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NUMERICAL STUDY OF CHORD LENGTH AND TWIST ANGLE EFFECT TOWARDS NACA 4415-FX60 AIRFOIL COMBINATION IN HORIZONTAL WIND TURBINES APPLICATION

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ABSTRACT

The selection of the appropriate blade shape requires optimization in order to be applied to the relatively low wind conditions in Indonesia. This study proposed a new approach of wind turbine blades design by utilizing the combination of NACA 4415 and FX 60. The effect of twist angle and the chord length carried out in this study to better understanding the blades characteristics. The 6 DoF analysis can be used to determines the theoretical mechanical power of the wind turbine blades. The blade twist geometry analyzed in this study is 15, 20, and 25 degree. From the simulation results, the highest mechanical power was obtained on blades with a twist angle of 5 degrees and a chord length of 0.15m with an average value of 39.95 W. The simulation results show that, at a speed of 8 m/s the blade with a chord length of 0.2 m and a twist angle of 5o has the greatest torque of 5.16579 Nm, with a rotational speed of 76.0668 rpm per minute, this combination can be applied to a low rpm generator A twist angle can improve torque distribution along the blade, but a twist angle that is too sharp can reduce lift and increase drag. It was found that a wider chord length tends to produce lower rotation in the wind turbine. This is caused by the increased surface area on the turbine blade with a longer chord length, which results in an increase in the torque required to rotate the blade at a given speed.

Keywords Wind Turbine; Twist Angle; Design; Materials; Energy
Paper type Research paper

INTRODUCTION

The decreasing energy sources of oil and gas and coal in the world are due to the increasing human need for electrical energy. Meanwhile, the high oil and gas and coal production is not matched by production and fossil energy sources which have limited capacity. Therefore, we need renewable and appropriate energy sources. In this case the wind turbine design is one solution to overcome it. Compared with fossil fuels, wind is an environmentally friendly energy source, no air pollution is emitted to the environment after consumption. As a result, the utilization of wind energy attracted widespread attention from academia to industry.

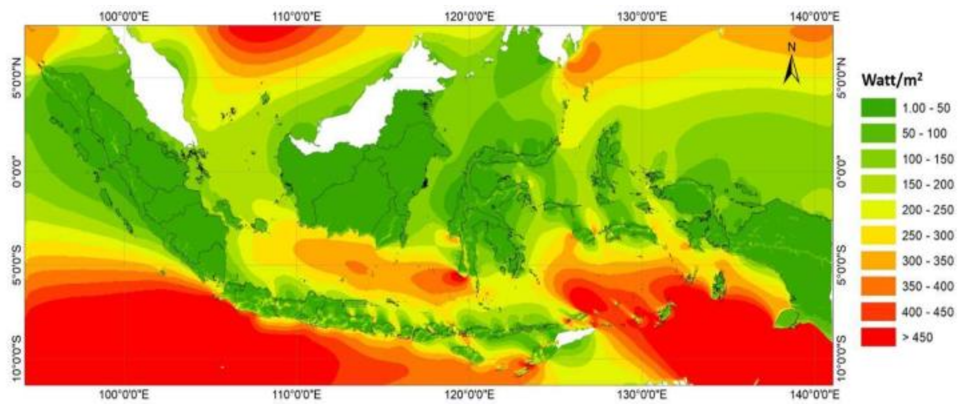

Figure 1. Wind power density in Indonesia [1]

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The basic working principle of a wind turbine is to convert mechanical energy from the wind into rotational energy in the windmill, then the rotation of the windmill is used to turn a generator, which will eventually produce electricity. This tool serves to change the low rotation of the wheel to high rotation. Utilization of wind energy can be carried out in sloping areas or highlands, it can even be applied at sea, in contrast to water energy [1].

However, in the Indonesian region, wind speeds are relatively low and the flow direction is always changing. One type of wind turbine is the horizontal axis wind turbine (TASH) which has a main rotor shaft and an electric generator at the top of the tower. Low wind conditions are the focus of this study. Figure 1 shows the wind power density obtained from the Nudging Four -Dimensional Data Assimilation System using two global data source from 2001-2015 which the models are verified using 111 station from BMKG and OGIMET. From the Figure 1 the wind power density above the islands are relatively low [1]. Thus the wind speed based from the wind power density classification has the range of 3.5-5.6 m/s and 5.6-6.4 m/s [2].

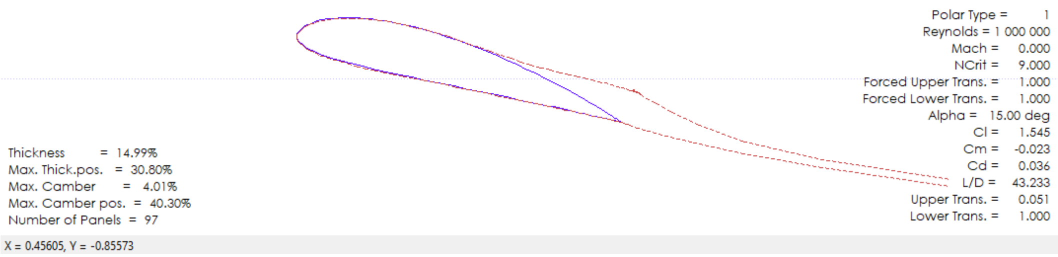


Figure 2. NACA 4415 Xfoil analysis results

The airfoil type determines the wind flow direction which has a significant effect towards the lift and drag coefficient. The NACA 4415 as seen in Figure 2. used in this study is a type of aerodynamic shape used primarily in aircraft wings. It was developed by the National Advisory Committee for Aeronautics (NACA) during the mid-20th century.The NACA 4415 airfoil is characterized by moderate camber, moderate thickness, and a relatively far-back location of maximum thickness. The NACA 4415 airfoil is known for its relatively high lift-to-drag ratio, which is beneficial for wind turbine applications. The moderate camber of the NACA 4415 airfoil allows for efficient lift generation, particularly at moderate angles of attack commonly encountered in wind turbine operation [3]. This helps optimize the blade's performance across a range of wind speeds.

