PVC or Polyvinyl Chloride is a thermoplastic polymer, cheap, and can be used to make pipes and fittings. PVC pipes can be used to make low-power wind turbine blades. PVC pipes have good mechanical properties, including impact strength, high flexibility, vibration resistance, and hydrostatic pressure. To modify the pipe into a wind turbine blade that is strong against loads and has torsional resistance, an efficient design and manufacturing method is needed. In the blade design, an aerodynamic analysis is also carried out to obtain maximum energy from the wind turbine which is the result of the blade design performance. The goal is to find a way to build a turbine blade using PVC pipe and the best aerodynamic behavior of the fluid around the turbine rotor. This research is based on the CFD simulation method and experimental studies using a wind tunnel. Based on the results of the ANSYS CFD simulation at the elbow end of the PVC pipe turbine blade with an angle of attack of 15° and 30°, it can increase the torque by about 200 % compared to without the elbow end. CFD simulation was conducted to test the load on the PVC pipe blade with wind speeds of 5 m/s, 6 m/s, and 7 m/s, and angle tip widths of 100 mm, 110 mm, and 130 mm. The torque generated by the turbine is influenced by the width of the elbow tip, where the maximum torque is achieved by an elbow tip width of 110 mm. Based on the optimization results, the turbine can produce the best torque performance with the lowest stress generated from the load. The results of the von Mises stress analysis show that the stress that occurs on the turbine blade is the lowest, making it the safest and most reliable design. The results of the torque analysis show that the addition of an elbow tip can increase the torque on the turbine blade

Keywords: wind turbine, PVC pipe propeller, optimization, stress analysis, CFD simulation

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OPTIMIZATION DESIGN OF WIND TURBINE PROPELLER USING PVC PIPE MATERIAL WITH ELBOW TIP ACCESSORIES

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1. Introduction

The development of renewable energy sources, especially in large-scale power plants, which concerns the issue of geographical position and financial considerations, needs to be continuously explored. A feasible approach to overcome this is the development of small-scale power plants, which can provide benefits, are more accessible, and cost-effective. The weakness related to the utilization of renewable energy sources is the inherent variability of its output, which is largely influenced by natural conditions [1]. However, there is strong anticipation in the community for the development of small-scale wind power plants with blades made of PVC pipes, which are available on the market, affordable, and easy-to-use technology [2]. Based on its orientation, there are two classifications of wind turbines, namely: Vertical Axis Wind Turbines (VAWT) and Horizontal Axis Wind Turbines (HAWT). Wind turbine blades are designed with aerodynamic principles to produce thrust and lift. VAWTs emphasize thrust while HAWTs emphasize lift. HAWTs have higher efficiency than VAWTs, although various efforts to improve them have encountered many obstacles.

Utilization of wind energy through wind turbines, such as HAWT, the mechanism is simple, namely the kinetic energy of the wind pushes the wind turbine, rotates the generator rotor, and produces electrical energy. Wind turbines utilize wind energy through three or four propeller blades, which are designed like airplane wings. To obtain high, consistent wind speeds and low turbulence, wind turbines are strategically positioned on top of towers [3]. Computational Fluid Dynamics (CFD) simulations are utilized to examine the impact of the deflector on optimizing wind flow direction and reducing negative torque. Optimizing solidity and blade count to achieve maximum power output while maintaining cost-effectiveness and mechanical simplicity are also important factors [4]. Numerical simulations are also employed to evaluate various blade geometries, identifying configurations that maximize aerodynamic efficiency and energy capture. Findings underline the significance of customizing blade designs based on local wind conditions to enhance turbine performance in low-wind environments [5]. When the propeller is exposed to wind force, it produces a low-pressure area at the bottom of the propeller. The reduced atmospheric pressure will exert force on the propeller and cause it to be pulled to the intended area. The resulting force is generally referred to as lift. Lift has a greater value than drag. The rotational motion of the rotor is caused by the combined effects of lift and drag, which work similarly to the propeller driving the rotation of the generator. Researchers usually conduct optimization studies on the variables of angle of attack, tip speed ratio (TSR), and number of blades to ensure optimal efficiency of horizontal wind turbines [6]. The study [7] examines the optimized design and performance parameters for wind turbine blades in a solar updraft tower (SUT) plant. Using Schmitz's theory and aerodynamic force analysis, the study identifies design configurations that improve energy generation efficiency within the unique SUT environment. The analysis [8] considers variability in input parameters to assess their impact on turbine efficiency and reliability. Results highlight the significance of accounting for uncertainties in wind conditions and material properties to improve the robustness and predictability of blade designs.

In Indonesia, the wind does not blow as hard as in some other countries and is included in Wind Class 1, where the wind speed at a height of 50 meters ranges from 0–6 m/s, with a wind power density of 0–200 W/m^2. At a height of 150 meters, the wind speed ranges from 0–7 m/s, with a wind power density of 0–320 W/m^2. This makes wind power generation a little more difficult. However, Indonesia still has the potential to implement a wind power generation system. This development will make a significant contribution to strengthening energy independence in Indonesia. To overcome this, it is important to design wind turbines that can produce greater torque to rotate the generator effectively. This greater torque is needed to compensate for the reduced kinetic energy available due to low wind speeds. The inclusion of elbow tips in the blade design plays an important role in increasing the torque produced. By directing the wind flow or changing the aerodynamic characteristics of the blade, elbow tips can help optimize turbine efficiency. This design can increase the interaction between the moving wind and the blade surface, effectively increasing the torque and power of the turbine. In addition, the elbow tip can help reduce energy losses caused by turbulence, ensuring a focused and consistent transfer of wind energy into mechanical energy. Therefore, the addition of the elbow tip is essential.

The use of PVC pipe for wind turbine blades requires modifications to the manufacturing process to have good aerodynamic properties. Although PVC pipe is easily available, affordable, and lightweight, it is not designed for applications that require optimal airfoil shapes and surfaces that can increase lift and reduce drag. To produce an efficient blade profile, the pipe must be modified through cutting, forming, and smoothing processes. In addition, to produce blades that can withstand strong wind thrust loads, the blade design needs to be subjected to stress analysis due to these loads. This adjustment is important to align the characteristics of the PVC pipe with the functional demands of wind turbine operations, ensuring efficiency and reliability. Computational Fluid Dynamics (CFD) analysis using the six-degree-of-freedom method is needed to thoroughly examine the energy conversion process from wind flow to turbine rotation. This approach allows detailed simulation of the aerodynamic forces and moments acting on the turbine blades when interacting with varying wind speeds and directions.

