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Numerical Study of Savonius Wind Turbine Performance at Tidar University under Wind Speed and Direction Angle Using the CFD Method

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Abstract

The savonius wind turbine is a type of vertical axis wind turbine (VAWT) that operates based on the drag force principle. Its simple design, featuring S-shaped blades arranged around a vertical shaft, enables the turbine to capture wind from any direction and operate effectively at low wind speeds, making it suitable for residential areas. This study investigates the performance of a three-bladed helical Savonius turbine with a 180° twist angle under variations in wind speed and wind direction. Numerical simulations were conducted using Computational Fluid Dynamics (CFD). Wind speed data were obtained from rooftop measurements at the Faculty of Economics, Tidar University, recorded at 08:00, 10:00, 12:00, 14:00, and 16:00, with average values of 1.9 m/s, 2.0 m/s, 2.2 m/s, 2.2 m/s, and 2.0 m/s, respectively. The analyzed wind direction angles were 15°, 25°, and 35°. Results show that a 15° wind direction produced the most stable and optimal performance, achieving a turbine power (P_T) of 0.0356 W, a power coefficient (Cp) of 0.0931, and a TSR of 0.525. This occurred because the airflow aligned more effectively with the rotor, improving kinetic energy capture, reducing drag flow on the convex returning blade, and minimizing vortex formation and negative torque. Peak performance occurred at 12:00 and 14:00 when wind speeds exceeded 2.0 m/s. However, the power coefficient showed a decreasing trend due to the presence of adverse flow phenomena that reduce the amount of wind energy converted by the turbine.

Keywords: *wind direction; computational fluid dynamics; twist angle; helical Savonius wind turbine; VAWT*

Abstrak

Turbin angin Savonius merupakan salah satu jenis *vertical axis wind turbine* (VAWT) yang bekerja berdasarkan prinsip gaya hambat (*drag*). Desain yang sederhana dengan bentuk *blade* menyerupai huruf “S” yang disusun melingkar terhadap poros, memungkinkan turbin ini mampu menerima angin dari segala arah dan beroperasi pada kecepatan angin yang rendah, sehingga cocok untuk daerah pemukiman. Penelitian ini menganalisis performa turbin angin Savonius menggunakan tipe heliks dengan konfigurasi 3 *blade* dan sudut puntir 180° berdasarkan variasi kecepatan dan sudut arah datang angin. Analisis dilakukan menggunakan simulasi numerik *computational fluid dynamics* (CFD) . Variasi kecepatan angin diperoleh dari pengukuran di *rooftop* Gedung Fakultas Ekonomi Universitas Tidar pukul 08:00, 10:00, 12:00, 14:00, dan 16:00 masing-masing memiliki rata-rata 1,9 m/s; 2,0 m/s; 2,2 m/s; 2,2 m/s; dan 2,0 m/s. Variasi sudut arah datang angin yang digunakan adalah 15°, 25°, dan 35°. Hasil penelitian menunjukkan, sudut arah datang angin 15° memberikan performa paling optimal dengan nilai P_T sebesar 0,0356 watt, Cp sebesar 0,0931, dan TSR sebesar 0,525. Kondisi tersebut dipengaruhi aliran angin yang lebih searah terhadap rotor turbin sehingga penangkapan energi kinetik angin lebih efektif dan pembentukan *dragging flow* di sisi cembung *returning blade* serta pusaran (*vortex*) lebih rendah dan torsi negatif berkurang. Puncak performa terjadi pukul 12:00 dan 14:00 ketika kecepatan angin berada diatas 2,0 m/s. Nilai Cp mengalami penurunan dipengaruhi fenomena aliran negatif yang berlawanan arah sehingga kehilangan energi angin yang dikonversi turbin.

Kata kunci: arah angin; *computational fluid dynamics*; sudut puntir; turbin angin Savonius heliks; VAWT

1. Introduction

Electrical energy sources in Indonesia are still largely dependent on new fossil energy, while their availability is depleting and energy needs continue to increase [1]. In 2022, about 71% of coal production has been used for power generation and this dependence is projected to continue into the next 10 years [2]. This condition encourages efforts to develop environmentally friendly and sustainable renewable energy, one of which is wind energy. Savonius wind turbines are a type of vertical axis wind turbine (VAWT) that works on the principle of drag [3]. This turbine has a simple design with a blade shape resembling the letter "S" arranged circular against the shaft, so it is able to receive wind from various directions and operate at low wind speeds [3,4]. These characteristics make Savonius wind turbines suitable for application in residential areas, including in the Tidar University environment. The working principle of the Savonius wind turbine is based on the difference in resistance on the concave side (advancing blade) and the convex side (returning blade) which results in a difference in torque, so that the rotor can rotate [3,5]

Several studies have modified the design of the Savonius wind turbine to improve its performance using the helical type by adding a twist angle. The results showed that the helical type with a torsional angle of 180° in a 3-blade configuration was able to produce a cut in speed of 1.51 m/s [6]. The experimental study [7], also stated that the minimum wind speed to rotate the shaft of the helical type Savonius 3 blade wind turbine is 1.6 m/s, and the increase in wind speed has an effect on increasing the turbine output power. Another study examined the variations in twist angles of 0°, 30°, 60°, 90°, 120°, 150°, and 180° in a 2-blade helical Savonius wind turbine using wind speeds of 3 m/s and 4 m/s. The results showed that the highest power coefficient (Cp) values were obtained with twist angles of 0°, 90°, and 180° of 0.468; 0,449; and 0.401 at a speed of 3 m/s [8].

Numerical studies using the computational fluid dynamics (CFD) method, also showed that an increase in the number of blades led to an increase in turbulence and pressure around the blade, thus forming a vortex that decreased the speed of fluid flow behind the blade [9]. However, studies that specifically examine the performance of helical-type Savonius wind turbines by varying the angle of the wind flow direction using the CFD method are still limited. Previous experimental studies have been more on conventional Savonius wind turbines. In an experimental study [10], examining a variation in wind direction angle of 15° – 30° on a conventional 3 blade Savonius wind turbine using a wind flow concentrator with wind speed variations of 1.8 m/s, 2 m/s, 2.5 m/s, 3 m/s, and 4 m/s, showed that angle 20 produced the highest electrical voltage at each wind speed variation [10]. Therefore, the influence of variations in the angle of the direction of the wind can be a consideration in determining the performance of the helical type Savonius wind turbine, especially in the numerical approach.

Central Java Province has potential in wind energy development with an estimated capacity of 5,213 MW [11]. Tidar University, which is located in Magelang City, Central Java, also has the potential for the application of Savonius wind turbines on a small scale. Based on Global Wind Atlas data, the average wind speed in Magelang City at an altitude of 10 m was recorded at 1.76 m/s. Based on this potential, this study aims to analyze the performance of a helical Savonius wind turbine with a twist angle of 180° to the variation in wind speed and angle of wind direction at Tidar University using the CFD method in a transient state. A numerical approach is used to determine the fluid flow pattern around the blade as well as its effect on turbine performance, which is difficult to do through experimental testing. The performance parameters analyzed include power coefficient (Cp), turbine power, and tip speed ratio (TSR) based on the wind speed measurement time, and the simulation results show that the variation in the angle of the wind direction has a significant influence on the performance of the helical Savonius wind turbine, with certain angle configurations resulting in better performance parameters.

