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Simulation Strength Analysis on PVC Pipe Blade Propeller Horizontal Axis Wind Turbine with Tip Elbow

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ABSTRACT

In general, the fundamental problem in wind energy technology for the general public is how to design a wind turbine easily using materials that are easily available on the market. Various wind turbine designs have been created, and one of our focuses is the horizontal axis wind turbine. This horizontal axis wind turbine has its constituent parts, namely the hub, blades, propeller, motor and turbine tail. In this article, the focus of horizontal axis wind turbines is on the blades. This blade has an important role in the process of transferring wind energy into rotational energy, so the material from which this blade is made must be flexible and strong. Apart from that, the blades must also have high durability to prevent frequent repairs and removal of horizontal axis wind turbine blades in practice. Research on the materials for making blades has also been carried out by several institutions, and one solution is to use PVC pipes as the material for making blades. This material is easy to find in building stores. However, it is necessary to analyze the working stresses that occur in the PVC blade construction, so that the PVC pipe propeller wind turbine is safe and durable when applied to the general public. The aim of this research is to determine the effect of wind speed and tip elbow width on working stress. The simulation testing method uses Ansys Flow Simulation Software then the results are exported to Static Simulation to determine the strength of the material. Simulation tests were carried out with wind loads on PVC pipe propellers with wind speeds of 5 m/s, 6 m/s, and 7 m/s and elbow tip widths of 100 mm, 110 mm, and 130 mm.

Keywords: HAWT, Propeller, PVC Pipe, Tip Elbow, and CFD Simulation

1. INTRODUCTION

In this moment, the requirement of fossil fuels energy is increasing. one day it will run out and there needs to be an alternative solution for energy needs. The wind energy is one of alternative energy which is environment friendly and have a good potential to be developed. [1]. Wind energy is one of the renewable energy potentials that can make a significant contribution to the need for electrical energy, especially in remote areas. Wind energy is an alternative that has large reserves with the advantage of little carbon pollution. [2]. The Most important of wind turbine design is the blade. Because this part have function to transfer wind energy into rotational or motion energy to a propeller [3]. Most wind turbine designs use NACA profile blades, but in this study, blades made of PVC pipe were used, then the pipe was cut by splitting and twisting in order to absorb wind energy optimally [4].

Horizontal Axis Wind Turbine (HAWT) is one type of wind turbine that is widely used in Indonesia. HAWT is one type of wind turbine that has the ability to convert energy with the greatest efficiency because the blades always move perpendicular to the wind, receiving power through all rounds. The geometry, dimensions and number of blades determine the efficiency of the turbine. [5]

Wind is one of the renewable energy sources which is very abundant and easily available in nature. Based on geographical location, each place has different wind potential, in tropical and sub-tropical areas it has different wind potential. Based on the topography, if it is in a mountainous area, the wind tends to rise and if the topography is flat, the wind will tend to be straight and flat.[6]

Model simulation test using Computational Fluid Dynamic (CFD) software, is generally used to determine the effect of interaction variables such as wind speed and number of blades on the output power as well as to obtain the most optimum power coefficient.[7]

With CFD simulation, it is possible to predict fluid flow patterns, heat transfer, chemical reactions and other phenomena through mathematical equations or mathematical models. In general, the calculation process for fluid flow is solved using the energy equation, momentum equation and continuity equation [8] . Numerical modeling of flow (Fluent Manual, Fluent Inc.) was carried out using mass conservation equations and momentum equations in integral form under stationary and steady conditions.[9]

Wind turbine models can also be tested experimentally using a wind tunnel, the function of the wind tunnel in aerodynamic research to study airflow characteristics. Wind tunnel is also used to simulate the actual situation on an object that is under the influence of aerodynamic forces in the field of aeronautics, namely to analyze the performance of flying mechanics of a flying object.[10]. The magnitude and direction of the Lift and Drag Forces vectors depend on the shape of the airfoil profile, for example a fluid moving on a curved surface will be shown in detail the streamlines and aerodynamic forces due to changes in momentum. The schematic diagram of the aerodynamic forces is shown in Figure 1. It is therefore very important to understand the importance of the phenomena behind the various shapes of Airfoils [11].