2. Literature review and problem statement

The methodology used for the optimization of the geometry of small wind turbine blades obtained from circular pipes: optimal chord distribution and airfoil sweep can be obtained by proper cutting paths. The main goal is to significantly reduce the cost and production time. The Blade-Element Method is used to obtain the blade shape and performance of the wind turbine. Heuristic algorithms are applied to obtain the wind turbine design with the best efficiency. The results obtained show that the optimal blade design can be obtained using this methodology [9]. The results of this study have not been compared with experiments on the obtained blade design. In addition, this research did not carry out a stress analysis of the blade designs obtained.

The results of this study describe the measurements of wind speed at several different locations using an anemometer and turbine speed using a non-contact tachometer. Using a three-blade configuration made from PVC material, with a turbine radius of 1.02 meters, at a wind speed of 8 m/s and a Tip Speed Ratio (TSR) of 4, the calculated power output was approximately 300 W [10]. However, this study did not include a stress analysis of the blade design used.

This study aims to design a small-scale wind turbine, which can be made using commercially available materials at affordable prices. This study focuses on designing blades to harness power in areas with low wind power density. The design of wind turbine blades has a great influence on the aerodynamic efficiency of the wind turbine. This is achieved by comparing the effectiveness of blades from various sizes of PVC pipes available in the market. This is further evaluated through experimental analysis, based on data and evaluation results on various sizes of PVC pipes to obtain the best design [11]. In the study, the design of wind turbine blades from PVC pipes of various sizes has been obtained. Next, it is necessary to make a prototype and conduct experiments. The data obtained is analyzed to obtain the most optimal design for the efficiency obtained. The study also does not discuss stress analysis, namely the analysis of design strength against external loads.

Brazilian Patent No. BRPI0901809B1, publication date June 2, 2020, describes the invention of a solid turbine blade twisted with twisted and conical tips. Wherein the blade for the wind turbine has a total backward twist of between about 6 and about 15 degrees or 1 percent to 10 percent of the rotor radius of the blade, and the total normalized twist change is between about one percent and about two percent applied or about ten percent of the outermost portion of the rotor radius of the rotor blade. At least the claims made relate to a modified NACA profile solid turbine blade [12]. CN101592122B, published on January 28, 2015, describes the invention of a wind turbine blade with a bent but worn tip. The blade for the wind turbine includes a total counter-rotation of about 6 degrees and about 15 degrees between the outermost portions of about 1 percent to about 10 percent of the blade rotor radius. The claim also relates to a modified NACA profile solid turbine blade [13]. The claims of both above patents describe a wind turbine blade design. However, neither describes how much efficiency is achieved. Furthermore, neither discusses stress analysis, which is an analysis of the strength of the design under external loads.

European patent EP2034178A3, publication date 03 August 2016, describes an invention concerning a wind turbine blade with a deflectable flap. A wind turbine typically comprises a blade consisting of a primary component in the form of an aerodynamic profile. This profile includes a leading edge, a trailing edge, and a pressure suction side located between the leading and trailing edges. A second component comprises an edge flange that can be deflected upward and/or downward to allow for changes in flow over the blade. The claim relates to a modified NACA profile solid turbine blade flange that can be moved to adjust to a specified pitch angle [14]. The claims in both patents describe wind turbine blades with flaps that deflect up and down, allowing for changes in flow over the blades. However, the claims do not discuss how much efficiency the claimed blade design can achieve. Furthermore, the claims do not discuss stress analysis, which is the analysis of the strength of the design under external loads.

The performance of a wind turbine is based on the power generated. Increased power can be obtained by enlarging the dimensions of the turbine wheel, enlarging the dimensions of the blades, and optimizing the shape of the blades so that the flow can be utilized to generate power. Through the shape of the blades from the base to the tip and the addition of a bent tip shape, the wind's kinetic energy can be optimized into additional torque, which can produce an increase in the power generated. The shape of the blades is designed so that it can receive wind thrust at the base and direct the wind towards the tip until it hits the bent tip. The resultant thrust along the blade to the bent tip multiplied by the radius is torque. The wind flow velocity produces the angular velocity of the turbine. The multiplication of torque and angular velocity is the power generated by the turbine. This increase in torque is an increase in the power generated by the turbine from the original 200 Watts to 400 Watts [15]. The claims in this patent show the design of wind turbine blades from bent-end PVC pipes. However, the claim does not discuss how much efficiency can be achieved by the claimed blade design. Furthermore, the claim does not discuss stress analysis, which is an analysis of the strength of the design under external loads.

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 wind turbine blades is still a debate because its fatigue properties cannot be predicted accurately.

3. The aim and objectives of the study

The aim of the study is to optimize the design of the PVC pipe blade with elbow tip which has the most effective design to achieve the higher torque of the turbine.

To achieve this aim, the following objectives are accomplished:

– to analyze the working stress that occurs in blade construction;

– to optimize the most effective elbow width for handling wind impact acting on the PVC pipe blade wind turbines.

4. Material and method

The object of this study is a wind turbine with PVC blades featuring elbow tips. The blades are 2 meters long, with a total of 4 blades, designed for generating 500 W of electricity. The wind speed applied in the CFD simulation analysis is based on the average wind speed data in Indonesia. Thus, this object is expected to serve as a reference for producing PVC pipe wind turbine blades with the best design that has the maximum strength to indulge wind velocity based on optimization results.

The main hypothesis guiding this research is that the power output of a propeller can be increased by optimizing its design using PVC pipe materials combined with elbow tip accessories. This approach is expected to enhance performance while maintaining cost-effectiveness. The study operates under several assumptions to simplify the analysis. These include steady-state flow conditions, incompressible flow, and turbulent flow mode. It also assumes negligible viscous effects and the absence of operational issues such as jamming.

To further streamline the research, several geometric simplifications are adopted. The blade shape is simplified, with a constant thickness maintained throughout. The geometry of the hub and shaft is disregarded, and the elbow tip accessory is treated as idealized. Additionally, the propeller blades are designed symmetrically to facilitate analysis and fabrication. These parameters and assumptions collectively form the foundation for exploring the potential of optimized propeller designs in achieving enhanced performance, cost efficiency, and durability.

The description of the state of the art in this research innovation consists of three aspects including aerodynamics, materials, and placement of the tip of the elbow on the outermost radius of the propeller blade:

1. Aerodynamic aspect. The design of the propeller considers the latest aerodynamic principles to achieve maximum efficiency. The 90-degree twisting of the blades allows for finely directed airflow at any angle of rotation, reducing turbulence and decreasing performance.