2. Material and Method

2.1. Research Time and Location

This research was conducted using a CFD based numerical simulation method on the Ansys 2024R1 software. Wind speed data was obtained through measurements on the rooftop of the Faculty of Economics Building, Tidar University which can be seen in Table 1. The measurements were carried out for 11 days, from July 30 to August 15, 2025 at 08:00, 10:00, 12:00, 14:00, and 16:00. Data collection is carried out every 5 minute interval to obtain an average hourly value. Consideration of the selection of measurement time in the range of the month is due to favorable weather conditions. The wind speed data obtained is used for the input parameter as the inlet velocity in the CFD simulation. The simulation process was carried out at the Computer Laboratory of the Sidotopo Campus, Tidar University.

Table 1. Wind Speed Data

Day to	**Wind Speed (m/s)**				
	08:00	**10:00**	**12:00**	**14:00**	**16:00**
Day 1	1.8	2.0	2.4	2.1	2.0
Day 2	19	1.8	2.3	2.0	2.3
Day 3	2.1	2.1	2.3	2.4	2.0
Day 4	1.9	2.0	2.3	2.1	2.4
Day 5	1.8	2.0	2.3	2.0	1.9
Day 6	1.9	2.3	2.1	2.2	1.8
Day 7	1.8	2.2	2.0	2.1	1.8
Day 8	1.8	1.9	1.8	2.3	1.8
Day 9	1.9	2.1	2.0	2.2	1.9
Day 10	1.8	2.0	2.0	2.6	2.0
Day 11	1.9	2.1	2.3	2.5	2.1
Average (m/s)	1.9	2.0	2.2	2.2	2.0

2.2. Geometry Turbine dan Domain

The Savonius wind turbine model is designed based on references [6] using a helical type with a 3-blade configuration and a 180° twist angle, because it has the lowest cut in speed of 1.51 m/s so that it matches the average wind speed at Tidar University. The turbine geometry uses a reference [12], with the formulation of aspect ratio (AR=H/D) of 2D and $(\boldsymbol{D_e})$ of 1.1D. The thickness of the blade and end plate is 1.4 mm and 2 mm respectively. The geometry and design of the Savonius wind turbine are shown in Table 2 and Figure 1.

Table 2. Dimensions of Savonius Wind Turbine

Parameter	**Simbol**	**Value**
Diameter rotor	D	180 mm
Rotor height	H	360 mm
Diameter end plate	D_e	198 mm
Diameter poros	D_s	12 mm
Revolution	-	0,5
Twist angle	θ	180°

Figure 2 shows the domain and boundary conditions used in this study. Domains consist of two parts, namely rotating domains and static domains. After domain creation, the determination of boundary conditions is required to define fluid flow, including inlets, walls, and outlets. The static domain design in this study used a reference [13], with a total length of 15D. The distance between the inlet and the turbine is 5D to minimize the turbine's influence on the development of the incoming airflow, while the distance between the turbine and outlet is 10D to allow room for the flow and whirlpool to develop naturally after passing through the turbine. Vertically and laterally have a size of 5D each to simulate open flow conditions and reduce the influence of boundary conditions on the distribution of wind flow. In addition, the rotating domain design is made with a diameter of 1.5D [14].

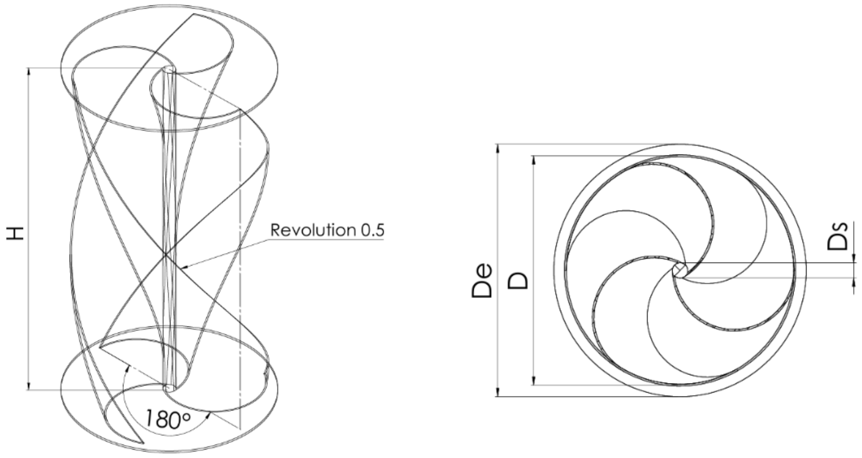


Figure 1. Savonius Wind Turbine

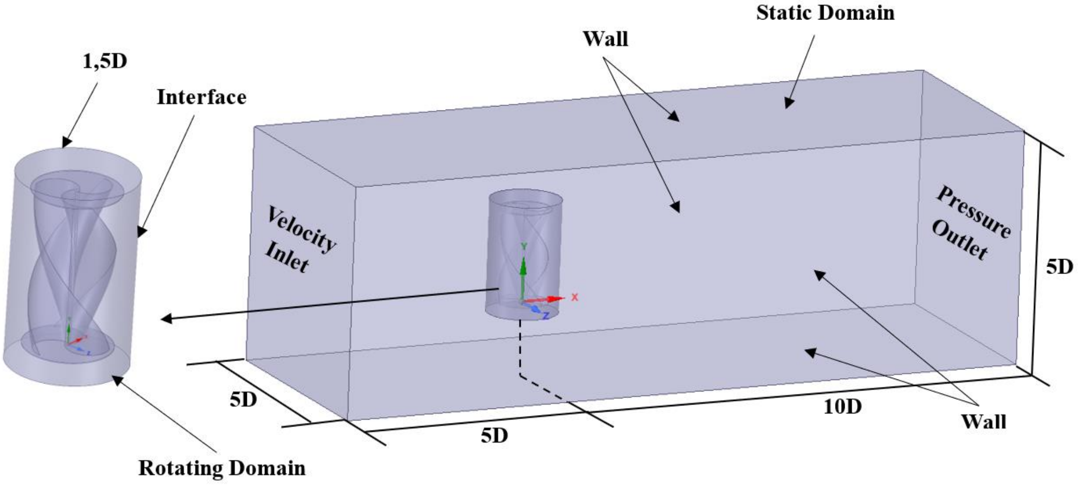


Figure 2. Domains and Boundary Conditions

2.3. Meshing

Figure 3 shows the meshing results on the Savonius wind turbine model and the domain. The meshing process in the Savonius wind turbine design is carried out by adding local sizing to the blade and boundary layer using a smooth transition of 10 layers on the blade wall to capture the physical phenomenon between the blade surface and the flow of fluid. This is done to obtain a Y+ value below 5 [15].

