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SIMULATION STUDY OF HORIZONTAL AXIS WIND TURBINE USING PVC PIPE PROPELLER WITH ELBOW TIP

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Abstract

The potential of wind as an energy resource is still not widely used by the community through simple technology to produce electrical power. One simple technology is to use PVC pipe as the basic material for making wind turbine propellers. The purpose of this study was to determine the effect of variations in angle of attack and wind speed on the performance of a PVC pipe propeller wind turbine with an Elbow Tip. Material of blade propeller made by PVC pipe are slice half and twist from hub until tip with 90 degree of rotation. Dimension of width blade wider on the hub (3/4 of circular) and smaller on the tip (1/7 of circular). Face of blade on the hub side facing wind direction (axial) and face of blade on the tip side facing tangential direction or opposite with rotation. On the tip side installed the slice elbow with fit tip blade width. The propeller using PVC pipe with elbow tip is the important part of new design which has been test with CFD simulation and wind tunnel research with best result performance. This research uses CFD simulation and experimental methods with a comprehensive study of the aerodynamic behaviour characteristics in and around the turbine rotor. The results of the CFD simulation was found that the phenomenon positioning of momentum force were place on the outer radius due to addition elbow tip cause increasing the torque. By using elbow tip on blade propeller PVC Pipe Horizontal Axis Wind Turbine with 15° and 30° angle of attack could increasing torque about 200 % than without the elbow tip. Beside, using 45° angle of attack although additional with elbow tip could not increasing the torque when the wind speed on 7 m/s. The result of this research is important to know by public who interest build small grid wind turbine with low cost and easy manufacturing.

Keywords: HAWT, Propeller, PVC Pipe, Elbow Tip, Flap, Twist Blade, Torque, and CFD simulation.

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1. Introduction

Indonesia is a tropical country that has a lot of wind potential, but until now wind power is still rarely used as an energy source. The potential of wind energy sources is quite large and the national target for installing wind energy power plants has not been achieved [1]. The potential for wind flow in Indonesia with an average speed of between 9 m/s to 12 m/s is an opportunity to be developed as a wind power plant [2].

The main problem faced in designing a wind turbine from PVC pipe material is that when determining the dimensions of the pipe it does not conflict with the potential wind speed and power designed. The real function of PVC pipes that are popular in the community is to drain liquids. Before this simple technology can be imitated by the community, it is necessary to analyze the working stress that occurs in the pipe propeller turbine construction using CFD simulation, so that the designed wind turbine can function properly before being applied to the community The variable that affects the performance of the wind turbine is wind speed, but very large wind speeds will make the propeller broken and unable to work. Based on this, before designing and building a wind turbine, it is necessary to first consider the potential wind speed at the location where the wind turbine tower will be built [3]. Similar research has been conducted by [4–6] entitled the effect of wind speed to obtain the maximum electrical power efficiency in wind turbines.

Based on **Fig. 1**, it explains that the graph of the relationship between the tip speed ratio (TSR) and the power coefficient (*Cp*) of various types of wind turbines that the propeller type wind turbine has the middle TSR and the high CP. In terms of tip speed ratio (TSR) defined as the relationship of angular velocity in the rotor (ω) divided by the wind speed (*v*), so to get a large tip speed ratio on the propeller wind turbine ω is needed a small value of v. Based on this definition, the TSR value of the propeller turbine is match with plotting area in **Fig. 1**, but it is still possible to increase the power coefficient to be higher. Many studies have been carried out to improve the performance of the propeller wind turbine. Among other things by using PVC pipe as propeller blades, widening blade with flap and installing pipe elbow at the end propeller λ.

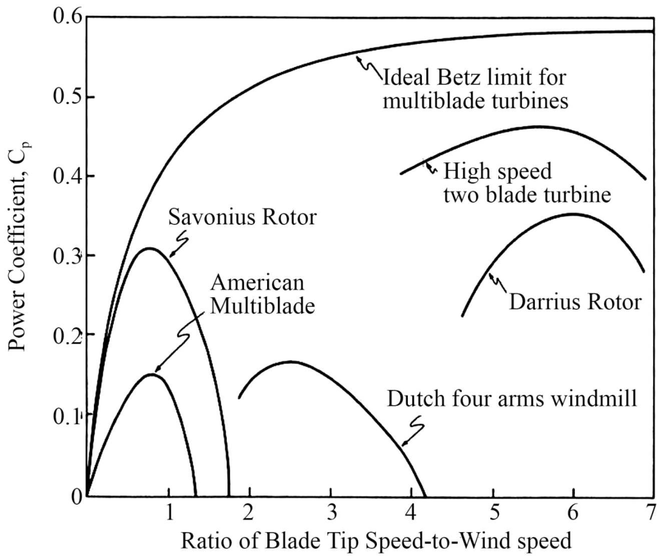


Fig. 1. Relationship between power coefficient (C_p) and Tip Speed Ratio (TSR) [7]

The Betz theorem provides an opportunity for researchers to achieve a maximum wind turbine efficiency of 0.59. Many creations and innovations were created to obtain power coefficients (*Cp*) in operational conditions called Tip Speed Ratio (TSR). TSR is the ratio between the rotational speed of the rotor (*U*) and the mainstream wind speed (*V*), this dimensionless number is more determined by two design factors, namely the shaft rotation design and wind speed at the location of the turbine to be built. The compromise of these two factors will lead to the TSR value that will be used as a guideline for selecting the type of suitable wind turbine according to the guidelines in **Fig. 1**.