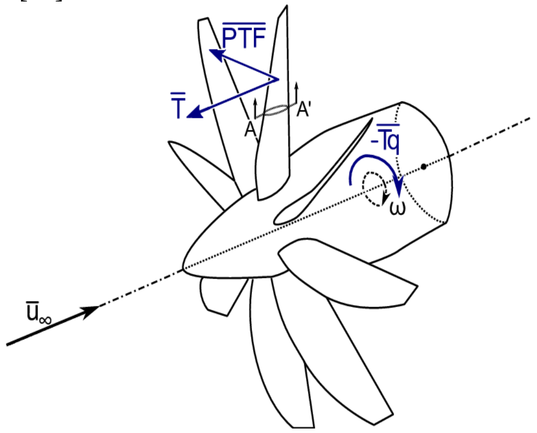

Figure 1 Aerodynamic Forces on Propeller Blade [11]

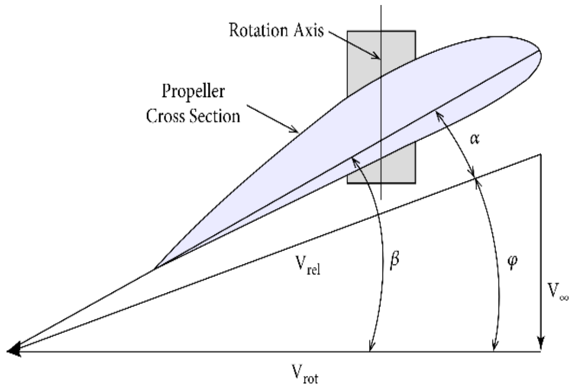

Figure 2 Velocity Diagram of Propeller Blade Cross Section [12].

The increase in the lift coefficient occurs gradually along with the shift of the separation points above the airfoil body and the effect of turbulence flow that is formed so that it affects the pressure resistance [13]. Based on Bernoulli's principle because the air flow over the airfoil produces a low-pressure zone and the high-pressure zone is on the lower surface, so that due to the pressure difference, a lifting force will be generated [14].

Previous research on blades describes a useful methodology for optimizing the geometry of small-size wind turbine blades obtained from circular pipes with optimal chord distribution and airfoil sweeps obtainable with precise cutting paths. Significant reductions in production costs and time can be achieved for blades which are important elements in wind turbine systems, especially in the case of renewable energy generation in developing countries [15], as shown in Figure 2 is the geometry of the turbine blades made of pipes that split with twist clock wise.

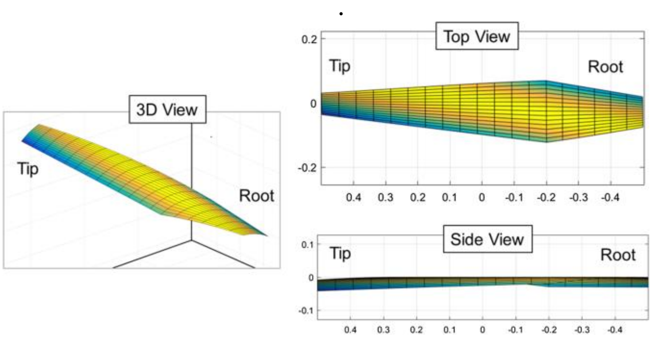

Figure 3: Geometrically and mesh of pipe blade.[15]

The kinetic energy of the wind according to classical physics of an object with mass m and speed v is E=½×m×v^2, but assuming that the speed v is not close to the speed of light. Since mass can be replaced by air density ρ, area A, and velocity v, it can be written: m = ρ.A.v is the mass flow rate of the wind. [16]

$$E = \frac{1}{2} \times m \times v^2 \qquad (1)$$

where: E= Energy (joule); m= Mass of air (kg) and v= wind speed (m/s).

Then the wind turbine power that can be generated per unit time is :

$$P_w = \frac{1}{2}\rho A v^3 \qquad (2)$$

P_w : wind power (watt).

Energy Conversion from Potential wind energy is able to rotate the turbine rotor, where this rotor is connected to a shaft that has been connected to a generator, causing an electric current. Parameters obtained from wind turbine testing are usually wind speed (v), rotation speed (n), current strength (I) and voltage (V). The value of electric power (P) is obtained by using the following equation:

$$P = V \times I \qquad (3)$$

where: P = Electric Power (Watt)
V = Voltage (Volt)
I = Electric current (Ampere)

The tip speed ratio is the ratio of the rotor tip speed to the free wind speed. For a certain nominal wind speed, the tip speed ratio will affect the rotor speed. Lift-type of wind turbines will have a relatively larger tip speed ratio compared to drag of wind turbines type. Tip Speed Ratio is calculated by the following equation [17]:

$$\lambda = \frac{2.\pi.n.r}{60 \times v} \qquad (4)$$

where: λ = Tip speed ratio
r = radius of rotor (m)
n = rotor speed (rpm)
v = wind speed (m/s)