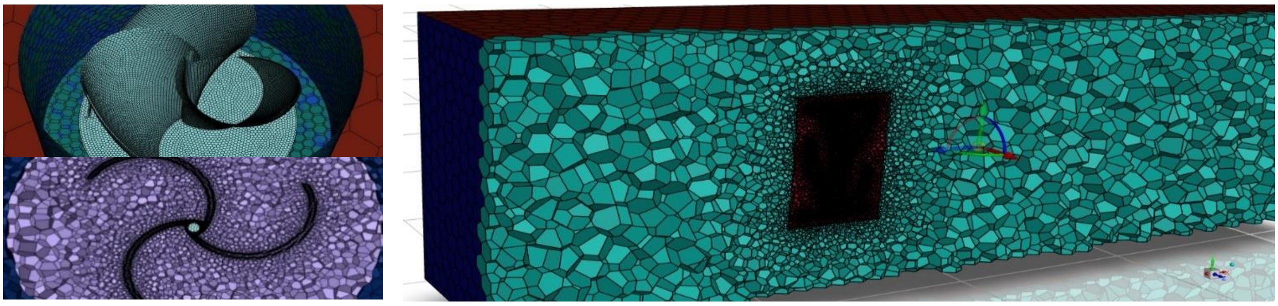


Figure 3. Meshing Results

2.4. Boundary Conditions, Simulation Parameters, and Analysis Equations

Table 3 shows the configuration of boundary conditions and simulation parameters used in this study. The simulation was performed under a transient state, aiming to capture changes in the inert flow and complex force interactions of the blade during rotation, which could not be accurately presented by the simulation in a steady state [16]. This study uses the k-ε Realizable turbulence model, because the model is suitable for the application of complex flows such as swirls with lower computational costs [17]. In addition, the k-ε Realizable is an extension of the standard k-ε model that can complete rotating turbulent viscosity flows, layers under strong pressure gradients, and flow separation with superior performance achievements, and this model excels at capturing average flows around complex structures [18]. The use of near wall function with the enhanced wall treatment type because this method can work adaptively on various layers, such as laminar sublayers, buffer regions, and turbulent. In addition, this method can work at both low and high Y+ values, so it can be used to analyze flows near the blade surface [19].

Table 3. Setting Up Boundary Conditions and CFD Parameters

Parameter	Value
Time	Transient
Models	Viscous: $\boldsymbol{k}$-$\boldsymbol{\varepsilon}$ Workable Near Wall Function: Enhanced Wall Treatment
Materials	Fluid: air Solid: aluminium
Density	$\mathbf{1,225\ kg/m^3}$
Viscosity	$\mathbf{1,7894 \times 10^{-5}\ kg/ms}$
Velocity Specification Method	Magnitude and Direction
Inlet	Velocity inlet
Outlet	Pressure outlet (0 Pa)
Turbine	Dynamics Mesh: Yes Six DOF: Yes Dynamic Mesh Zones: Blade - Rigid Body Interface Rotating - Rigid Body Interior Rotating - Rigid Body Interior Static – Stationary Rotating – Rigid Body
Solution	Time Steps Size: 0.05s Number of Time Steps: 500 Max Iterations: 30
Post Processing	Torque Omega Velocity Vector

The variation in the angle of the wind direction used was 15°, 25°, and 35° which were implemented using the velocity specification method magnitude and direction at the velocity inlet. The selection of the angle range of the wind direction is based on the results of the study [10], which shows the optimum performance of a conventional Savonius wind turbine with a 3 blade configuration obtained at an angle of 20°**.** Based on this, variations in the direction of wind direction 15°, 25°, and 35° were selected to evaluate the performance of the helical type Savonius wind turbine against changes in the direction of the wind from small deviations to larger ones. Each variation of the angle of the wind direction is simulated for each wind speed by deflecting the direction of the wind flow at the inlet velocity. Referring to Table 3, the results obtained are in the form of torque and angular rotation speed (omega). These results were used to evaluate performance parameters including turbine power ($\boldsymbol{P_T}$), power coefficient (Cp), and tip speed ratio (TSR).

Turbine power ($\boldsymbol{P_T}$) is the kinetic energy of the wind that has been converted by the wind turbine into mechanical energy. To find out the power of a turbine, the following equation can be used:

$$\boldsymbol{P_T = T \times r} \tag{1}$$

Where: $\boldsymbol{P_T}$ = daya turbin (watt); $\boldsymbol{T}$ = torsos (Nm) and $\boldsymbol{\omega}$ = angular rotational speed (rad/s)

The power coefficient (Cp) is a large ratio of the turbine power generated to the available wind power, so it can be formulated into the following equation:

$$\boldsymbol{C_P = \frac{P_T}{P_W}} \tag{2}$$

Where:

As for the wind force ($\boldsymbol{P_W}$), it can be obtained by using the following equation:

$$\boldsymbol{P_W = \frac{1}{2}\rho A v^3} \tag{3}$$

Where: $\boldsymbol{v}$ = wind speed (m/s) $\boldsymbol{A}$ = Turbine sweep area (m^2); $\boldsymbol{\rho}$ = air density ($\mathbf{kg/m^3}$) and $\boldsymbol{P_W}$ = wind power (watts).

The area of the turbine sweep area (A), is obtained using the following equation:

$$\boldsymbol{A = D.H} \tag{4}$$

Where: $\boldsymbol{D}$ = diameter turbin (m) and $\boldsymbol{H}$ = turbine height (m).

To determine the efficiency of the turbine in converting wind kinetic energy, the tip speed ratio (TSR) can be obtained using the following equation:

$$\boldsymbol{\lambda = \frac{\omega . r}{v}} \tag{5}$$

Where: $\boldsymbol{\lambda}$ = *tip speed ratio* and $\boldsymbol{v}$ = wind speed (m/s).

3. Results and Discussion

3.1. Grid Independence Test

The grid independence test is carried out by gradually smoothing the size of the mesh, starting from rough to smooth conditions or reaching the grid independence limit (GIL), which aims to ensure that the simulation results do not experience significant changes to the addition of the number of cells [20]. The results of the grid independence test can be seen in Table 4 and Figure 4.