TSR is the magic number which most simply describes of a wind turbine rotor type selection. It is how many times faster the rotation than the wind speed on the blade tip. A wind turbine rotor does not simply have a best rotational speed (e.g. 750 rpm), but optimum rpm will depend on the wind speed, the diameter and the TSR. The wind turbine rotor will do best performance at a particular TSR, but it will inevitably have to work over a range of speeds. The power coefficient 'CP' will vary depending on TSR, for any particular rotor design. The turbine performance will be best at rated TSR but acceptable over a range of speeds. In regards of dimensional value, the torque or power coefficient vs TSR curves should always maintain the same shape and trend [8].

Based on **Fig. 2** above described the power coefficient of a typical rotor designed to operate at a TSR of 7.34 by using Maximum Power Point Tracker (MPPT). A small shift in rpm or wind speed will not make much difference. But, if the rpm is too low compared to the wind, then it will be stall (fall), and performance will drop. If there is no load on the rotor (maybe because a wire broken in the electrical circuit) the rotor will over-speed until it reaches a certain point, where it becomes so inefficient that it has no power to go faster, most wind turbine will be quite noisy and alarming at runaway tip speed.

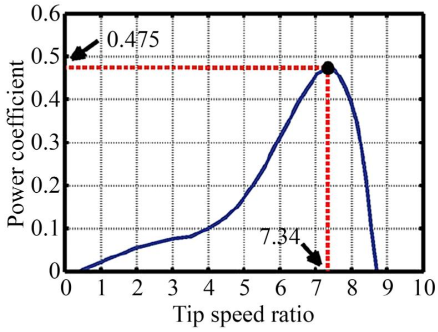


Fig. 2. The coefficient of power (CP) wind turbine as function of Tip Speed Ratio (TSR) [7, 8]

According Betz theorem that remaining wind energy is 0.59 power coefficient (CP), added losses due to drag 10 % become 0.53 CP and losses due to resistance and rectifier on generator will lose about 20 % become 0.42 CP. Then what steps must be taken to try and fill this gap and improve this situation be the best efficient. Whereas to achieve more than 0.42 CP is an extraordinary effort of this research.

Aerodynamic design principles for wind turbine blades must take into account the careful blade design, airfoil selection, and optimal angle of attack. The aerodynamic performance of horizontal axis wind turbines is highly dependent on many parameters, including airfoil type and blade geometry [9]. The method used to optimize the geometry of small wind turbine blades is obtained from a spiral split circular pipe with an optimal distribution and airfoil sweep can be obtained with the right cutting path. The geometry of the blade is obtained by folding the shape of the blade surface into the pipe, it is very difficult to describe the shape of the blade in the pipe. Moreover, the surface is located in three-dimensional space. In **Fig. 3, *a*** there are three sections of the blade (tip, hub, and intermediate) and their relative positions on the longitudinal axis of the blade [10].

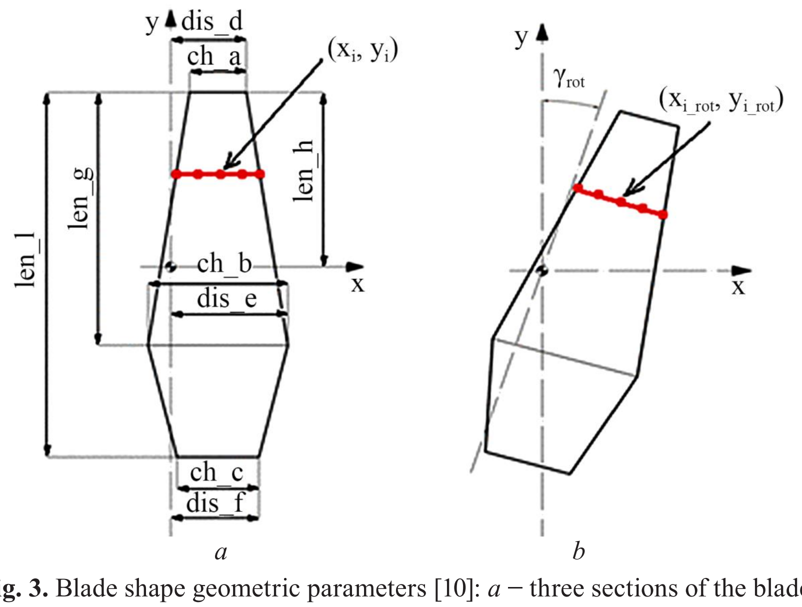


Fig. 3. Blade shape geometric parameters [10]: *a* – three sections of the blade; *b* – rotated blade respect to the origin of the axis