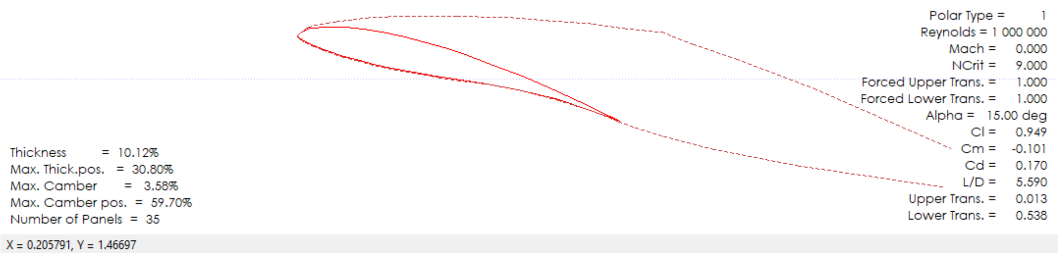


Figure 3. Fx 60 Xfoil analysis results

The NACA FX60 airfoil as seen in Figure 3 is a specialized aerodynamic profile designed for specific applications, including wind turbine blades. The FX60 series airfoils are known for their high lift coefficients, it can generate significant lift even at low wind speeds. This characteristic is advantageous for wind turbine blades as it allows for efficient energy capture across a wide range of wind conditions. While providing high lift, the FX60 airfoil series also typically maintains relatively low drag characteristics. This is essential for wind turbine blades to maximize energy conversion efficiency by reducing the amount of energy lost to aerodynamic drag.

Current commercial blade specifications require relatively high wind speeds. The selection of the type of airfoil is carried out using a static test CFD at a certain angle of attack [4]. By using the CFD analysis 6 DOF method the process of observing the aerodynamics can be carried out in detail. The solver tracks the motion of a rigid object within the airflow [5]. It calculates the aerodynamic forces and moments acting on the object due to factors like pressure and shear stress. The results of the optimization of the blade model using CFD are used as a reference for the composite blade manufacturing process [6] [7] [8].

Mechanical power is the power produced by the blade due to the wind passing through the blade/blade [9]. So the mechanical power produced by the circular motion of the blade can be formulated as follows: [10].

$$P = \mathrm{T} \times \omega \qquad (1)$$

Where :

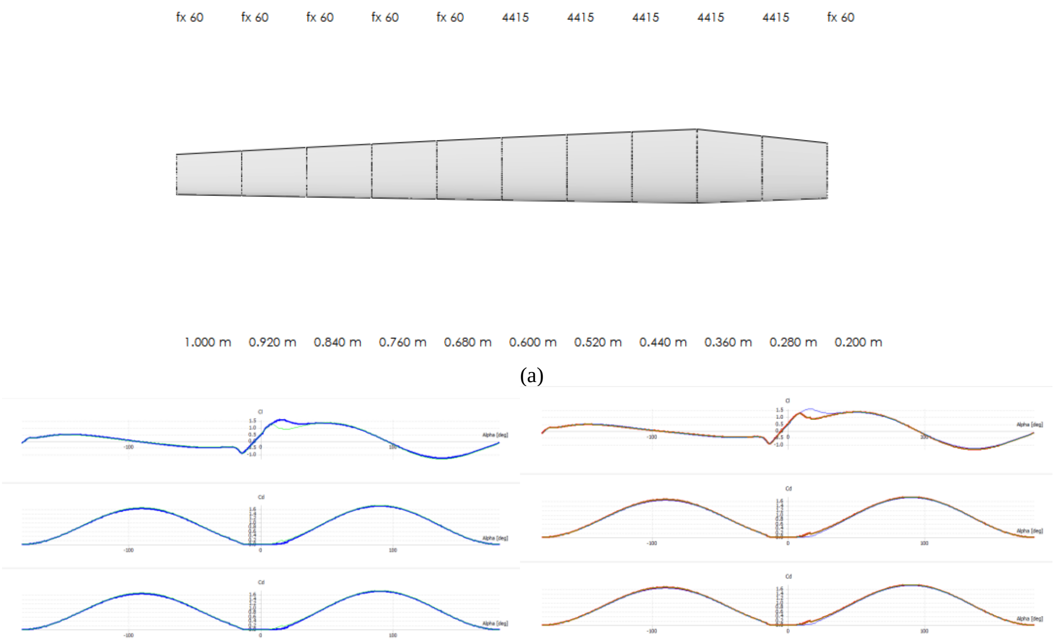
P : Power produced (watts)
T : Torque (N.m)
ω : Angular speed (rad/s)

Power coefficient is the percentage of power received by a wind turbine through the swept area of the turbine blade. The maximum power coefficient that is theoretically possible is called the Betz limit which is 0.593. Most turbines today have a power coefficient between 0.3 and 0.4. The simple Betz element momentum theory is described by a two-dimensional flow model of wind passing through the rotor, illustrating the principle of wind energy conversion in a wind turbine. The airflow velocity decreases and the flow lines bend as they pass through the rotor. The reduction in total energy is caused by rotor rotation resulting in changes in wind speed in the tangential direction. Thus wind turbines cannot convert more than 60% of the total wind power that can be used for power generation [11] [12].

More in-depth research is still needed to produce blade types that have performance that is suitable for wind conditions in Indonesia. Based on the wind density data, it is required to study the wind turbine blades which optimized for low wind speed condition. This study proposed a new approach of wind turbine blades design by utilizing the combination of NACA 4415 and FX 60. The effect of twist angle and the chord length carried out in this study to better understanding the blades characteristics. The 6 DoF analysis can be used to determines the theoretical mechanical power of the wind turbine blades.