Table 4. Grid Independence Test

Fineness Level	Number of Cells	Mesh Cell Size (mm)	Cp	Y+
1	248,997	6	0.0565	0.72
2	291,921	5.5	0.0557	0.67
3	345,324	5	0.0576	0.61
4	876,627	3	0.0594	0.38
5	1,256,058	2.5	0.0588	0.31

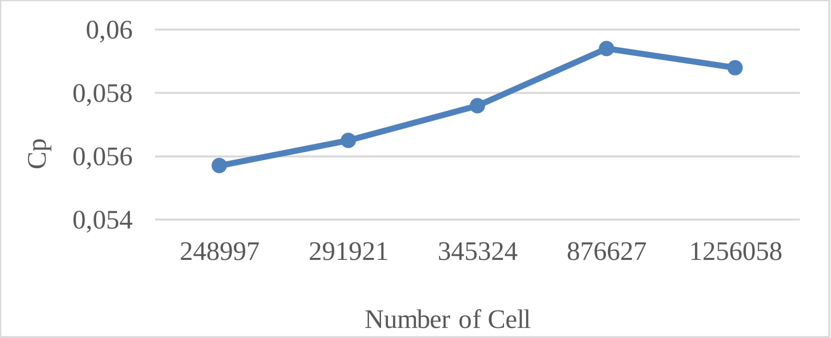
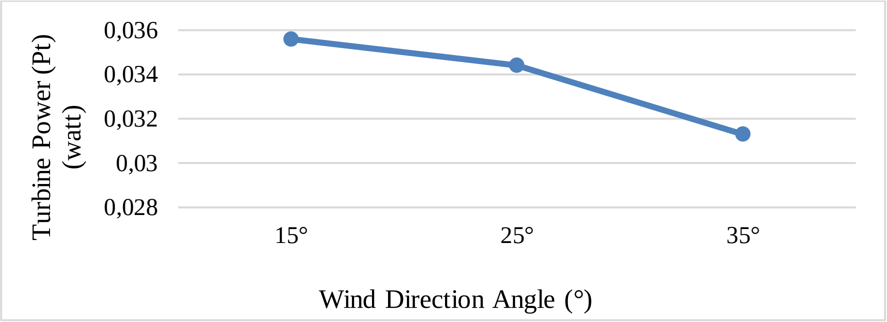


Figure 4. Grid Independence Test

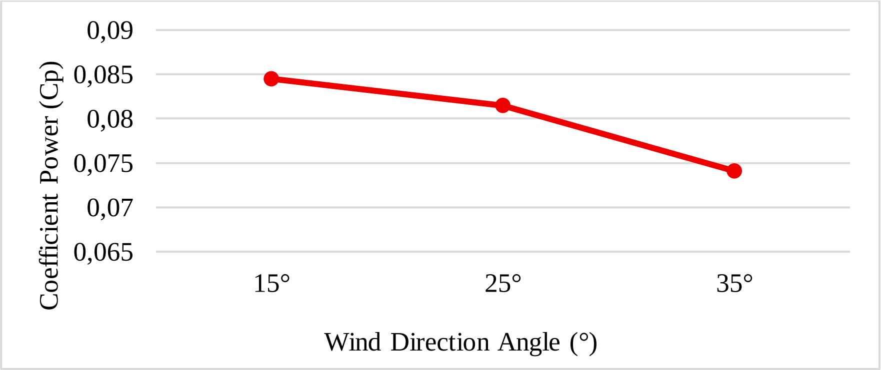
In Table 4, the results of the grid independence test show that the Cp value changes at each level of mesh fineness, but the difference between mesh fineness levels 4 and 5 does not change significantly. This shows that the decrease in the size of the mesh cell can be said to no longer affect the Cp value, so that the cell size at the smoothness level of mesh 5 with the number of cells of 1,256,058 is considered optimal. In addition, the Y+ value of the entire mesh smoothness level is below 5 and the fine mesh has the lowest Y+ value, which is 0.31.

3.2. Turbine Performance Based on Wind Direction Angle

Figure 5 shows the change in the angle of the wind direction affects the amount of values $\boldsymbol{P_T}$, Cp, and TSR produced by the turbine. The graph pattern shows a decrease, that is, the greater the angle of direction of the wind, the performance of the turbine produced decreases. The best and highest performance was obtained in the variation of the angle of the wind direction 15° with the acquisition of values $\boldsymbol{P_T}$, Cp, and TSR of 0.0356 watts; 0.0845; and 0.525, respectively. This is based on the direction of the spread of the wind flow speed of any variation in the angle of the direction of the wind coming against the turbine rotor.



(a)



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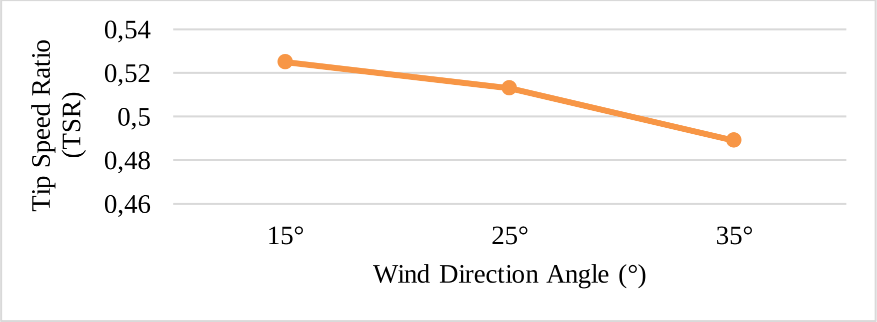
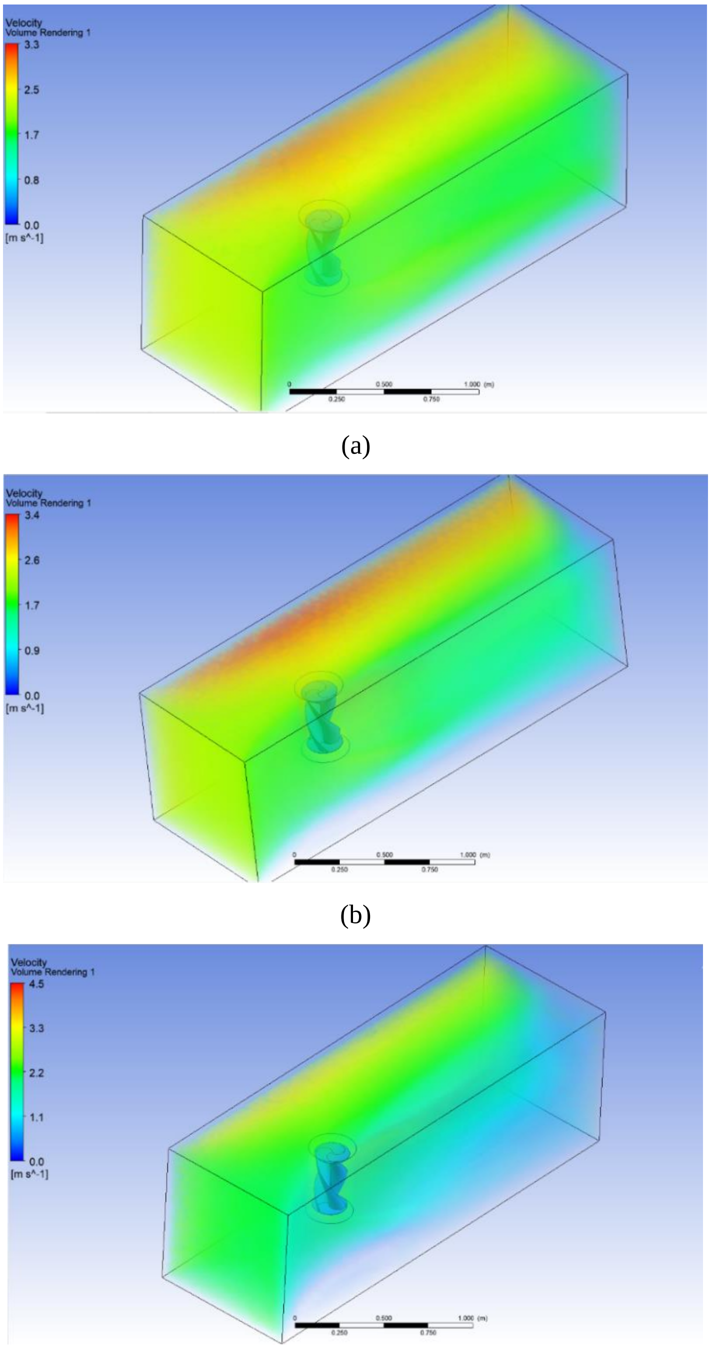