2. Material aspect. The use of PVC pipe as a material for wind turbine blades is a recent innovation in this industry. PVC pipe has the advantages of being lightweight, corrosion resistant, and lower production costs compared to traditional materials such as metal. This design takes advantage of these materials to reduce the overall weight of the propeller without sacrificing its structural strength.

3. Elbow tip placement aspect. The addition of a 90-degree elbow segment at the tip of the blade aims to optimize the direction of airflow entering the propeller. These elbows help to efficiently divert air to the desired angle, improving propeller performance and minimizing energy losses due to turbulence.

The description of the novelty of this research innovation consists of three aspects including the twisting of the blade, the tip of the elbow, and the application of PVC pipe as a propeller blade:

1. Twisted blades. The use of blades that rotate 90 degrees from the hub to the tip is an innovation rarely found in conventional wind turbine propeller designs. This shape aims to optimize the speed and direction of airflow at each angle of rotation, increasing the efficiency of the power generated.

2. Elbow tip. The addition of a 90-degree elbow segment at the tip of the blade is a feature that is rarely used in wind turbine propeller designs. These elbows help divert airflow more effectively, reduce energy losses due to turbulence, and increase the overall efficiency of the wind turbine.

3. PVC material blade. The use of PVC pipe as a material for wind turbine propeller blades is an innovative idea in combining structural strength with lightweight, corrosion resistance, and low production costs. This can open opportunities for the use of more economical and environmentally friendly materials in the wind turbine industry.

The design of wind turbine propellers using pipe blades has been carried out by several previous researchers using special mathematical equations. The results of the engineering design of propeller blades from PVC pipes can be seen in Fig. 1.

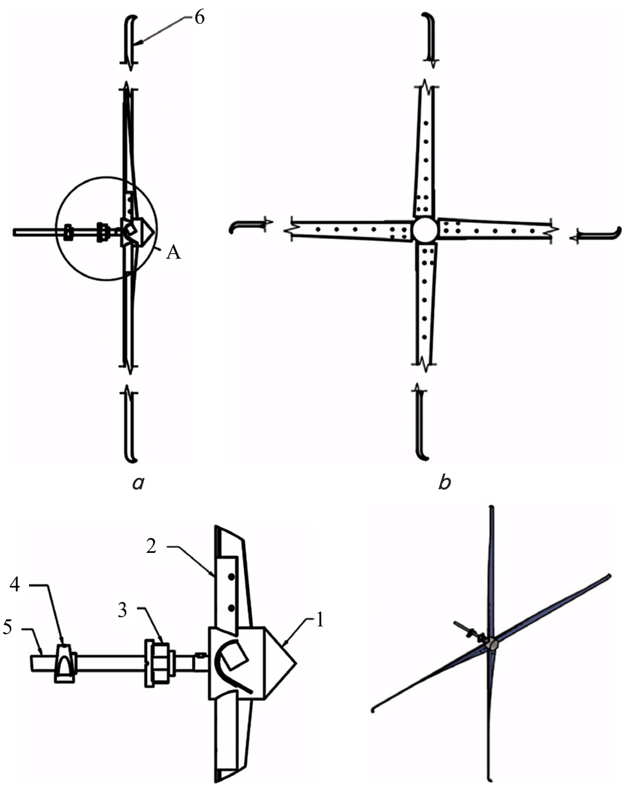

Fig. 1. Result of propeller design: *a* — front view; *b* — right view; *c* — detail of A; *d* — isometric view

The propeller design, as shown in Fig. 1, consists of 6 (six) main components, namely:

1) hub;
2) blade holder;
3, 4) bearing;
5) shaft;
6) tip blade (elbow).

The expression for the kinetic energy of an item influenced by wind, with mass denoted as m and velocity as v, can be represented as seen in equation (1) It is important to note that this equation is valid under the condition that the velocity v remains significantly below the speed of light. The equation (2) represents the relationship between mass flow rate ($\dot{m}$), air density (ρ), area (A), and velocity (v), where mass flow rate can be expressed as the product of air density, area, and velocity. The expression for kinetic energy in a wind turbine is as follows:

$$E_k = \frac{1}{2} m v^2. \quad (1)$$

The mass flow rate equation is:

$$\dot{m} = \rho A v. \quad (2)$$

The potential power estimated from the wind velocity can be formulated by substituting the air mass at (1) with (2):

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

The coefficient of power (C_p) is a ratio of output power (P_m) and input power (P_w):

$$C_p = \frac{P_m}{P_w}. \quad (4)$$

Mechanical power produced by a wind turbine:

$$P_w = \frac{1}{2} \rho A v^3 C_p. \quad (5)$$

The tip speed ratio refers to the proportion between the tangential speed of the blade tip and the velocity of the surrounding airflow. The spinning of the rotor can be influenced by the tip speed ratio at specific wind speeds. According to references [16, 17] it can be observed that the lift-type wind turbine exhibits a comparatively higher tip speed ratio in comparison to the drag wind turbine:

$$TSR = \lambda = \frac{2\pi n r}{60 v}. \quad (6)$$

Fig. 2 represents a plot of the Power Coefficient (Cp) versus the Tip Speed Ratio (TSR, λ**)** for a wind turbine.

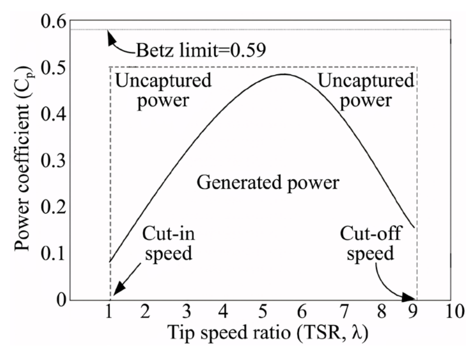

Fig. 2. Tip speed ratio vs. power coefficient

The wind turbine's power coefficient, when operating at the Betz limit, attains a maximum value of 59.26 %. Nevertheless, in practical applications, the power coefficient typically yields a value of approximately 45 % [18]. The study [19] challenges conventional theories, it acknowledges the Betz coefficient as a foundational concept in wind energy conversion efficiency. Another study [20] explains that the maximum theoretical efficiency of a wind turbine is approximately 59 %, as determined by the Betz coefficient, and discusses practical considerations that affect real-world turbine performance. Computational methods can be employed to enhance blade performance, aiming to approach the theoretical efficiency limits defined by the Betz coefficient [21]. By emphasizing practical design improvements, it acknowledges the Betz limit as the benchmark for maximum possible efficiency in wind energy conversion. While the Betz coefficient is primarily associated with horizontal axis wind turbines, the study [22] references it as a comparative benchmark for assessing the efficiency of vertical axis designs. There are various losses and inefficiencies that prevent real-world turbines from reaching the theoretical maximum efficiency defined by the Betz coefficient [23]. The graph depicted in Fig. 2 illustrates the relationship between the Betz ideal constant and the actual turbine power coefficient, with the independent variable being the Tip Speed Ratio [24].