METHOD

Blade Design and CFD Methods



(a)

(b) (c)

Figure 4. (a) Airfoil NACA 4415-Fx60 distribution along the turbine blade, (b) polar extrapolation result of NACA 4415, (c) polar extrapolation result of FX60 airfoil

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Figure 4 (a) shows the distribution of Airfoil NACA 4415-Fx60 combination throughout the turbine blade profiles. The NACA 4415 mainly located in the base of the blades to maximize the starter movement which expected to reduce the cut-in wind speed. Meanwhile the Fx 60 mainly located in the tip of the blade to optimize the blades performance in high rotation. The drawing processed using Q-blade opensource software. The airfoil was generated according the NACA database. The airfoil profile was analyzed using the XFOIL as seen in figure 2 and 3. An extrapolation of the polar data was generated by using the Montgomerie's method as seen in Figure 4 (b) and (c). The coefficient of drag and lift for each angle of attack in specified polar data can be determined from the Figure 4.

The maximum chord length located at 0.16 m position. In this study 3 different chord length are used to be compared which is 0.1, 0.15, and 0.2 m. The twist angle used in this study are are 0^0, 10^0, and 20^0. The detailed design data can be seen in Table 1-3.

TABLE I. CONFIGURATION OF CHORD LENGTH 0.1 M

No	Pos (m)	Twist 0°			Twist 10°			Twist 20°		
		Chord (m)	Twist	Foil	Chord (m)	Twist	Foil	Chord (m)	Twist	Foil
1	0	0.075	25	Fx60	0.075	25	Fx60	0.075	25	Fx60
2	0.08	0.0875	25	4415	0.0875	25	4415	0.0875	25	4415
3	0.16	0.1	25	4415	0.1	25	4415	0.1	25	4415
4	0.24	0.09375	21.875	4415	0.09375	23.13	4415	0.09375	24.375	4415
5	0.32	0.0875	18.75	4415	0.0875	21.25	4415	0.0875	23.75	4415
6	0.4	0.08125	15.627	4415	0.08125	19.375	4415	0.08125	23.13	4415
7	0.48	0.075	12.5	Fx60	0.075	17.5	Fx60	0.075	22.5	Fx60
8	0.56	0.06875	9.375	Fx60	0.06875	15.625	Fx60	0.06875	21.875	Fx60
9	0.64	0.0625	6.25	Fx60	0.0625	13.75	Fx60	0.0625	21.25	Fx60
10	0.72	0.05625	3.125	Fx60	0.05625	11.875	Fx60	0.05625	20.625	Fx60
11	0.8	0.05	0	Fx60	0.05	10	Fx60	0.05	20	Fx60

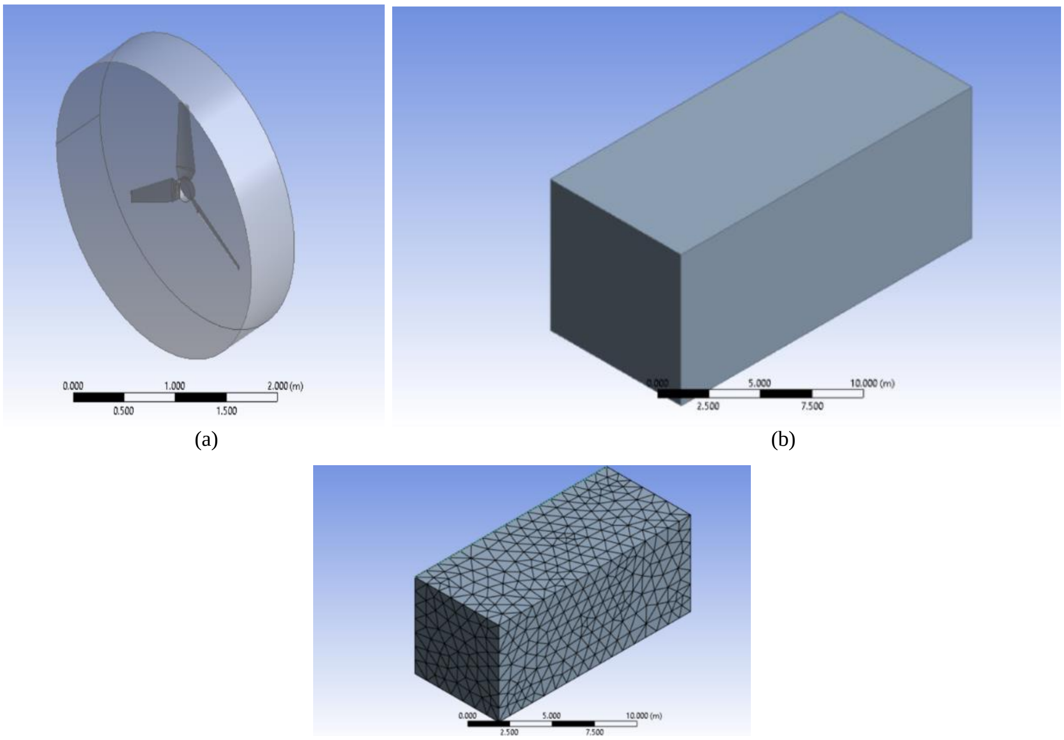
TABLE II. CONFIGURATION OF CHORD LENGTH 0.15 M

No	Pos (m)	Twist 0°			Twist 10°			Twist 20°		
		Chord (m)	Twist	Foil	Chord (m)	Twist	Foil	Chord (m)	Twist	Foil
1	0	0.125	25	Fx60	0.125	25	Fx60	0.125	25	Fx60
2	0.08	0.1375	25	4415	0.1375	25	4415	0.1375	25	4415
3	0.16	0.15	25	4415	0.15	25	4415	0.15	25	4415
4	0.24	0.14375	21.875	4415	0.14375	23.13	4415	0.14375	24.375	4415
5	0.32	0.1375	18.75	4415	0.1375	21.25	4415	0.1375	23.75	4415
6	0.4	0.13125	15.627	4415	0.13125	19.375	4415	0.13125	23.13	4415
7	0.48	0.125	12.5	Fx60	0.125	17.5	Fx60	0.125	22.5	Fx60
8	0.56	0.11875	9.375	Fx60	0.11875	15.625	Fx60	0.11875	21.875	Fx60
9	0.64	0.1125	6.25	Fx60	0.1125	13.75	Fx60	0.1125	21.25	Fx60
10	0.72	0.10625	3.125	Fx60	0.10625	11.875	Fx60	0.10625	20.625	Fx60
11	0.8	0.1	0	Fx60	0.1	10	Fx60	0.1	20	Fx60