According to the Betz limit theory that the maximum power coefficient that can be achieved is 59.26 percent. But in practice, the value that can be obtained from the center of the power coefficient is about 45 percent [18]. This value is below the theoretical limit due to inefficiencies and losses caused by different configurations, blade geometries, finite wings, friction, and turbine designs. Figure 3 shows the various type of wind turbine propeller, and the actual wind turbine power coefficient (Cp) as a function of Tip Speed Rasio (TSR). [19]

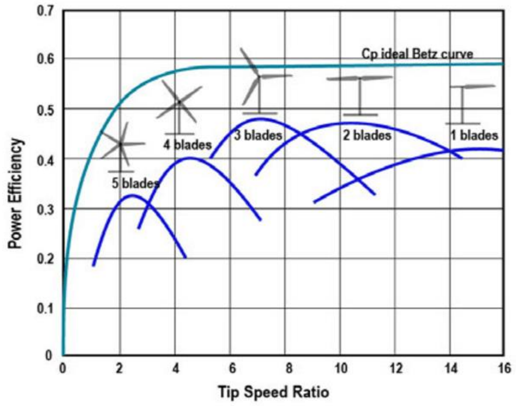

Figure 4 Wind Turbine Performance Diagram [19]

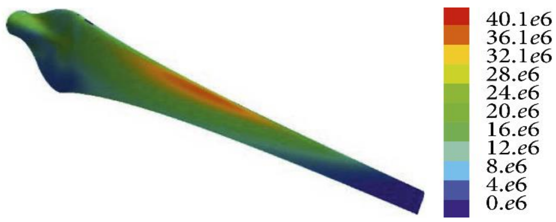

Figure 5: Von Mises Stress evaluation for E-glass-epoxy and basalt-epoxy at 40 m/s using CFD simulation [20]

In the study of the strength of the basalt-epoxy composite material for wind turbine blades, the maximum stresses were identified in two zones that can be considered critical, the first one close to the shaft and the second in the center zone of the blade due to the pressure contours generated by the wind impacting the turbine blades. Based on the von Mises stress formula in the CFD simulation, it was found that positive basalt fiber-based compounds for conventional material substitution can reduce deformation up to 96%. [20] A von Mises stress is a measure of the total overall stress acting on material included normal stress in the x and y direction as well as the shear stress.

$$\sigma_{VM} = \sqrt{\sigma^2 x + \sigma^2 y + \sigma x \sigma y + 3\tau xy} \quad (5)$$

Where σVM is the Von Mises Stress
σx is the normal stress x component
σy is the normal Stress y component
τxy is the Shear Stress

Wind turbine blades require high flexural stiffness properties as they are exposed to phenomena such as fatigue, traction and flexion. Therefore, the use of PVC pipe material to produce rigid but flexible. [21]

PVC is considered to have high bending properties because PVC pipe material has the ability to accept and absorb high pressure surges that come suddenly or constantly without experiencing damage to the bending surface of the pipe. [22]

The flexible ability of this PVC pipe can also keep the life of the horizontal axis wind turbine blades longer with a predicted life of up to 50 years of use under sudden load surges or constant loads. [23]

PVC material has other advantages, namely that it is lighter than other blade making materials, apart from that, this material is also easy to shape by heating without having to use a molding machine. With these advantages, PVC blades have the advantage of channeling motion energy without burdening the wind turbine as a whole. wind turbine blades is still a debate because its fatigue properties cannot be predicted accurately [24].

2. RESEARCH SIGNIFICANCE

This research is important because the results of this research can be used as a basis to ensure that this PVC material is suitable as a basis for making horizontal axis wind turbine blades.

Through ANSYS simulation, the ability of PVC materials to receive loads from wind loads can be seen and compared without having to carry out experimental practices that require a long time and money.

This research can also predict the approximate load received by the blade using the highest wind speed in the Indonesian climate and predict its lifespan to ensure that this PVC material has high durability.

Apart from that, 4" PVC pipe material is also very easy to find on the market. Even if we try to look around us, every building shop will definitely have stock selling 4" PVC pipes. This means that the public can have confidence in using PVC material and assembling it into a horizontal axis wind turbine that is suitable for small grid farm or household purposes.