For this research, wind speed data was used which was adjusted to wind conditions in Indonesia, as shown in Table 1. Basically, the kinetic energy of wind speed affects the stress on the turbine blades. The wind speed used represents moderate to relatively strong wind conditions. Meanwhile, three elbow width conditions were used for optimization.

In this study, the CFD simulation experiment utilizes wind speed and elbow width as variables, as outlined in Table 1.

These variables are used to investigate the aerodynamic behavior of the blade, specifically in terms of stress distribution, displacement (blade deflection), and streamlines, which are represented in visual form.

Table 1

Variable speed and width elbow

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

By using Table 1 as a research reference, several stages of research were carried out to obtain relevant data. CFD analysis was used to examine the stress that occurs on the turbine blades due to wind impact. The results of the CFD analysis were used to extract stress data for visual analysis. The deflection and aerodynamics that occur on the turbine are discussed in the discussion section. The summary of the CFD analysis results serves as a reference for optimization using the Taguchi method.

5. Stress analysis and optimization results

5. 1. Stress analysis results

In the current study, the design in Fig. 3 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 Fig. 3 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.

Fig. 3. Propeller blade PVC pipe with tip elbow

The CFD simulation results, as shown in Fig. 4, reveal that the wind flow over the blade with an elbow tip width of 110 mm forms a perfectly streamlined pattern. This is characterized by the alignment of the wind flow in the direction of the propeller's rotation and the absence of turbulence, evidenced by the lack of counterflow arrows behind the blade. Based on the simulation outcomes, the blade with an elbow tip width of 110 mm demonstrates optimal performance compared to other configurations. It not only maintains a streamlined flow but also generates the highest torque when compared to blades with elbow tip widths of 100 mm and 130 mm. These findings indicate that the 110 mm elbow tip width is the most effective design for maximizing turbine efficiency and performance. The surface contour of the split pipe blade is meticulously engineered to effectively capture the wind's mass, directing it radially toward the elbow section at the propeller's end. This configuration contributes to the generation of momentum force, ultimately enhancing the turbine's torque. Fig. 4 shows a unique aerodynamic phenomenon where a propeller with a tip elbow width of 110 mm has better torsional stability than a width of 100 mm and 120 mm. At the tip elbow width of 110 mm, there is no significant turbulence and disturbance so it can be expected to provide the best aerodynamic performance. With the CFD simulation results, a 110 mm tip elbow width can be chosen to be connected to the outer radius end of the wind turbine propeller when the manufacturing process is carried out.

The simulation test with 110 mm width elbows and wind speed 7 m/s results in Fig. 4 show that streamline compaction occurs in the direction of the propeller rotation without any turbulence behind the blades. The air collision from the mainstream direction on the concave part of the pipe is forwarded in a radial direction against the tip elbow to create a double effect in increasing torque. Usually, this phenomenon is interpreted as a Coanda effect on an airplane wing whose ends are equipped with flaps to increase lift forces. With the simulation results, a turbine with an elbow width of 110 mm works best among other variables as shown in Table 1 and produces a maximum torque of 12.031 Nm.

Fig. 5 shows the density of streamlines in the elbow tip. It indicates the flow trapped in the elbow tip that increases the wind harnessing. The 110 mm width variation has the most higher torque results.

The width elbow of 130 mm has less torque as seen in Fig. 6. From the streamlined plot it shows the fluctuation in the elbow width has made a turbulence area. This resulting of less wind converted into thrust of the blade.

As seen in Fig. 7, the resulting displacement of elbow width 100 mm has the largest displacement. It indicates that the structural strength can't maintain the shape of the wind blade at windspeed 7 m/s. It can be seen from Fig. 7 shows that critical operating conditions, the simulation results show an Von Mises stress of 39187892 N/m^2 or 39.1 MPa and a total displacement 1071 mm with red color marking in blade body it is very dangerous condition when using width elbow 100 mm with 7 m/s wind speed.

The displacement and the von misses stress at elbow width 110 mm can be seen in Fig. 8. The graph shows that the red regions have relatively small areas. It indicates that the structure can resist better than the other width elbow variations. Based on Fig. 4, 8 from the CFD simulation for operating conditions of a typical PVC pipe split twist blade by equipping the tip elbows in the outer radius with equivalent stress 37931224 N/m^2 or 37.9 MPa and total displacement 1069 mm when the wind speed condition is 7 m/s at 110 mm elbow width.

But with using 130 mm width elbow in the same speed, it can be seen Fig. 9 that the critical von Mises stress value is 39026256 Pa or 39.0 MPa which appears near the hub. Stress analysis based on simulation results obtained in normal or critical conditions to ensure the safe operation of the wind turbine.

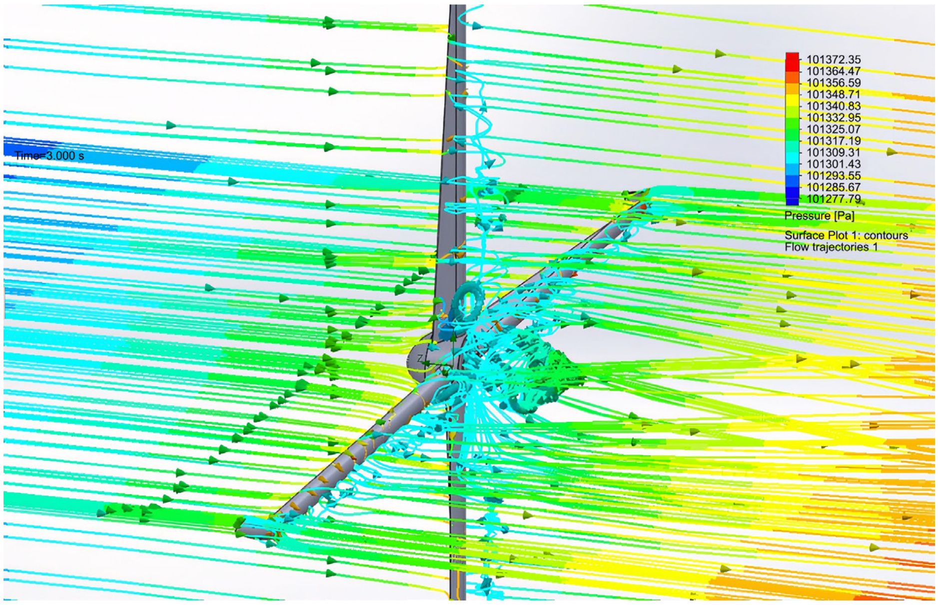

Fig. 4. Streamline of aerodynamic in around of blade at a wind speed 7 m/s and blade width 110 mm