TABLE III. CONFIGURATION OF CHORD LENGTH 0.2 M

No	Pos (m)	Twist 0°			Twist 10°			Twist 20°		
		Chord (m)	Twist	Foil	Chord (m)	Twist	Foil	Chord (m)	Twist	Foil
1	0	0.175	25	Fx60	0.175	25	Fx60	0.175	25	Fx60
2	0.08	0.1875	25	4415	0.1875	25	4415	0.1875	25	4415
3	0.16	0.2	25	4415	0.2	25	4415	0.2	25	4415
4	0.24	0.19375	21.875	4415	0.19375	23.13	4415	0.19375	24.375	4415
5	0.32	0.1875	18.75	4415	0.1875	21.25	4415	0.1875	23.75	4415
6	0.4	0.18125	15.627	4415	0.18125	19.375	4415	0.18125	23.13	4415
7	0.48	0.175	12.5	Fx60	0.175	17.5	Fx60	0.175	22.5	Fx60
8	0.56	0.16875	9.375	Fx60	0.16875	15.625	Fx60	0.16875	21.875	Fx60
9	0.64	0.1625	6.25	Fx60	0.1625	13.75	Fx60	0.1625	21.25	Fx60
10	0.72	0.15625	3.125	Fx60	0.15625	11.875	Fx60	0.15625	20.625	Fx60
11	0.8	0.15	0	Fx60	0.15	10	Fx60	0.15	20	Fx60

The blade geometry from the Q-blade software was exported and converted into 3D drawing using an opensource CAD software. An aerodynamic study carried out using the CFD software based on the previous 3D drawing setup. The drawing scaled in 1:1, with the length of the blade are consistently keep in 80 cm. 3 bladed wind turbine used in this study.



(a) (b)

(c)

Figure 5. The inner domain (a) and outer domain (b) of CFD analysis, (c) the meshing profile

The CFD study are using the 6 DoF method, thus a domain separation is needed for the mesh movement. Figure 5(a) shows the inner domain where the turbine blades plotted. The inner domain will be the moving mesh rigid body. The outer domain in Figure 5(b) are used to be the fluids zone. The inlets boundary condition in front side and the outlet boundary condition located at the rearside. The wind velocity inlets in this study remains constant at 8 m/s. In this fluid flow simulations using the finite volume method, the gradient in the conservation equation can be calculated via one of the discretization schemes, Second Order Upwind.

A transient study conducted in 30 seconds by using 0.5 s timestep. By using the 6 DoF method the initial rotation of the wind turbine can be analyzed. Data of torque and tangential velocity recorded in every timestep. The tangential velocity is the converted into angular speed to calculate the mechanical power by using the (1) equation. The data for every timestep depicted in figures [13].

DISCUSSION

CFD Results of Torque Values at Initial Rotation

Torque in a wind turbine is the rotational force generated by the turbine blades due to the difference in pressure on the surface of the blades. In this simulation, a wind turbine that is stationary being blown by the wind with the constant speed of 8 m/s, then the turbine starts rotating at a low speed to its optimum in every timestep.

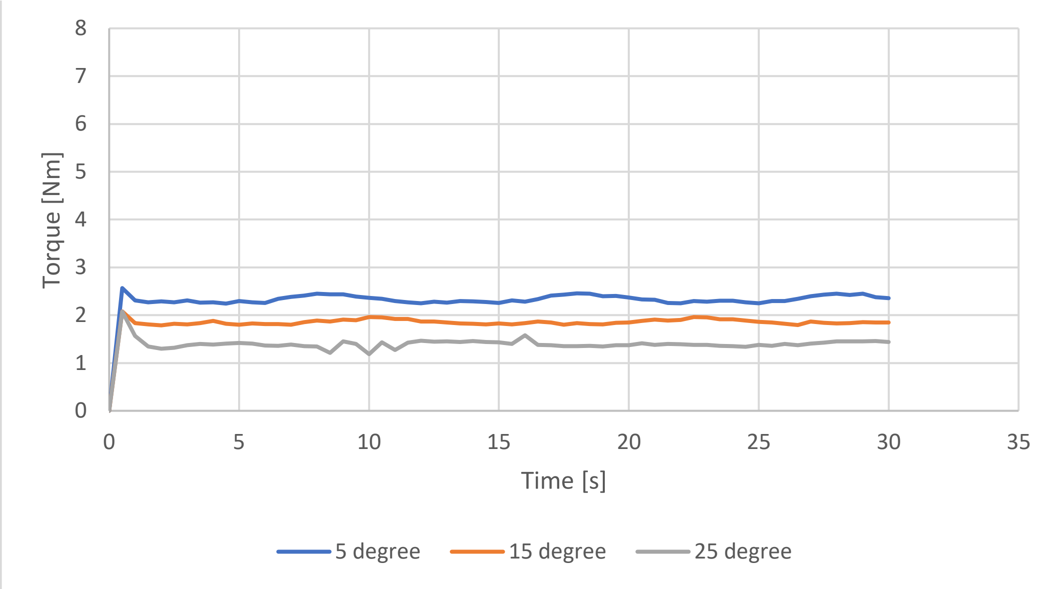


Figure 6. Torque development values in chord length of 0.1 m

Figure 6 shows the development of the initial rotation torque of the turbine. When the turbine is still not rotating, it requires high torque to fight inertia when it is stationary. The torque value tends to be greater at a smaller Twist angle value. In this data, the highest torque value was obtained at a twist angle variation of 5 degrees with an average value of 4.03 Nm. Meanwhile, the torque values at twist angles of 15 degrees and 25 degrees have an average of 3.21 Nm and 2.23 Nm.