The geometry of the blade is obtained by folding the shape of the blade surface into the pipe, it is very difficult to describe the shape of the blade in the pipe. Moreover, the surface is located in three-dimensional space. The shape of the surface parameters shown in **Fig. 3, *a*, *b*** are the three sections of the blade and their relative positions on the longitudinal axis of the blade. The shape of the blade surface can also be rotated with respect to the origin of the axis (x, y, z) from the angle γ_{rot}, can be seen in **Fig. 3**.

Although the measurement data (experiment-based) is able to provide precise information on the proper wind turbine performance parameters of the flow around the blade, the development of more effective designs is still going to be a slow process based on trial and error. Various Computational Fluid Dynamic (CFD) techniques have been used to predict the field flow around wind turbine blades and their efficiency [11]. Hence to overcome the limitations of the experimental methodology, this study used CFD simulations to investigate the aerodynamics of the flow field around the blade.

Understanding the aerodynamics of the blade airfoil is an important ingredient for improving the physical characteristics needed to calculate the aerodynamics of the entire rotor [12]. The development of methodologies and techniques for modeling the interaction between realistic wind loads and component construction is the most desirable way to improve designs that will be better in complex operational environments covering the fields of aerodynamics, elasticity, and wind simulation [13].

Although measurement data (experiments) are able to provide precise and good wind turbine performance parameters on the flow around the blades, usually the development of more effective designs remains a slow process on a trial and error basis. Various Computational Fluid Dynamic (CFD) techniques have been used to predict the field flow around the wind turbine blades and their efficiency [14]. Therefore, to overcome the limitations of the experimental methodology, this study uses CFD computational fluid dynamics simulation to investigate the aerodynamics of the flow field around the blade.

To estimate wind turbine efficiency and fluid flow behavior, usually an accurate analysis of the flow field at the turbine blade is required to predict aerodynamic performance [15]. Computational Fluid Dynamic (CFD) is a calculation for analyzing fluids with various treatments, such as fluid flow, heat transfer and wind speed. In this study, testing the horizontal wind turbine simulation using dynamic mesh, the 6-DOF feature in ANSYS Fluent uses object forces and moments to calculate the translational and angular motion of an object's center of gravity.

Based on CFD simulation research on the aerodynamics of the HAWT, it covers most of the aerodynamic predictions of the HAWT which focuses on the airfoil blade, tip shape, blade load, stall dynamics, blade geometry but ignores the tower and nacelle. In most cases, only one blade is included in the calculation which can represent several important effects [16].

In the 6-DOF Dynamic Mesh method, a User Define Function (UDF) is needed to give parameters to the rotor properties. Turbine rotor properties consist of mass and moment of inertia which are parameters of rotor rotational speed, and rotor degrees of freedom which consist of translational and rotational movements about the x, y, z axis [11, 17, 18].

The wind kinetic energy of an object with mass m and velocity v is $E = 0.5 \times m \times v2$, assuming that the velocity v does not approach the speed of light. Since mass can be replaced by air density ρ, area A, and velocity v, it can be written: $m = \rho \cdot A \cdot v$.

The formulation of kinetic energy in a wind turbine is:

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

The mass flow rate equation is:

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

By changing the air mass at (1) with (2), the formulation of the potential power calculated from the wind velocity is:

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

Coefficient of power is ratio output and input:

$$Cp = \frac{Pm}{P_a}. \quad (4)$$

The mechanical power of wind turbine:

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

The tip speed ratio is the ratio of the blade tip tangential speed to the free wind speed. For certain wind speeds, the tip speed ratio will affect the rotation of the rotor. The lift type wind turbine will have a relatively larger tip speed ratio compared to the drag wind turbine [11–13].

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

The maximum power coefficient that can be achieved by the wind turbine according to the Betz limit is 59.26 %. However, in practice the value obtained from the center of the power coefficient is around 45 %. **Fig. 4** is a graph depicting the Betz ideal constant and the actual turbine power coefficient as a function of TSR [11].