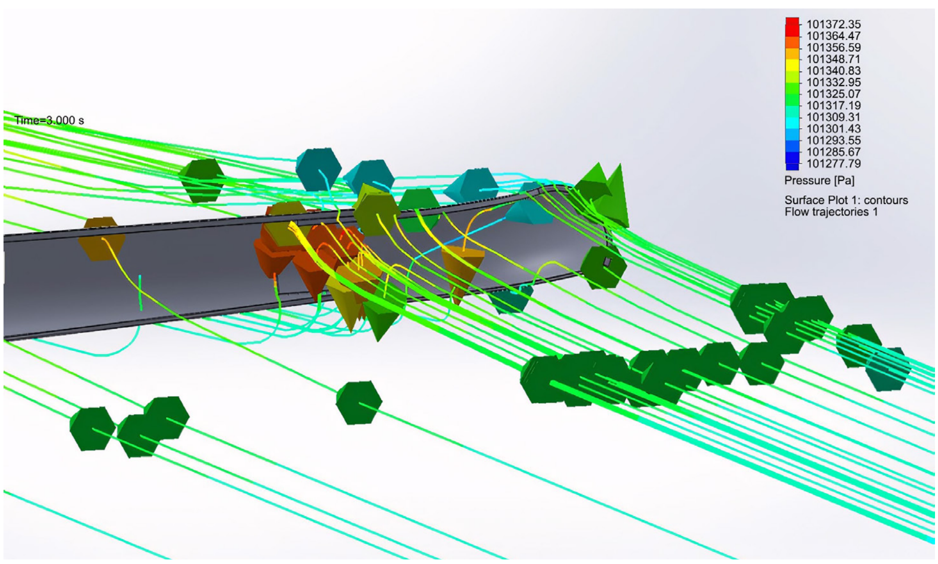

Fig. 5. The density of the streamlines occurs on the outer part of the blade radius when the wind speed is 7 m/s and the elbow width is 110 mm

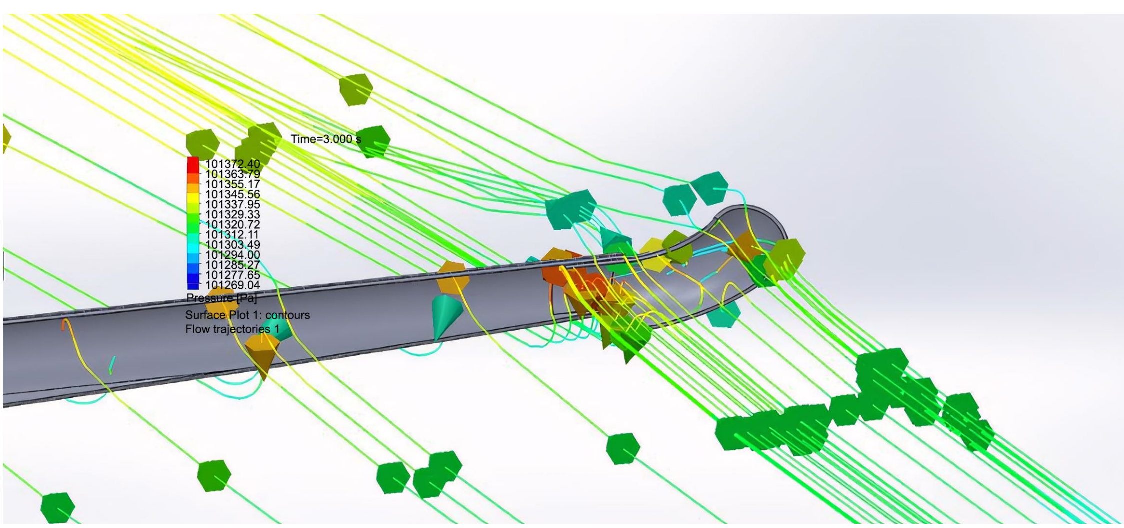

Fig. 6. The density of streamline occurs on the outer of radius blade when wind speed 7 m/s and elbow width 130 mm

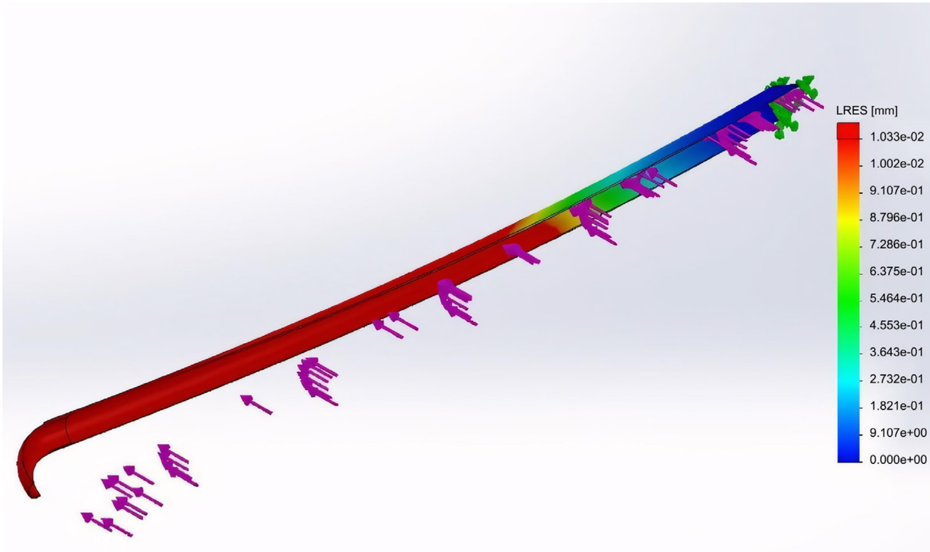

Fig. 7. Von Mises stress and displacement on wind speed 7 m/s and elbow width 100 mm