Observations using CFD analysis shows that turbulence occurs at a chord length variation of 0.1 m and twist angle of 250. This causes the turbine rotation to be hampered by the turbulent zone so that the resulting torque is not optimal.

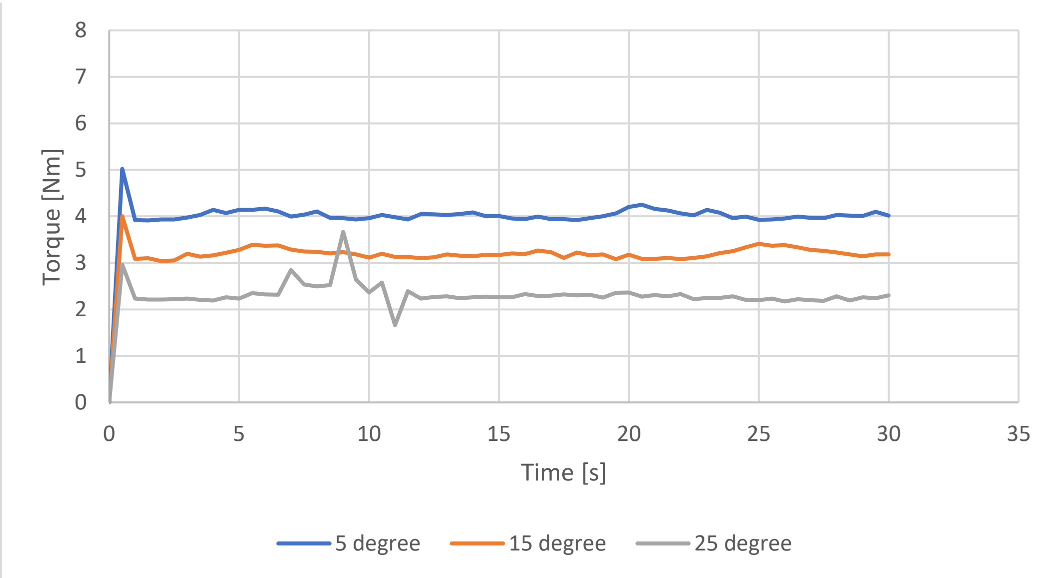


Figure 7. Torque development values in chord length of 0.15 m

The torque value at a chord length of 0.15 m has a higher average compared to 0.1 m. With the highest average torque value at a 15 degree twist angle variation of 4.85 Nm. Meanwhile, at twist angles of 15 degrees and 25 degrees, the average torque value is 3.85 Nm and 2.84 Nm. The same tendency occurs at a chord length value of 0.15 where the blade with a twist angle of 5 degrees has a higher torque value.

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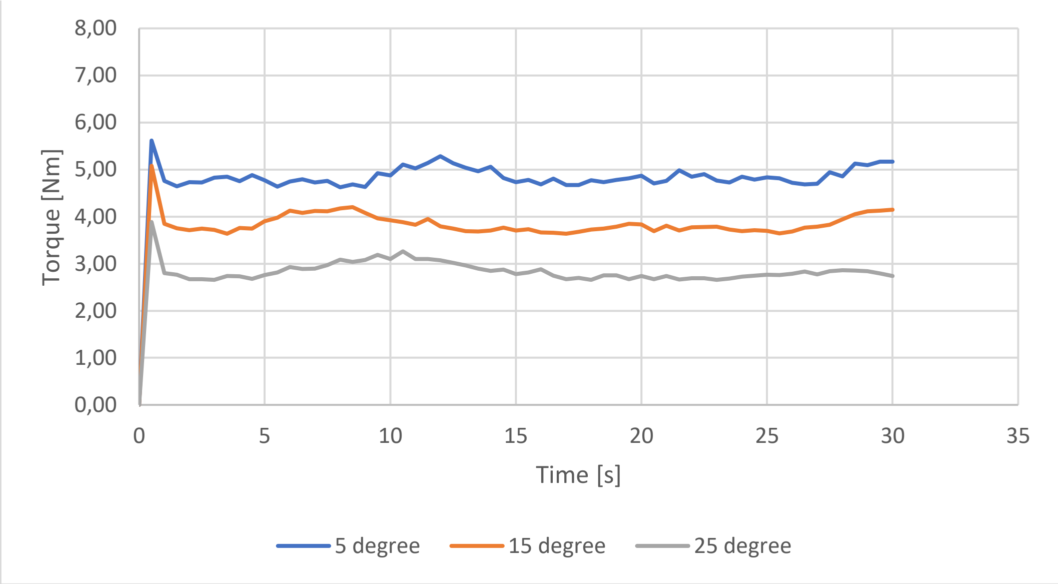

Figure 8. Torque development values in chord length of 0.2 m

Based on the Figure 8, a longer chord length tends to produce greater torque because it has a wider surface area to interact with the wind flow. The torque produced by blades with a chord length of 0.2 m tends to be greater than blades with chord lengths of 0.1m and 0.15 m. A twist angle can improve torque distribution along the blade, but a twist that is too sharp can reduce lift and increase drag. The type of airfoil also influences the good twist angle to apply to the blade. In this study, the torque produced by blades with a twist angle of 15° and 25° tended to be lower than blades with a twist angle of 5°.