(c)

Figure 5. Turbine Performance Graph Based on Wind Direction Angle: (a) P_T, (b) Cp, and (c) TSR

In Figure 6 showing the visualization of the rendering volume of the distribution of the wind flow around the turbine rotor, there is a difference in each variation in the angle of the wind direction. At the angle of the wind direction 15°, it has a higher distribution of wind flow speed and directly leads to the turbine rotor. This is indicated by the predominance of yellow around the turbine rotor which causes greater kinetic energy of the received wind and results in higher turbine performance. Meanwhile, at angles 25° and 35°, it shows a lower distribution of wind flow speed with a predominance of yellowish green color, and there is even blue around the turbine rotor which indicates a decrease in flow speed. This is due to a change in the angle of the direction of the wind coming in the direction of the wind, causing the wind flow to tend to turn and reduce the intensity of the wind kinetic energy received by the turbine rotor, thereby reducing the performance of the turbine.



(a)

(b)

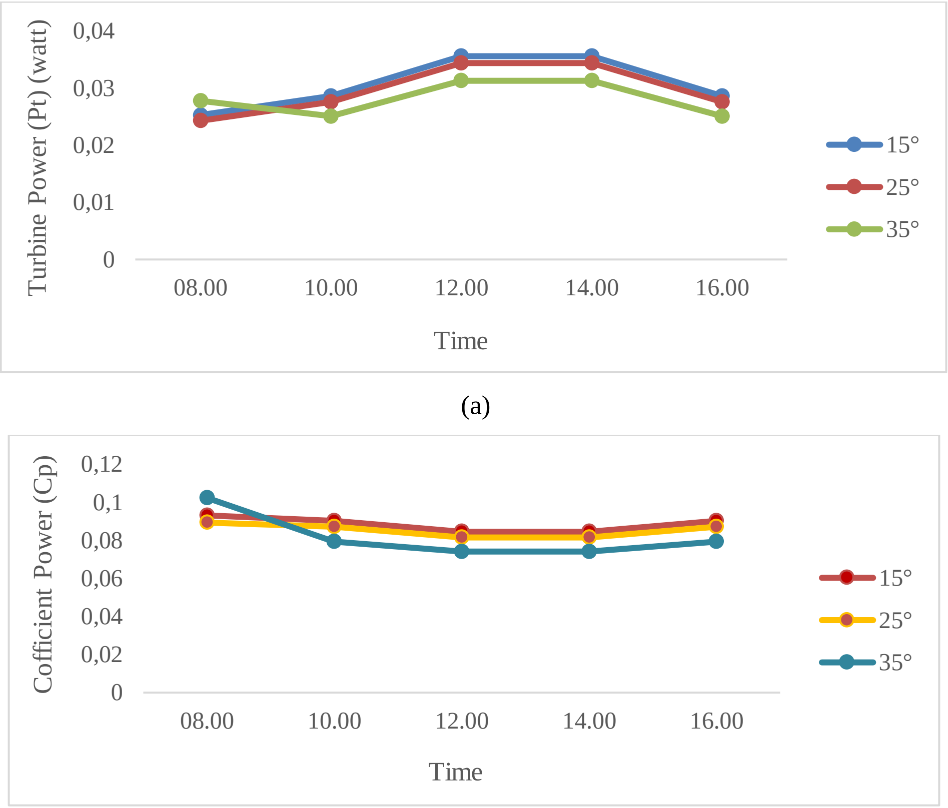
(c)

Figure 6. Windflow Rendering Volume at 12:00 and 14:00 at Angles: (a) 15°, (b) 25°, and (c) 35°

3.3. Performance of Turbines with Variations in Wind Direction Angle Based on Time

Figure 7 shows the effect of wind speed based on the measurement time on turbine power ($\boldsymbol{P_T}$) and power coefficient (Cp) on the change in the angle of the wind direction showing a graph with the same pattern pattern. The value $\boldsymbol{P_T}$ increased at 10:00 to reach its highest point at 12:00 and 14:00 because it obtained a higher average wind speed, then decreased again at 16:00. The amount of turbine power depends largely on the wind speed. The study [8], also found that turbine power increases as the wind speed increases, this is caused by the kinetic energy of the converted wind.

Meanwhile, the Cp value decreased at 10:00 a.m. until it reached its lowest point at 12:00 and 14:00, then increased again at 16:00, indicating that the increasing wind speed the Cp value could decrease. This decrease can be influenced by a change in the angle of the wind direction that deflects the flow direction against the advancing side of the blade which generates rotational momentum. In addition, it can also be affected by the phenomenon of negative flow on the turbine blade in the opposite direction, so that the turbine loses the wind energy to be converted and the resulting increase in turbine power is not proportional to the increase in the available wind speed [8]. The results of the study [8], also found that the Cp value produced by the helical Savonius wind turbine with a 180° higher twist angle at low wind speeds. This is in line with Betz's law regarding the maximum limit of energy that can be converted by wind turbines, which is 59.3% [8].



(a)

(b)

Figure 7. Turbine Performance Graph: (a) P_T vs Time, and (b) Cp vs Time

In Figure 8, the TSR graph shows an increasing trend as the wind speed increases at each time of measurement. This is due to the kinetic energy of the wind received by the turbine rotor getting bigger and making the turbine rotation higher. The study [21], also found an increase in the TSR value as the wind speed increases. A similar phenomenon was also found in the results of the study [8], increasing the wind speed from 3 m/s to 4 m/s can increase the TSR value produced by the turbine. In addition, changes in the angle of wind direction also have a significant effect on the direction of wind blowing that hits the turbine rotor.