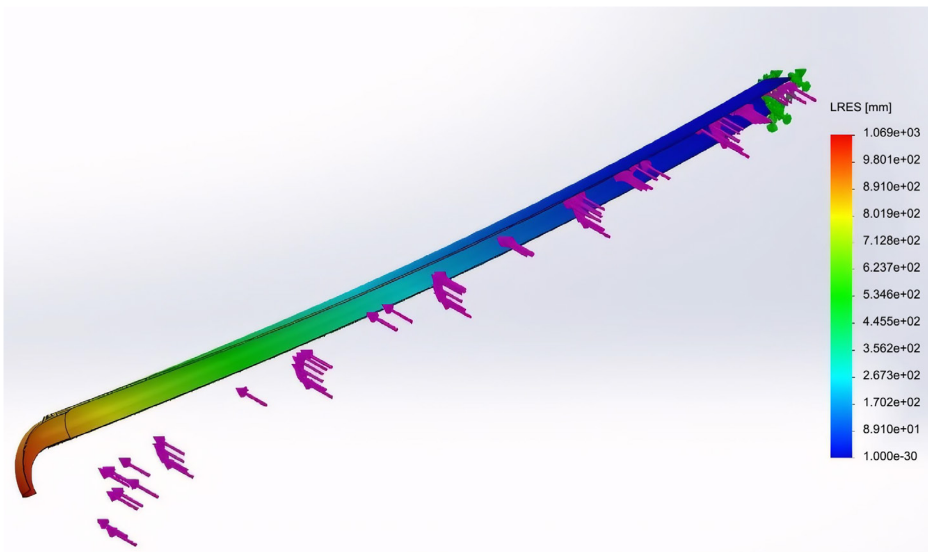

Fig. 8. Von Mises stress and displacement on wind speed 7 m/s and elbow width 110 mm

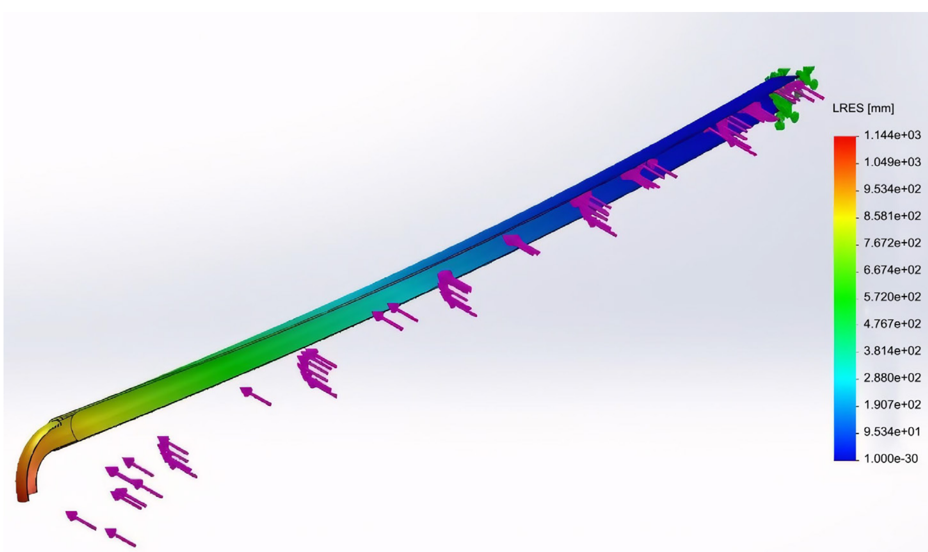

Fig. 9. Von Mises stress and displacement on wind speed 7 m/s and elbow width 130 mm

The use of PVC pipe as a blade is better at capturing wind energy and can increase strength and stiffness from the hub zone to the end zone. Based on Fig. 10 the higher torque available on elbow width 110 mm and no significant difference in working stress (Fig. 11).

The working principle of a PVC pipe propeller wind turbine with an Elbow Tip is as follows; the wind comes from the front of the turbine. The wind hits the surface of the blade from the base of the blade (inner radius) to the tip of the blade (outer radius). At the base of the blade, there is a wing/flap with an angle of attack of 30 degrees which functions to provide lift forces to initiate rotation. From the base of the blade, the wind flows radially through the surface of the blade pipe wall towards the tip elbow or tip of the blade. This wind flow produces thrust at the tip elbow based on the principle of change in momentum. The thrust which is located at the outermost radius point (tip elbow) is what can increase the torque. Based on research torque can be increased up to two times or 200 % as seen in Fig. 12.

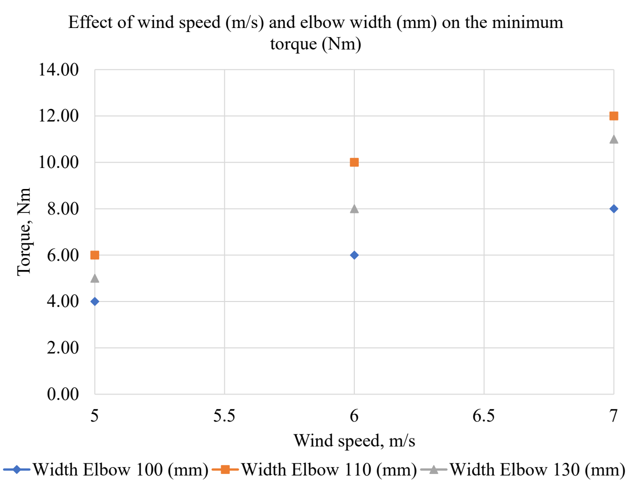

Fig. 10. Width elbow versus torque

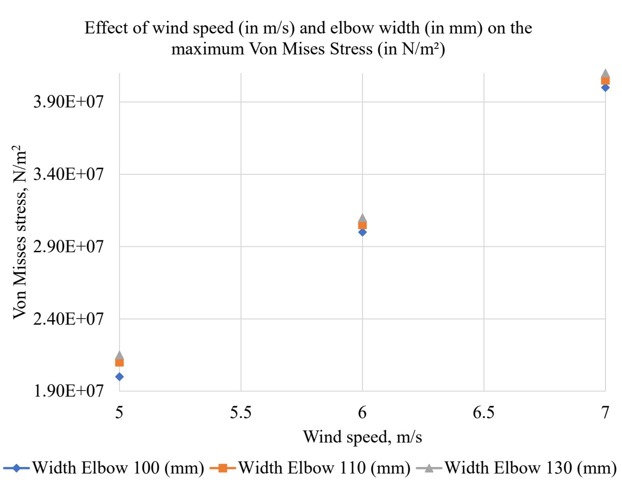

Fig. 11. Width elbow versus Von Mises stress

width elbow tip on the propeller blade. This is caused by the phenomenon of pressure accumulation that occurs at the end of the blade surface as shown in Fig. 14, which looks like a cloud which is a high-pressure area that can push the propeller blades to rotate more powerfully.