CFD Results Tangential Speed Values at Initial Rotation

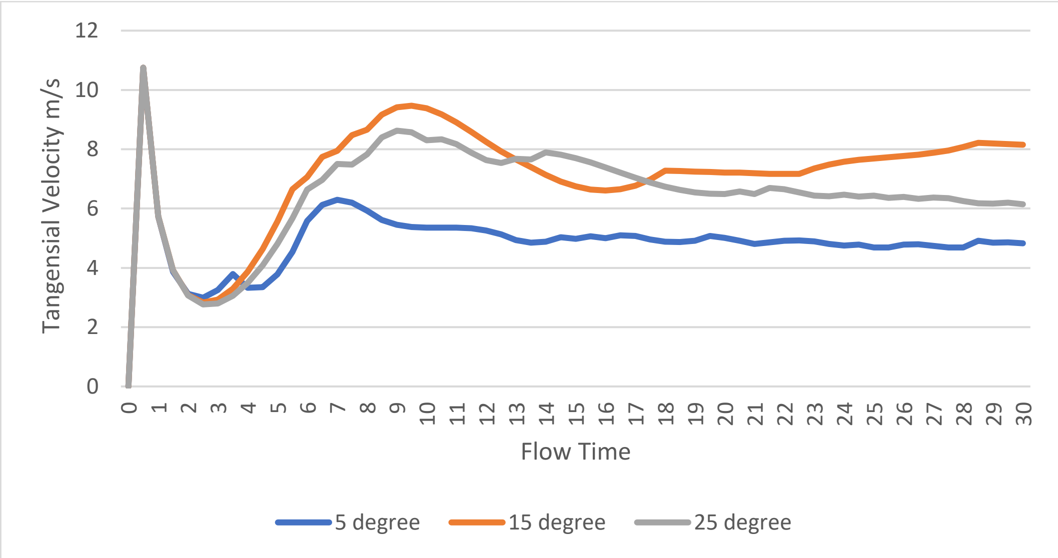

Figure 9. Tangential velocity development values in chord length of 0.1 m

The tangential velocity value at a chord length of 0.1 m has a stable value at 20 seconds. This shows that at 20 seconds the flow from the inlet reaches the fully developed flow phase. The highest average tangential speed value was obtained at a twist angle of 15 degrees with a value of 7.21 m/s. At a twist angle of 25 degrees, the average tangential speed value is 6.59 m/s. Meanwhile, at a twist angle of 5 degrees, the average tangential speed value is 4.96 m/s.

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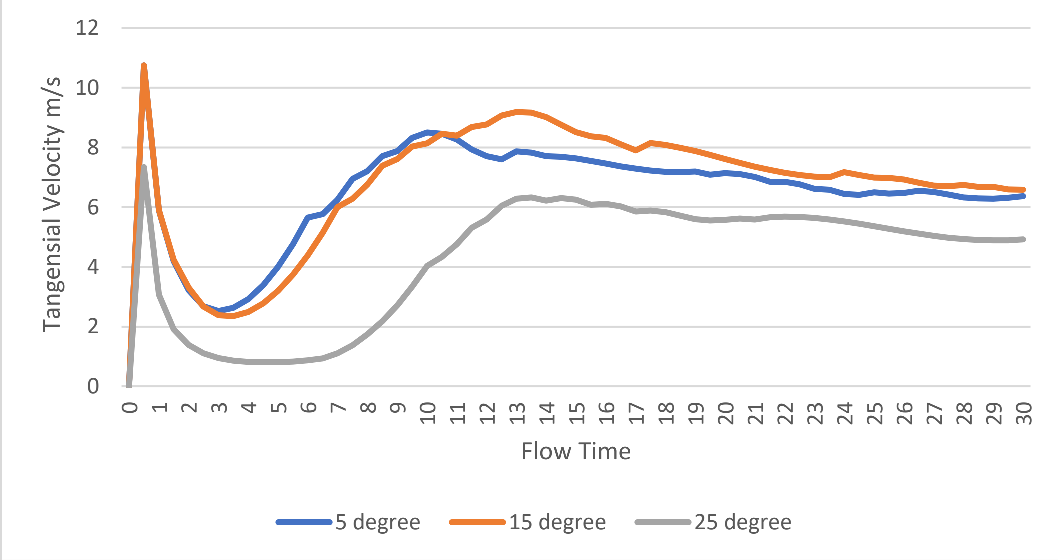

Figure 10. Tangential velocity development values in chord length of 0.15 m

The average value of tangential velocity at a chord length of 0.15 m has a higher average than 0.1 m. With the highest average value of tangential speed at a 15 degree twist angle variation of 6.84 m/s. Meanwhile, the twist angles of 25 degrees and 5 degrees have an average tangential speed value of 6.56 m/s and 4.32 m/s.

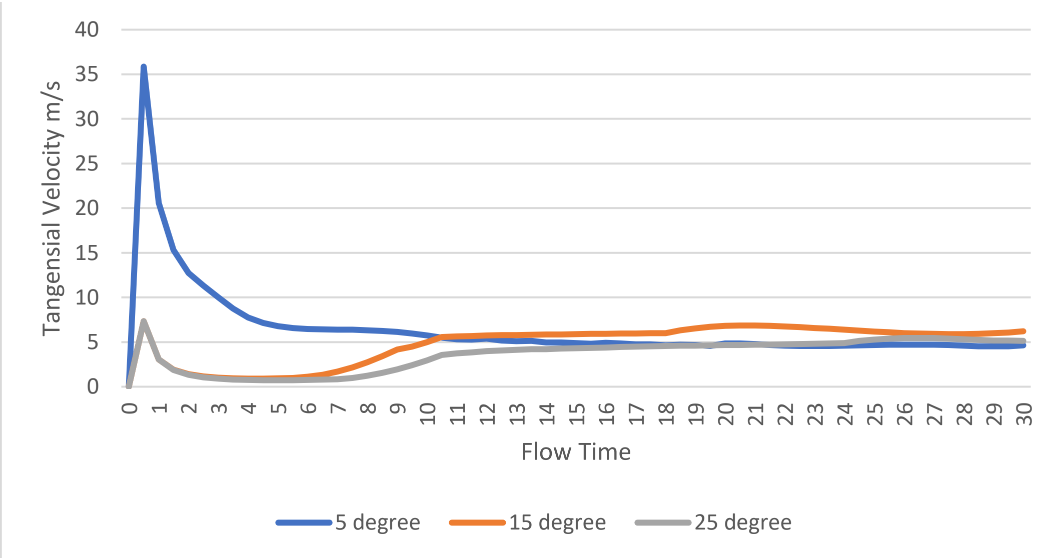

Figure 11. Tangential velocity development values in chord length of 0.2 m

At a chord length of 0.2 m, there is a spike in tangential speed at a twist angle variation of 5 degrees. This is because the blade with a twist angle of 5 degrees has a sloping cross-section so that the energy conversion of the fluid flow through that cross-section is greater.