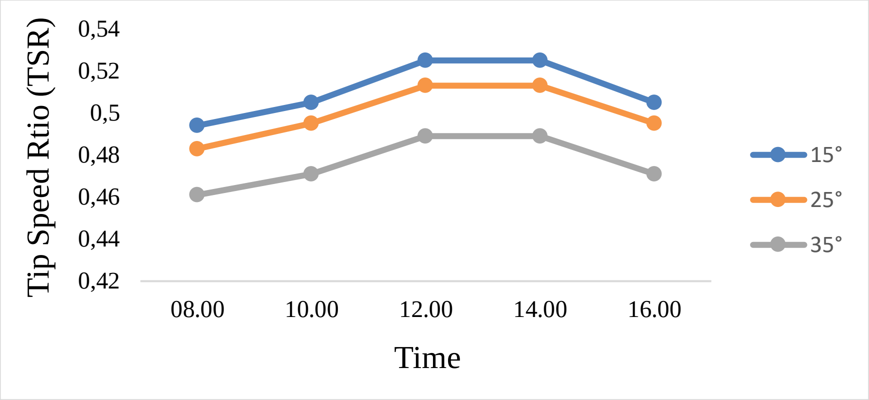
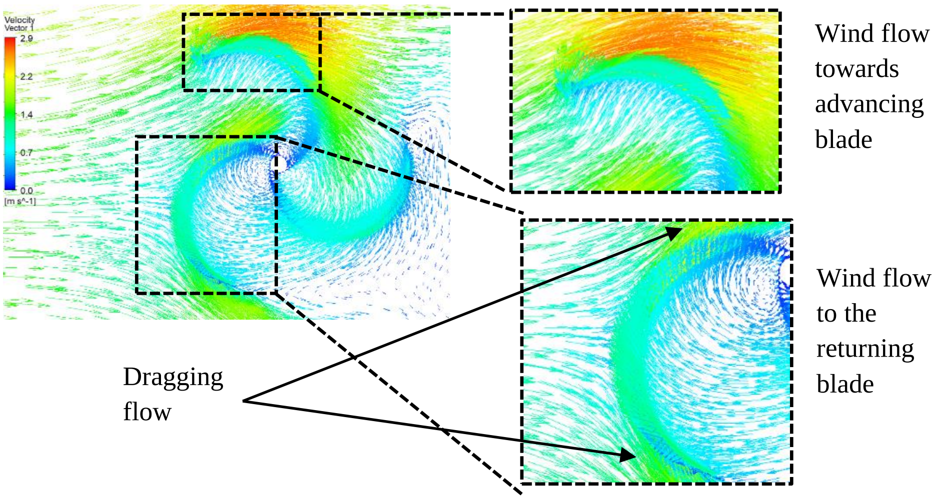


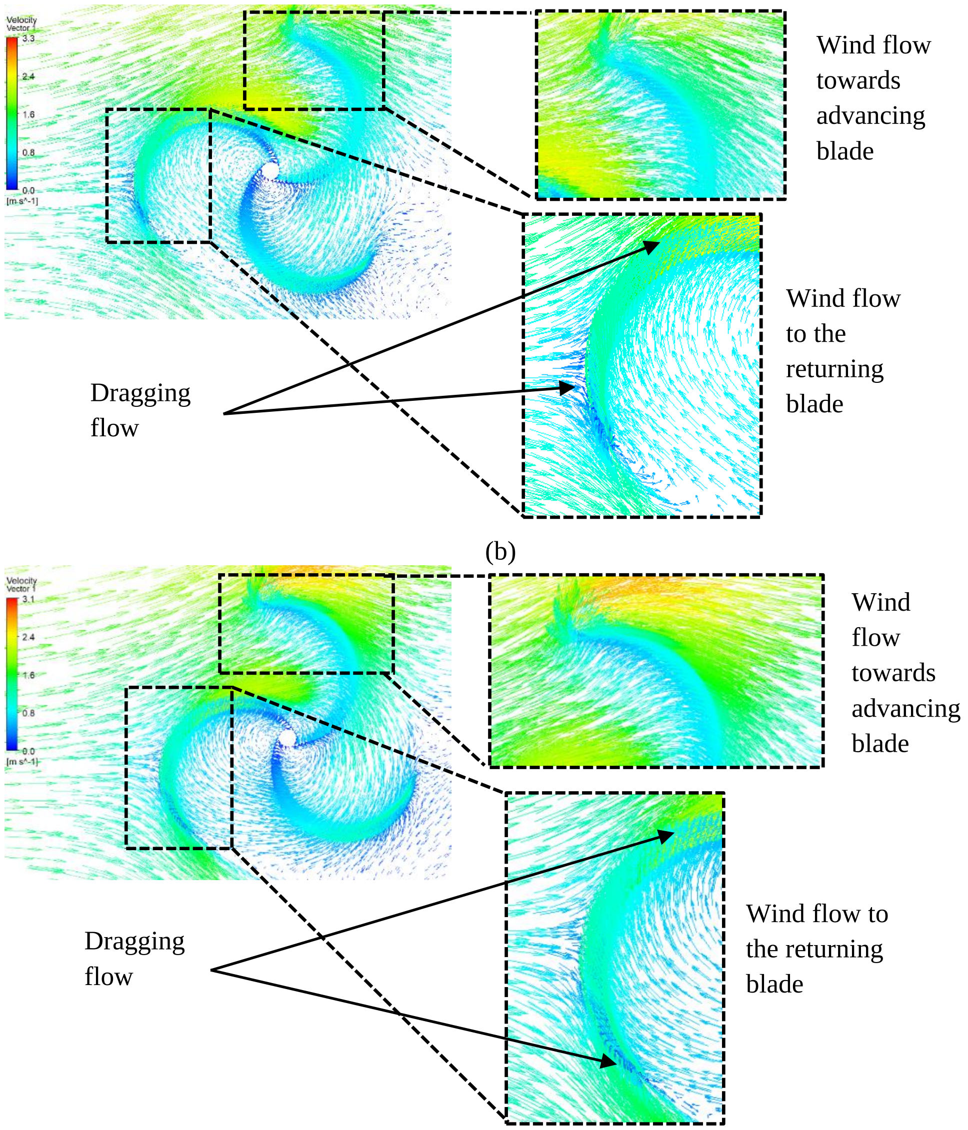
Figure 8. TSR vs Time

The results of the CFD simulation, show the difference in velocity vector at each variation of the angle of the direction of the wind. However, there are times with the same speed vectors, namely 10:00 and 16:00 then 12:00 and 14:00, because they obtain the same average wind speed at that time. In addition, differences are also seen in the position of the advancing blade and returning blade which affects the performance of the turbine. This difference is influenced by the angle of the wind direction and the speed of the wind flow that hits the blade surface.

Based on Figure 9, at 08:00 at the angle of the wind 15° looks more optimal than the variation of angles 25° and 35°, because the position of the advancing blade is parallel to the returning blade, so it looks like it can capture a larger wind flow and receive the flow directed from the convex side of the returning blade. However, angle 35° has a flow speed distribution towards the concave side of the advancing blade which is directed by the convex side of the returning blade is larger and the dragging flow on the convex side of the returning blade is smaller than angle 15°, so it has a better self start at low speeds. Because the advancing blade and returning blade positions that are aligned can cause the convex side of the returning blade to be exposed to greater dragging flow and lower positive torque. According to [22], dragging flow on the convex side of the returning blade can cause a decrease in turbine performance because it produces negative torque. Meanwhile, at angle 25°, the position of the advancing blade is seen behind the returning blade, causing the dragging flow that hits the convex side of the returning blade to be relatively larger.