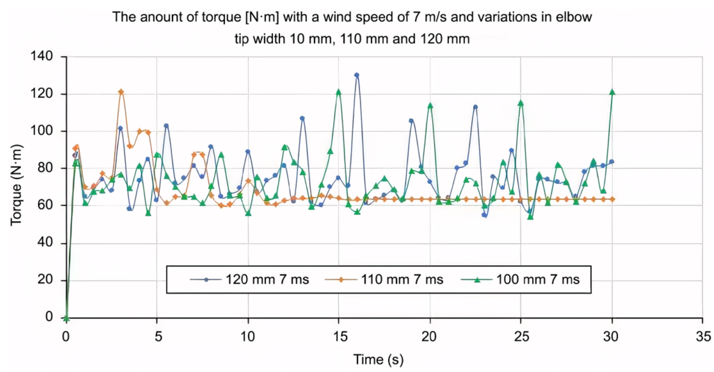

Fig. 12. The torque distribution with elbow tip width variations

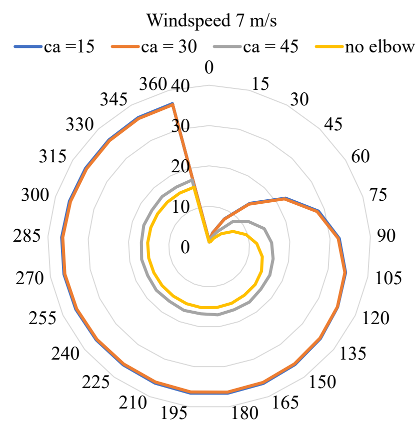

Fig. 13. Torque radar chart using a variable of wind speed (v) and angle of attack (°)

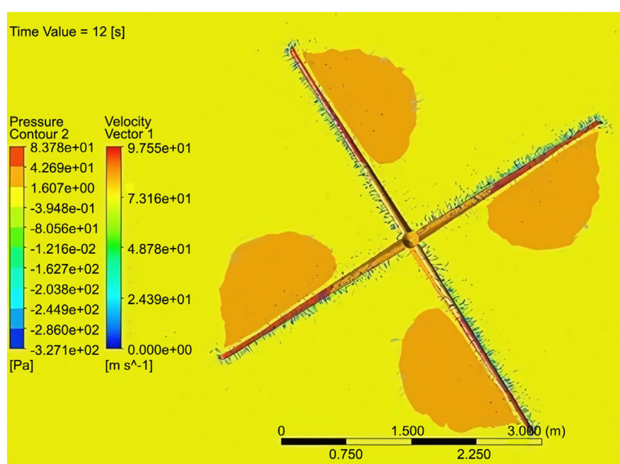

Fig. 14. Pressure contour at time value 12 s of propeller with 110 width elbow tip shows creating the pressure accumulation on tip region cause increasing torque

When compared between propellers using elbow tip and without elbow tip shows a significant gap [15, 18]. In Fig. 13, the torque radar graph also shows that at an angle of attack of 30 degrees the turbine propeller has a significant increase in torque. Increasing torque is also caused by using a 110 mm width elbow tip on the propeller blade.

Fig. 15 shows the results of the torque distribution in the turbine blade at each angle. The torque varies with the angle, which shows the dependence of the torque on the angular position of the turbine blade. As seen in Fig. 15, the blade with an elbow width of 110 mm shows a stable condition.

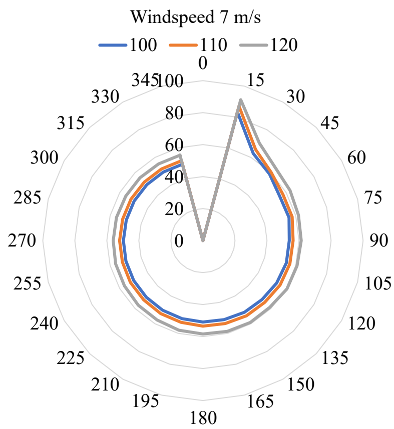

Fig. 15. Torque radar chart using variable of wind speed (v) and elbow tip width (w)

The use of variations in Elbow Tip Width has a significant effect on increasing the Average Torque on the turbine shaft with a PVC propeller pipe diameter of 4 Inch (101.60 mm) as shown in Fig. 12. However, considering the stability and reliability of the propeller it is more appropriate to choose an elbow tip width of 110 mm. Thus, for design considerations for future researchers, the aspect ratio for the width of the tip elbow is $w/D=110/101.60=1.09$. While the angle of attack on the blade flap based on Fig. 15 is recommended to use an angle of 30 degrees.

5. 2. Data optimization of elbow tip

Based on analysis from the data obtained, an optimization using Taguchi methods are held. By implementing the equation (1), (2) the optimization focused on torque and width elbow.

From Fig. 16 it is a clear inverse relationship between wind speed and SNR for Von Mises Stress. As the wind speed increases from 5 m/s to 7 m/s, the SNR consistently decreases for all elbow widths (100, 110, and 130 mm). This trend indicates that higher wind speeds lead to an increase in Von Mises Stress on the turbine blades, which is undesirable since smaller SNR values (more negative) signify higher stress.

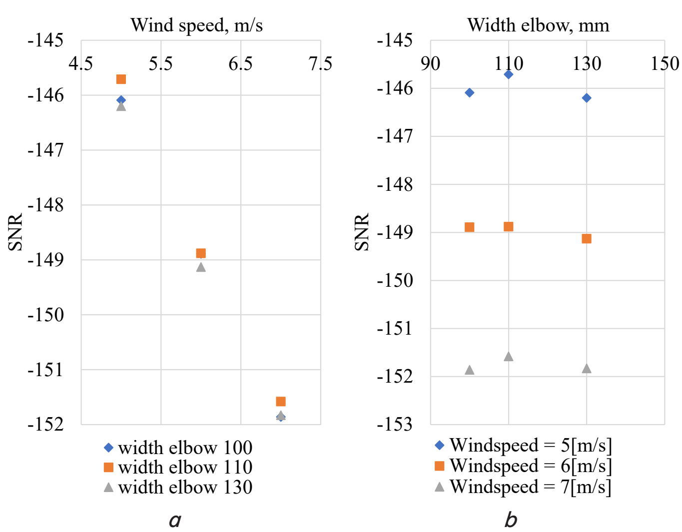

Fig. 16. The relationship between Signal-to-Noise Ratio (SNR) for Von Mises stress towards: *a* – wind speed; *b* – width elbow

In simpler terms, the turbine blades experience greater stress at higher wind speeds, which could affect the turbine's longevity and structural integrity. Notably, the slope of the SNR decline is relatively consistent across all elbow widths, indicating that wind speed is a dominant factor in influencing the stress on the blades.