The wider the chord length, the greater the cross-sectional area of the wind impact, so the impact of the impact is also greater. Due to the spike in tangential speed, the average value of tangential speed at a twist angle of 5 degrees has the highest value, namely 6.51 m/s. Meanwhile, at twist angles of 15 and 25 degrees, the average tangential speed is 4.87 and 3.66 m.

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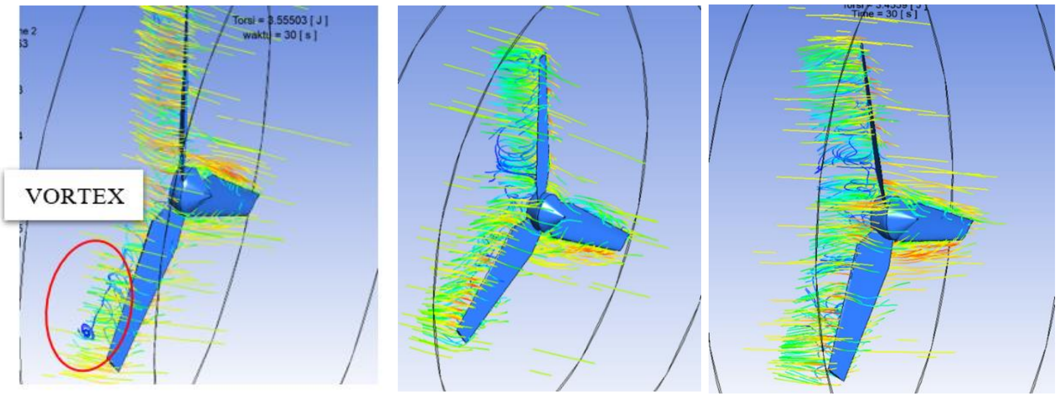

Figure 12. Vortex identification in CFD results

In Figure 12 there is a red circle which shows the presence of a vortex. Vortex is a fluid flow pattern that rotates or swirls around a point or axis. Vortexes can form as a result of differences in flow velocity, changes in pressure, or a combination of both. When the fluid flow experiences a sudden acceleration or deceleration or when the fluid flow experiences a change in direction, a vortex can form.

The red circle shows the presence of a vortex or vortex in the fluid flow behind the blade, this can cause a drag force on the wind turbine so that the performance of the turbine will decrease. The drag force on the blades can cause turbulence and influence the turbine rotation due to braking (breaking) which makes the turbine rotation unstable. The occurrence of breaking can affect the aerodynamic characteristics of the turbine so that the power produced by the wind turbine becomes less than optimal.

CFD Results of Mechanical Power Values in Initial Rotation

Mechanical power can be calculated using the equation(1). Where T is torque [Nm] and ω is angular velocity [rad/s]. The angular velocity value can be derived from the tangential velocity divided by the maximum radius of the blade. In this study, a blade with a length of 0.8 m was used so that by using these calculations the value of mechanical power [W] was obtained.

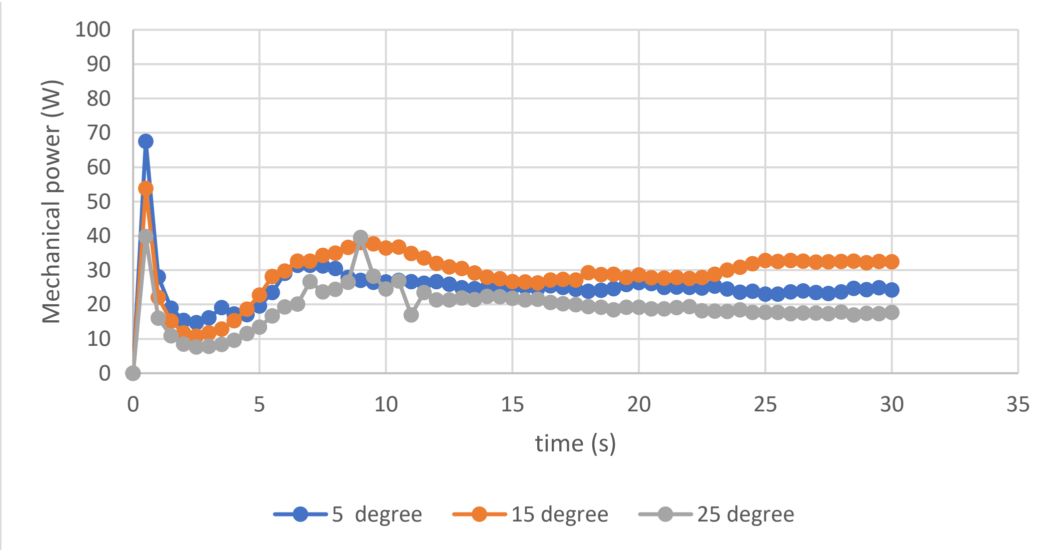

Figure 13. Mechanical power development values in chord length of 0.1 m

The highest mechanical power at a chord length of 0.1 m was obtained on blades with a twist angle of 15 degrees with an average value of 29.03 W. For a twist angle of 5 degrees the average was 25.17 W, while for a twist angle of 25 degrees the average was 19.03 W.