3. RESEARCH METHODS

3.1 Material

The wind turbine construction built in this study has the following parts: (1) Hub, (2) Blade, (3) Tip Elbow, (4) Shaft, (5) Generator Box, (6) Tail, (7) Tower, as shown in Figure 6.

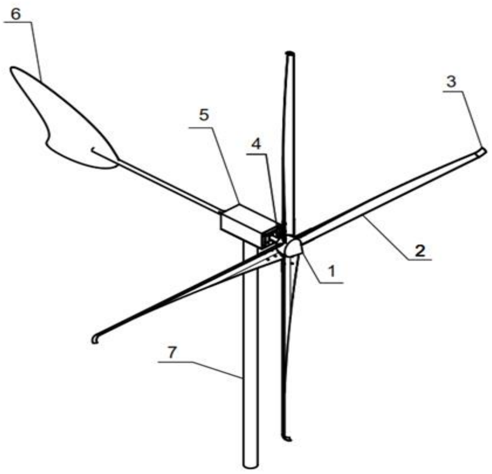

Figure 6: Design of Wind Turbine PVC Pipe Propeller

3.2 Experimental Procedure

In this study, numerical methods were used according to field conditions or actual conditions. The numerical method used is based on Computational Fluid Dynamics (CFD) simulation using both AnSys and Solidwork, where the airfoil used is designed to be a blade that is used as a single rotor reference [25]. Then the design results are simulated and will be validated with experimental results using a wind tunnel and measurements on sensors attached to the blades. This study also refers to the experimental report of Bartl and Sætran using 4 blades obtained CP max = 0.468 at TSR = 6 with a wind speed of 11.5 m/s (rotor rotation 1395 rpm) [26]. The numerical computations for static strength analysis of the propeller blade structure were carried out using commercial ANSYS 2023 Simulation software (ANSYS, 2023).

The novelty of the shape of a wind turbine blade using pipe with twist sliced was inspired by Newton's Second Law, when a force is occure due to a momentum change when fluid flows through a pipe elbow. The ends of pipe blade as shown in Figure 5 are made of elbow PVC pipe fixed to the ends of the propellers. Radial wind flow in the vane of the inner wall pipe and wind flow from the main stream will strike the elbow end producing additional force due to the momentum change.[27]

4. RESULTS AND DISCUSSION

Based on the theory of fluid mechanics, water turbine designers always rely on changes in momentum to produce maximum torque and power. The design geometry is manifested in the size of the diameter, angle of curvature of the blade, angle of the guide blade or nozzle, and others. While in the design of wind turbines, especially horizontal turbines, the designer always considers the limitations of the Betz theorem (max Cp < 0.59), as well as optimization of wind speed variables and geometric variables to produce lift and drag vectors in producing maximum torque or power [28].

In previous studies [29,30], a spiral split PVC pipe blade model has been produced with an optimum angle of attack of 30 degrees to the wind direction on the hub side. While at the end of the outer radius the blade plane is twisted up to 90 degrees (the concave plane of the pipe faces the tangential direction) as shown in Figure 6 below.

In the current study, the design in Figure 6 added an elbow at the end using standard elbow accessories on the market. The standard elbow is split with various widths and then connected to the tip of the blade so that the concave surface is facing tangentially. By making the width of part number 3 in Figure 5 as a research variable, it is hoped that it will be found how wide the size of the standard elbow section will be connected to the tip of the outer blade of this new wind turbine model.