The relationship between SNR and Elbow Width at different wind speeds (5 m/s, 6 m/s, and 7 m/s) as in Fig. 19 the values remain relatively constant across different elbow widths, with only slight fluctuations. The SNR values are slightly better (less negative) at the width elbow 110 mm, particularly at higher wind speeds (6 m/s and 7 m/s). This suggests that this elbow may help reduce the Von Mises Stress marginally by altering the aerodynamic flow, though the impact is not substantial.

Elbow Width has a relatively smaller effect on the SNR, although increasing the elbow width to 110 mm can slightly improve the SNR at higher wind speeds. This suggests that increasing the width of the elbow can be a potential strategy to mitigate stress at high wind speeds, but other design optimizations would likely be necessary to achieve more substantial improvements.

6. Discussion of design optimization results

From the research background, it shows that design optimization is needed to obtain a PVC pipe wind turbine blade design that has good strength and aerodynamic properties. The use of PVC pipe as a material for forming wind turbine blades requires modifications in terms of its manufacturing to be able to produce decent aerodynamic properties. In contrast to reference [10], the manufacturing process uses a different shape and there is the addition of an elbow tip. The addition of an elbow tip functions to increase the thrust of the turbine.

In accordance with its application in Indonesia which has a low average wind speed, it requires additional torque to be able to rotate the generator effectively. This study focuses on the structural analysis of wind-induced impact forces on the system. The research aims to understand how these forces interact with the materials and design of the structure, specifically targeting the performance and durability of PVC pipe materials under varying wind conditions. Wind impact forces are dynamic and can lead to deformation, stress accumulation, or even failure if the material and design are not optimized. It is essential for ensuring the reliability and longevity of the system. The strength of PVC pipe materials in resisting wind forces coming from the front direction is a central aspect of this study. Computational Fluid Dynamics (CFD) simulations are employed in this research to model and analyze the behavior of PVC pipes when subjected to direct wind impacts.

From the results of this study, the influence of elbow width on the structural durability of PVC turbine blades has been thoroughly explained. Fig. 4 is the result of a simulation using the 6 DoF method. The results of the simulation show that the addition of an elbow tip can trap and direct the wind to increase the rotational torque of the turbine. Fig. 5, 6 show a detailed view of the fluid streamline in elbow areas. As seen in these figures the wind flow direction changed in contact with the elbow resulting in force to generate torque towards the turbine. However, it should be underlined that with the presence of large torque, it will affect the structural strength of the turbine blades. So, in the structural analysis in Fig. 7–9, it can be seen how the deformation occurs due to wind impact.

The position of the elbow tip at the end of the blade makes the force arm larger, in this study it was found that the force working at a wind speed of 7 m/s can still be withstood by the blade design. Using stress analysis, the deformation occurring in the turbine blades can be predicted. The magnitude of the deflection can result in suboptimal turbine rotation and disrupt the aerodynamic movement of the wind. Among the three variations of elbow width, the 100 mm width shows the greatest indication of deformation. This is likely due to the blade structure being unable to withstand wind speeds of 7 m/s. Although it has not yet reached its plastic deformation point, excessive shape deformation can significantly affect the rotation of the turbine.

The wind speed in this study was examined at speeds of 5–7 m/s, which were derived from the average annual wind speed in the Indonesian archipelago. However, it is possible that at certain times and locations, higher wind speeds could occur, especially during storms. Fig. 10 shows a significant increase in torque values at a wind speed of 7 m/s. Similarly, Fig. 11 shows a relatively high increase in Von Mises stress values at this wind speed. The data obtained from the results of the Taguchi analysis shows that the application of a width of 110 mm has the smallest stress response and relatively good torque. Based on this data, it can be a reference for experimental trials. As wind speed increases, the torque generated by the turbine increases for all elbow tip widths. This trend aligns with the physics of wind turbines, where higher wind speeds result in more energy transferred to the blades, thereby increasing torque. The slope of the torque increase varies depending on the elbow width, indicating that the design of the elbow tip significantly influences performance. From the transient analysis, in Fig. 12 shows the distribution of the torque generated fluctuates in each second. However, the 110-width elbow shows stable results than the others.

Fig. 13 shows the absence of an elbow significantly reduces efficiency, highlighting the importance of this design feature in improving turbine output. This significance can also be seen in Fig. 14 that shows the pressure contour in the elbow tip areas, indicating the torque generated due to the geometry. The radar graph in Fig. 15 shows that the 110 mm elbow width appears to strike an optimal balance between aerodynamic efficiency and design considerations. While increasing elbow width beyond 110 mm slightly reduces performance, narrowing it below 110 mm significantly diminishes energy capture.

The results of this study indicate that an elbow width of 110 mm provides optimal performance for application as seen in Fig. 16. This analysis is expected to serve as a solution for implementing wind turbines made from PVC pipes that exhibit strong structural durability under wind conditions, particularly in Indonesia. With readily available materials, the maintenance process for the turbines will also become more manageable, especially for implementation in remote areas where these turbines are specifically intended. However, a full-scale (1:1) experimental analysis is still needed for this research. While laboratory-scale studies and CFD simulations provide valuable insights, they cannot fully replicate the environmental stresses that turbine blades experience in real-world conditions. Factors such as prolonged exposure to direct sunlight, high temperatures, and frequent rainfall can significantly affect the durability and quality of the PVC material used. These conditions may lead to material degradation over time, which cannot be thoroughly assessed through simulations or controlled laboratory testing alone.

High temperatures resulting from direct sunlight can accelerate the thermal aging process in PVC, potentially weakening its structural integrity. Similarly, exposure to rain and moisture can introduce additional challenges, such as surface erosion, material swelling, or the development of microcracks. These factors highlight the importance of conducting full-scale experiments to evaluate the long-term performance and reliability of PVC turbine blades in actual weather conditions.

7. Conclusions

1. From the stress analysis, the elbow width modification plays a significant role in the aerodynamic of the blade. As wind speed increases, the torque generated by the turbine increases for all elbow tip widths. From the displacement result, the elbow width 130 mm gained slightly smaller displacement due to the stiffer construction. The maximum von Mises stress obtained for a width elbow of 110 mm is 2.1×10^7 N/mm^2 at the wind speed of 5 m/s, 3.05×10^7 at 6 m/s, dan 4.05×10^7 at 7 m/s. These results fall between a width elbow of 100 mm and 130 mm. However, the transient analysis resulting 100 m and 130 mm elbow width configurations show significant fluctuations in torque, suggesting less stability compared to the 110 mm width.

2. Based on the optimization result, the turbine with 110 mm width has the best torque and stress performance. The turbine with a width of 110 mm has the smallest maximum stress (Von Mises stress), supporting a safer and more reliable design. Torque analysis shows that the addition of the elbow tip increases the torque from the turbine's rotation.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research, and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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