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It can be seen in Figure 13 shows that at the beginning of the blade rotation with a twist angle of 5 degrees the power value is relatively high, but at 6 seconds onwards the power value of this blade decreases and tends to be constant.

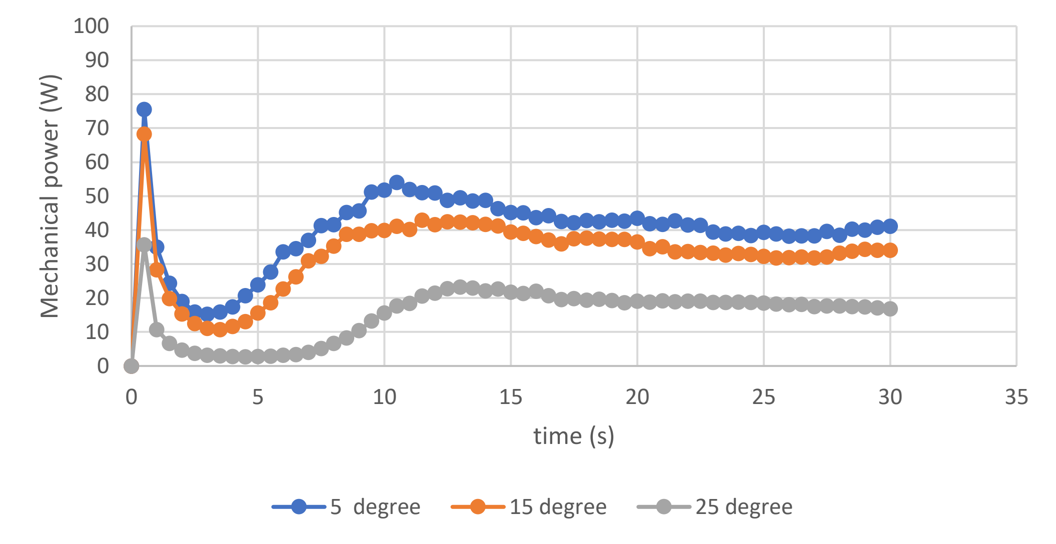

Figure 14. Mechanical power development values in chord length of 0.15 m

At a chord length of 0.15 m, the blade with a twist angle of 5 degrees has the highest average power with a value of 39.95 W. The average mechanical power on the blade with a twist angle of 15 degrees is 33.03 W. Meanwhile, for the blade with a twist angle of 25 degrees, the average value is obtained. average mechanical power of 15.43 W.

Even though a blade with a Twist angle of 15 degrees has a higher tangential speed than a Twist angle of 5 degrees, the torque produced by the blade also determines the value of mechanical power.

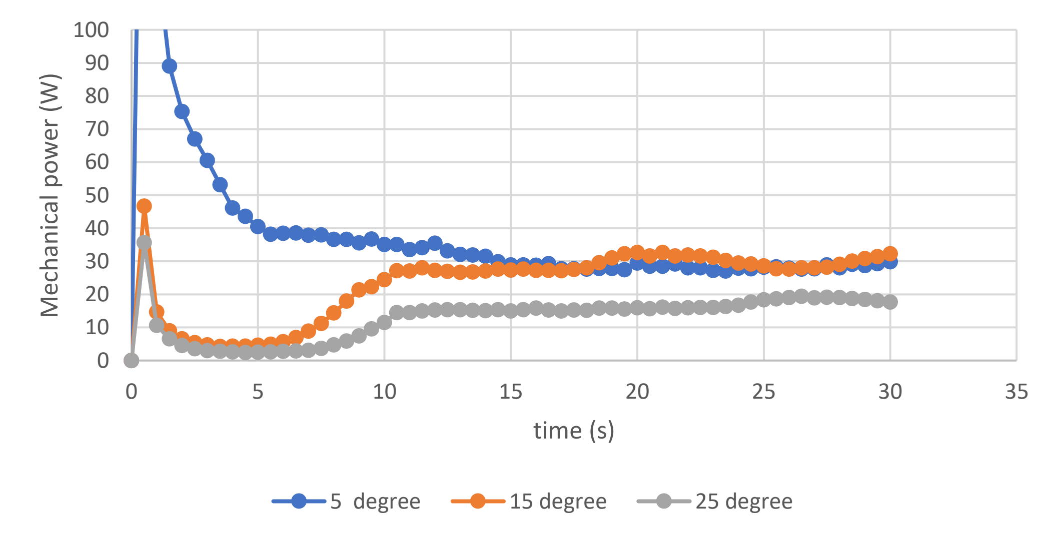

Figure 15. Mechanical power development values in chord length of 0.2 m

At a chord length of 0.2 m, it was found that the blade with a twist angle of 5 degrees had the highest mechanical power with an average of 39.89 W. Meanwhile, the blade with a twist angle of 15 degrees and 25 degrees had an average mechanical power value of 23.4 W and 13.06 W. The occurrence of a spike in tangential speed at the beginning of the blade rotation with a twist angle of 5 degrees makes the resulting mechanical power higher than other blade variations.

CONCLUSION

From the results of this research several conclusions can be drawn, including:
Based on simulation analysis, the rotation characteristics of each blade geometry variation are obtained. The twist angle can affect the rotation of the wind turbine, especially at low speed winds. A twist angle can improve torque distribution along the blade, but a twist angle that is too sharp can reduce lift and increase drag. The simulation results show that, at a speed of 8 m/s the blade with a chord length of 0.2 m and a twist angle of 5o has the greatest torque of 5.16579 Nm, with a rotational speed of 76.0668 rpm per minute, this variation can be applied to a low rpm generator.
It was found that a wider chord length tends to produce lower rotation in the wind turbine. This is caused by the increased surface area on the turbine blade with a longer chord length, which results in an increase in the torque required to rotate the blade at a given speed.

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