(a)



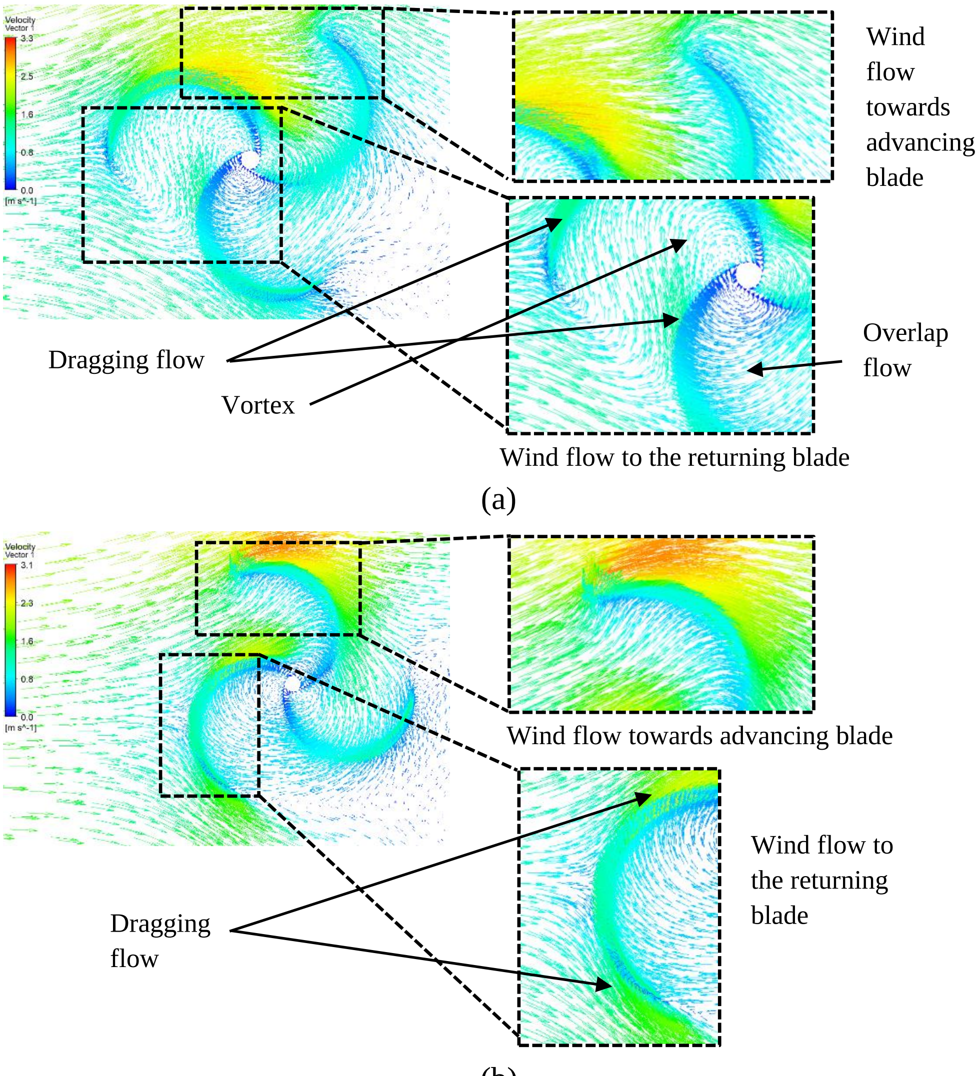
(b)

(c)

Figure 9. Vector of Wind Flow Velocity at 08:00 at Angles: (a) 15°, (b) 25°, and (c) 35°

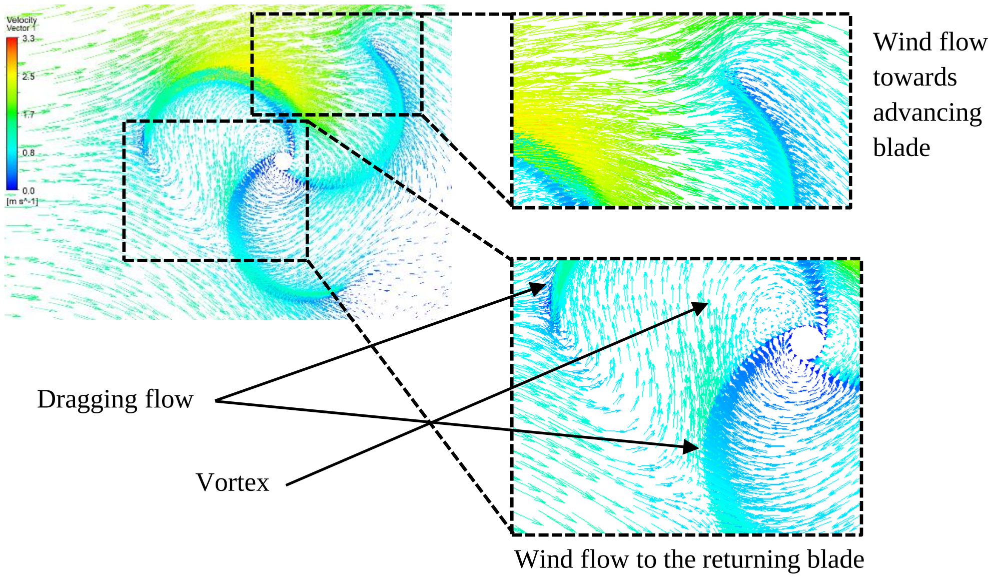
Meanwhile, at 10:00 and 16:00 shown in Figure 10, the distribution of flow velocity towards the advancing blade at the angle of the wind 25° appears to be more optimal than the variation of angles 15° and 35°. This is shown in the position of the advancing blade parallel to the returning blade, which is able to receive the flow of wind directed by the convex side of the returning blade. However, due to its parallel position, it can cause dragging flow on the convex side of the returning blade. At angle 15°, although the position of the advancing blade is behind the returning blade, the distribution of the flow speed that passes through and directs the convex side of the returning blade towards the concave side of the advancing blade is relatively large (shown in green to orange). This generates drag and overlap flow that helps increase rotational momentum and reduce the negative torque caused by dragging flow on the convex side of the returning blade [9]. The same phenomenon also occurs at angle 35°, but the difference is that the distribution of flow velocity passing through and directed the convex side of the returning blade is smaller than at angle 15° (shown in yellowish-green). In addition, the dragging flow and vortex formed are relatively larger than the angle 15°. This happens because the angle of wind direction 15° is more in the same direction as the turbine rotor shown in the rendering volume of Figure 11. Vortex occurs due to the convergence of overlapping flows from the concave side of the advancing blade and dragging from the convex side of the returning blade and can reduce turbine performance [22].

The highest performance occurs at 12:00 and 14:00 because the average wind speed obtained when the measurement at that time is the highest. In Figure 11, it shows that the distribution of flows towards the concave side of the advancing blade looks more optimal at the angle of the wind direction 15° and 25° compared to the variation of angle 35°. This happens because the position of the advancing blade is slightly in front of the returning blade, which is the most optimal position to capture and receive the wind flow directed by the convex side of the returning blade more optimally, and causes the dragging flow that hits the convex side of the returning blade to be smaller, thereby reducing negative torque. The difference between the two angles is in the distribution of the speed of the wind flow that leads to the concave side of the advancing blade, where at angle 15° it is relatively larger (shown by the dominance of yellow to orange colors). In addition, this happens because the angle of wind direction 15° is also more in line with the turbine rotor based on the rendering volume in Figure 6. Meanwhile, at angle 35°, it can be seen that the position of the advancing blade is behind the returning blade, thereby increasing the dragging flow that hits the convex side of the returning blade which causes a decrease in positive torque. This is shown by the yellowish-green color on the returning blade.



