can be determined as:

\[
C_p = \frac{\text{Rotor power}}{\text{Actual wind power}} = \frac{P}{P_w} = \frac{P}{0.5\rho A V^2}
\]  

(4)

Where \(P = T \cdot \omega\)

(5)

2. EXPERIMENTAL PROCEDURE

![Figure 3. Research Activity Flow Chart](image)

The tests were carried out using 3 Savonius-Darrieus VAWT models using NACA airfoil as its blade: NACA 4515 airfoil with a combination of NACA 0012 airfoil, NACA 6515 airfoil with NACA 0015 airfoil combination, and NACA 8515 airfoil with a combination of NACA 0018 airfoil, hereinafter referred to as VAWT A, B, and C. NACA airfoil was plotted using Airfoil Tools software with the help of AUTOCAD 2017 software to create a design.

VAWT has a three-blade configuration which is positioned as far as 120° between one another. VAWT model have total diameter, \(D = 100 \text{ mm}\) and height, \(H = 100 \text{ mm}\). Savonius NACA 4515, 6515, and 8515 have a chord length of 40 mm and H-rotor Darrieus NACA 0012, 0015, and 0018 have a chord length of 30 mm.

These VAWT design will be realized to solid model, made from polylactic acid (PLA) through 3D printing, then will be placed on top of four-legged support to maintain its stability, showed in figure 4. Wind VAWT then will be coupled to a generator through gears with ratio of 1:1 and a digital volt-ampere meter and will be ready for wind tunnel testing, showed in figure 5.
Experimental testing was carried out at different wind speed variations conducted at room temperature using subsonic wind tunnel with turbulent wind flow. Wind speed is measured using a digital anemometer and VAWT placed at 30-centimeters from the wind tunnel outlet, showed in figure 6.

The wind tunnel speed has been changed by changing the frequency of its inverter. Wind speed (V) will be increased gradually: 3 m/s, 6 m/s, 9 m/s, 12 m/s, and 15 m/s. In each wind speed, the electrical voltage and current is measure by reading the volt-ampere meter, which will be calculated to find its electrical output power ($P_L$):

$$P_L = v_L \cdot I$$  \hspace{1cm} (6)

Where $v_L$ is electrical voltage (volt), $I$ is electrical current (A).

Modern electric generators generally have a power factor ($\eta$) of 0.8 so that the rotor power ($P$) can be determined as:

$$P = \frac{1}{\eta} \cdot P_L = 1.25 \cdot P_L$$  \hspace{1cm} (7)

The number of rotation ($N$) performed by VAWT is measured using an infrared digital tachometer.

### 3. RESULT AND DISCUSSION

Based on the results of research through experimental testing using subsonic wind tunnels, several important points will be analyzed:

#### TSR ($\lambda$) vs Wind Speed (V)

![Figure 7. TSR ($\lambda$) related to wind speed (m/s)](image)

Based on the test results showed in figure 7, the three VAWT increased in TSR values along with the increased in wind speed, and achieved stability at wind speeds between 9 m/s to 12 m/s, VAWT B has the highest TSR value of 0.4188 at wind speeds of 15 m/s.

#### Torque (T) vs Wind Speed (V)

![Figure 8. Torque (Nm) related to wind speed (m/s)](image)
Figure 8 shows that VAWT A and C have the same initial torque value, 0.0023 Nm at wind speeds of 3 m/s, this shows that VAWT A and C have the ability to self-start better than VAWT B. Whereas VAWT B has highest torque value, 0.00358 Nm at wind speed of 15 m/s.

Power (P) vs Wind Speed (V)

![Figure 9. Power (watt) related to wind speed (m/s)](image)

The experimental results in figure 9 shows that power generated by the three VAWTs will increase along with the increase in wind speed. VAWT B produces the highest power, 0.45 watts at a wind speed of 15 m/s.

Torque Coefficient (Ct) vs TSR (λ)

![Figure 10. Torque coefficient (Ct) related to TSR (λ)](image)

Figure 10 shows that VAWT A and C have the maximum torque coefficient, 0.0309 at the lowest TSR value, which is around 0.348. This shows that both VAWTs have the best efficiency at low TSR and decreases with increasing TSR values. VAWT B shows the opposite result, with the lowest power coefficient, 0.0145 at a TSR value of around 0.368 and reaching a maximum power coefficient, 0.0271 at TSR around 0.389 and decreasing to 0.0222 at TSR around 0.403.

4. CONCLUSIONS

Based on the results of experimental tests and data analysis, the result can be concluded:

1. VAWT B has the best overall performance. With highest TSR 0.4188 at a wind speed of 15 m/s.
2. VAWT A and C more efficient at low wind speed and have better self-starting abilities compare to VAWT B.
3. The power generated by the three VAWTs will increase with increasing wind speed. VAWT B has highest output of 0.45 watts at wind speed of 15 m/s
4. VAWT B has the best power coefficient and torque coefficient at high TSR, while VAWT A and C show the opposite results.
5. The three VAWTs reach a stable point and the most optimal performance is at wind speeds between 9 m/s to 12 m/s.

REFERENCES