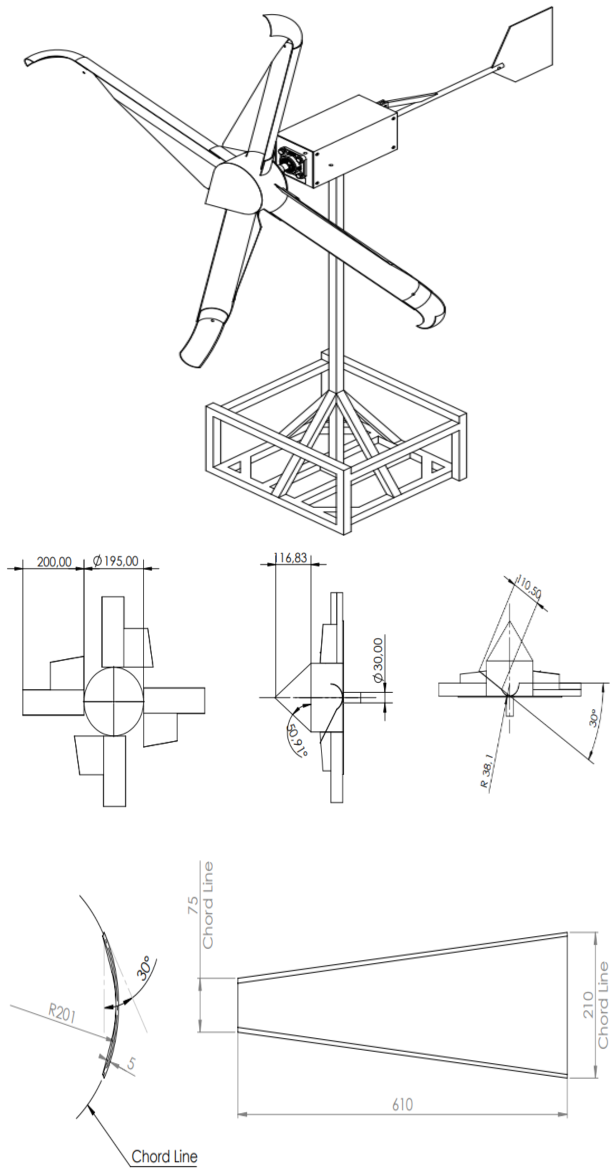

Figure 7. Propeller blade PVC pipe

Tablel 1 Variabel Speed and width elbow

Elbow width (mm)	Wind Speed (m/s)		
100	5	6	7
110	5	6	7
130	5	6	7

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Tablel 2 Stress & Displacement value

Wind Speed (m/s)	Tip Elbow Width (mm)	Stress (N/m2)		Dislacement (mm)	
		Min	Max	Min	Max
5	100	1,74E-05	0,18583	0	0,92715
	110	1,69E-05	0,18599	0	0,94625
	130	1,66E-05	0,18771	0	0,97242
6	100	2,79E-05	0,26652	0	1,3332
	110	2,44E-05	0,26743	0	1,3554
	130	2,38E-05	0,26905	0	1,3983
7	100	3,52E-05	0,36344	0	1,8179
	110	3,31E-05	0,36468	0	1,8483
	130	3,24E-05	0,36688	0	1,9067

In this research, the CFD simulation test uses wind speed and elbow width variables as shown in table 1. With these variables, we want to know how the aerodynamic behavior in and around the blade is in the form of images of stress distribution and displacement (blade deflection)

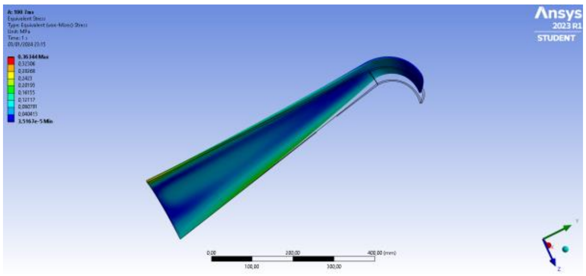

Figure 8. Von Mises Stress on wind speed 7 m/s and elbow width 100 mm

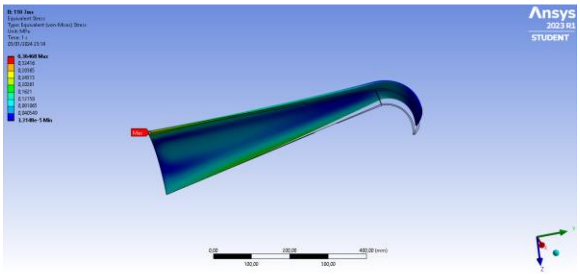

Figure 9. Von Mises Stress on wind speed 7 m/s and elbow width 110 mm

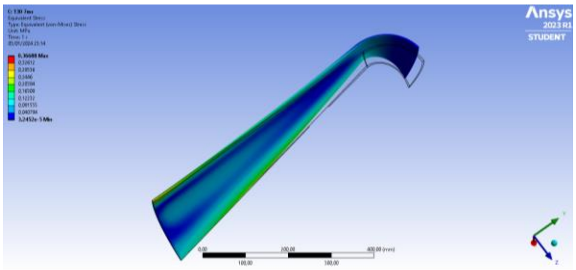

Figure 10. Von Mises Stress on wind speed 7 m/s and elbow width 130 mm

Simulation tests with an elbow width of 130 mm and a wind speed of 7 m/s produced the results in Figure 8, Figure 9 and Figure 10 showing that conditions with a wind speed of 7 m/s with an elbow width of 100 mm produced a maximum stress of 0.36344 N/m2, conditions A wind speed of 7 m/s with an elbow width of 110 mm produces a maximum stress of 0.36468 N/m2 and a wind speed of 7 m/s with an elbow width of 130 mm produces a maximum stress of 0.36688 N/m2. Stress occurs when there is an increase in speed and an increase in the width of the tip elbow.