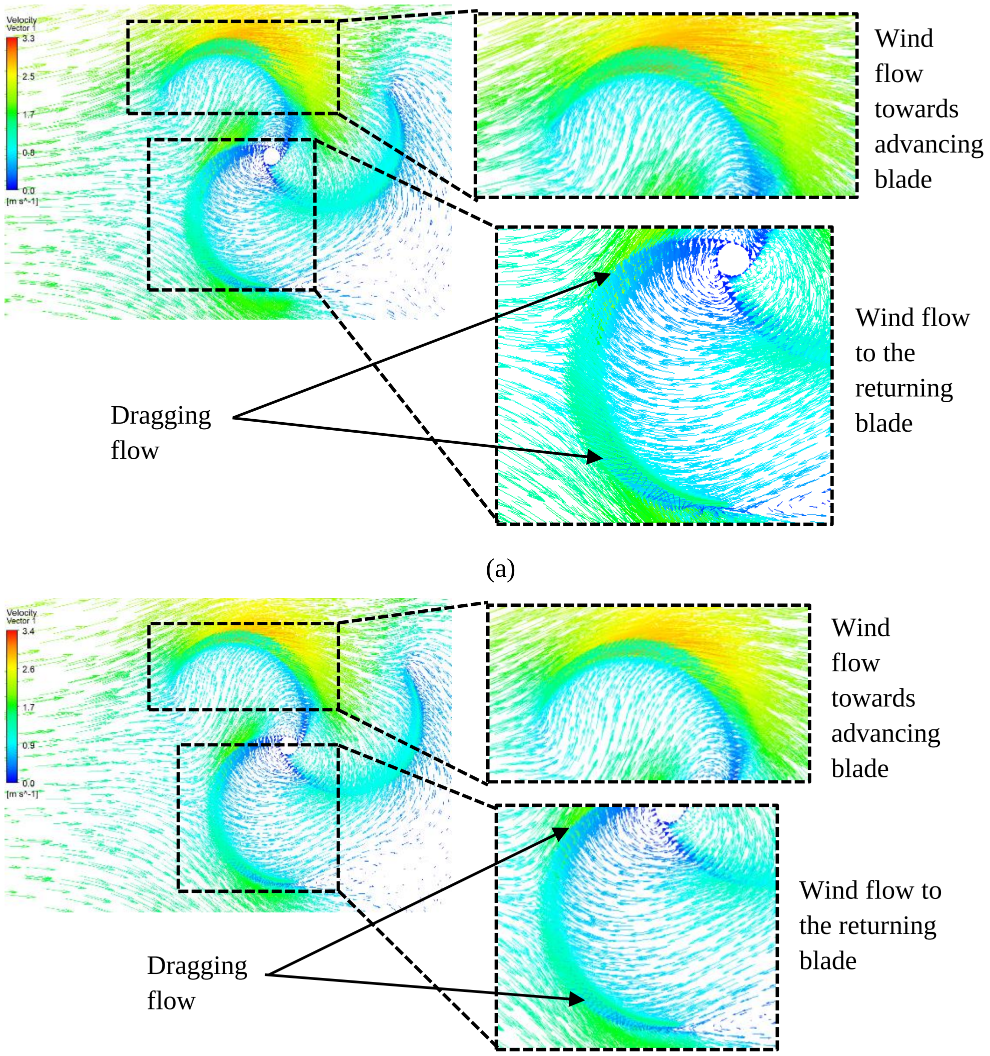
(a)

(b)



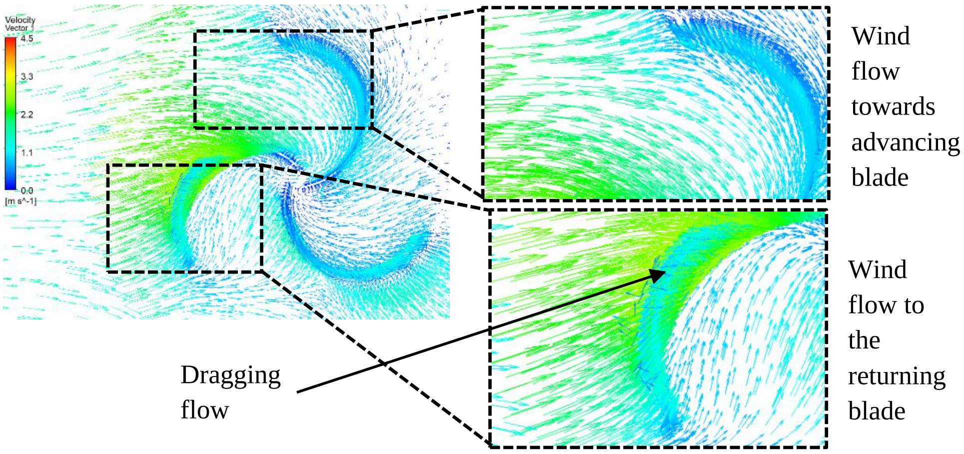
(c)

Figure 10. Vector of Wind Flow Velocity at 10:00 and 16:00 at Angles: (a) 15°, (b) 25°, and (c) 35°



(a)

(b)



(c)

Figure 11. Vector of Wind Flow Velocity at 12:00 and 14:00 at Angles: (a) 15°, (b) 25°, and (c) 35°

4. Conclusion

Based on the results of the CFD simulation, it can be concluded that the variation in the angle of the wind direction has a significant influence on the performance of the helical Savonius wind turbine. The angle of the wind direction of 15° provides the most optimal performance compared to angles 25° and 35°, shown by the high and stable values $\boldsymbol{P_T}$, Cp, and TSR obtained. An increase in the angle of wind direction tends to lead to a decrease in turbine performance, which causes the direction of wind flow to be inclined to turn and the intensity of wind energy capture by the rotor to decrease. In addition, the increase in the angle of the wind direction also causes dragging flow on the convex side of the returning blade and the formation of a vortex around the blade is larger, thus increasing negative torque.

The peak performance of this helical type Savonius wind turbine occurs at 12:00 and 14:00 when the wind speed is above 2.0 m/s. The increased performance is due to greater wind kinetic energy produced, thus increasing $\boldsymbol{P_T}$ and TSR. However, the increase is not followed by an increase in the value of Cp. This is due to the phenomenon of negative flow in the opposite direction that causes the turbine to lose the wind energy to be converted and also indicates the limitation of energy conversion from the wind turbine based on Betz's law, so that even if the TSR increases or reaches the optimal point, the resulting increase in turbine power is not proportional to the increase in wind speed.

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