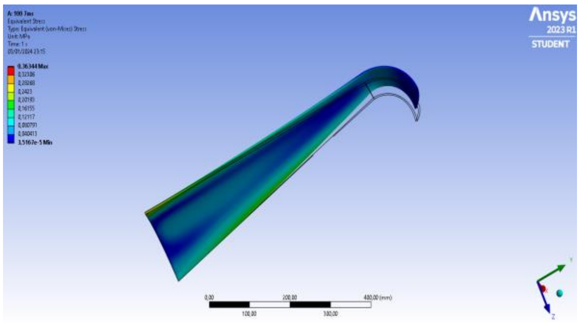

Figure 11. Displacement on wind speed 7 m/s and elbow width 100 mm

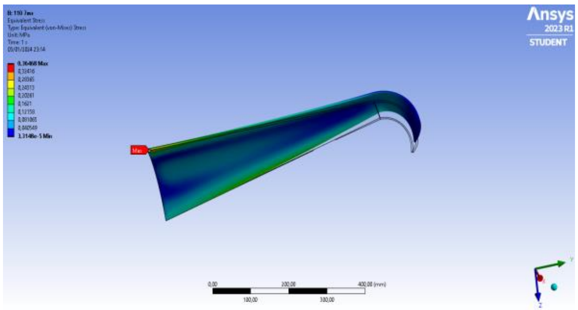

Figure 12. Displacement on wind speed 7 m/s and elbow width 110 mm

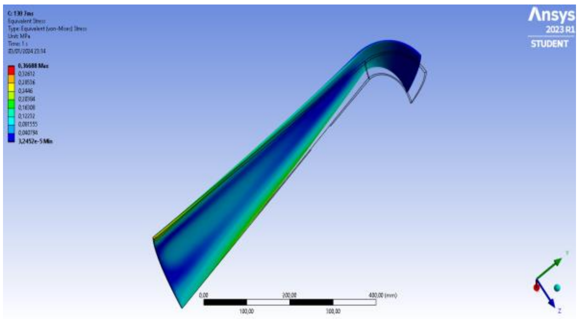

Figure 13. Displacement on wind speed 7 m/s and elbow width 130 mm

Then the simulation test with an elbow width of 130 mm and a wind speed of 7 m/s also produces the results in Figure 11, Figure 12 and Figure 13 showing that the condition of a wind speed of 7 m/s with an elbow width of 100 mm produces a maximum displacement of 1.8179 mm, condition A wind speed of 7 m/s with an elbow width of 110 mm produces a maximum stress of 1.8483 mm and a wind speed of 7 m/s with an elbow width of 130 mm produces a maximum stress of 1.9067. There is an increase in displacement when speed and the width of the tip elbow increase.

5. CONCLUSIONS

The simulation results show that the Von Mises stress is 0.36688 and the total displacement of 1.9067 mm in the blade body is the most optimal condition. If we look at the overall condition of the simulation using CFD, we don't see any red or critical conditions

In the simulation results, this means that in the most optimal conditions, blades made from PVC are still very safe to use.

From the simulation results we can also see that the use of a wide tip elbow can capture the wind power thrown to the outside of the blade, thereby increasing the efficiency of the horizontal axis wind turbine. Any increase in wind speed and increase in tip elbow width can increase the efficiency of the horizontal axis wind turbine and is safe to use.

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7. AUTHOR CONTRIBUTIONS

Conception and design: Bagus Wahyudi
Methodology: Aji Tisa Prayudha, Bagus Wahyudi
Data acquisition: Aji Tisa Prayudha
Analysis and interpretation of data: Aji Tisa Prayudha, Bagus Wahyudi
Writing publication: Aji Tisa Prayudha, Bagus Wahyudi
Approval of final publication: Aji Tisa Prayudha, Bagus Wahyudi
Resources, technical and material supports: Aji Tisa Prayudha, Bagus Wahyudi
Supervision: Bagus Wahyudi

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