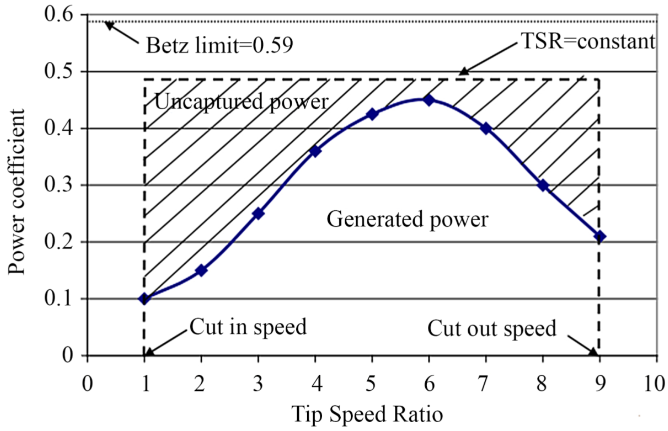


Fig. 4. Wind Turbine performance diagram

The purpose of this research is to develop a wind turbine propeller blade design made of PVC pipe in order to obtain a better performance. The problem to be solved is how to make a new design with a constant rotor diameter size to produce a larger torque. The solution to this problem is by adding a pipe bend component made of PVC 90° standard elbow which is sliced with a certain width. The addition of this pipe elbow wedge on the outer radius will produce a tangential force which is able to increase torque. Further research can be applied on a prototype scale with actual boundary conditions at the wind farm location.

2. Materials and methods

This research was conducted using two methods, namely experimental tests in wind tunnels and CFD simulations, from both methods obtained data and the influence value (P-value) of wind speed and angle of attack on wind turbine shaft torque. Experimental testing was carried out in a wind tunnel laboratory with a pipe propeller wind turbine using an elbow tip as a model test as shown in **Fig. 5**. However, the torque results from wind tunnel testing are not from direct measurements but from the calculation of the electrical power output divided by the radial speed of the tachometer. Whereas CFD simulation can obtain the torque by using AnSys R19 software. Both torque from experimental and simulation was compared using speed variable or TSR.

The method used in this study is a numerical method. Numerical models are made according to field conditions or actual conditions. The numerical method used is based on computational fluid dynamics (CFD), where the airfoil used is designed become a blade that is used to become single rotor reference. Then the result of The design is simulated and the result will be validated with experimental results using a wind tunnel referring to the report of Bartl and Sætran experiments using 4 blades obtained $CP_{max} = 0.468$ at TSR = 6 with wind speed 11.5 m/s (rotor rotation 1395 rpm) [19].

The next step is to create a computing domain model. The numerical model used is a model with only 1/3 of the domain using the assumption of periodicity on cross-section of the interface with defines as periodic then the numerical model is rotated 120° for 1/3 domain solution with condition limit.

Fig. 5. The PVC pipe propeller wind turbine using Elbow Tip on position wind tunnel testing

For the single-rotor simulation stage, using FLUENT ANSYS software, where the solver used is pressure-based with absolute velocity formulation, pressure-velocity solution scheme coupling used coupled algorithm. While the iteration procedure, solution method solving the pressure equation using second order, then equation momentum and turbulence using schema QUICK, which corresponds to the mesh type i.e. hexahedral so the calculation accuracy to be better. For the volume equation set using the continuity equation and Translated Navier-Stokes equation in rotational form, so it has advantages in making simulations where no need for deep moving mesh take into account blade rotation with moving reference frames (MRF), assuming periodicity in cross-sectional interface by defining as linked face for periodic. In the validation stage of the single-rotor simulation based on the performance of the rotor blade by displaying the power coefficient parameter. Using the momentum theory, obtained the calculation of the turbine power coefficient (*Cp*) which is the result of the division between mechanical power generated by the rotor turbine (*Pout*) with total power in wind flow (*Pin*) for the obtained rotor sweep area, *Q* obtained from the simulation results. This analysis obtained from the following equation (4) above. The realizable $k-\varepsilon$ turbulence model used in this study to improve the calculation of the flow. The enhanced wall treatment allows a smoother calculation within the wall layers.

Blade of propeller made by PVC pipe are slice half and twist from hub until tip with 90 degree of rotation. Dimension of width blade wider on the hub (3/4 of circular) and smaller on the tip (1/7 of circular). Face of blade on the hub side facing wind direction (axial) and face of blade on the tip side facing tangential direction or opposite with rotation. On the tip side installed the slice elbow with fit tip blade width. The propeller using PVC pipe with elbow tip is the important part of our claim novelty has been test with CFD simulation and wind tunnel research with best result performance. The cross section of blade segment on the hub side was formed to become like hook with adjustable angle of attack on the straight side of segment. This turbine propeller arranged with four blade using PVC pipe material.

The idea of developing the shape of the pipe propeller wind turbine using elbow tip was inspired by momentum change phenomena when fluid flow through the pipe elbow could producing drag forces. The elbow tip as shown in **Fig. 5**, **6** are made of elbow pipe PVC that are assembled on the end of propeller. The radial wind flow on inside wall pipe propeller and the wind flow from mainstream will attack the elbow tip resulting additional force due to change momentum.

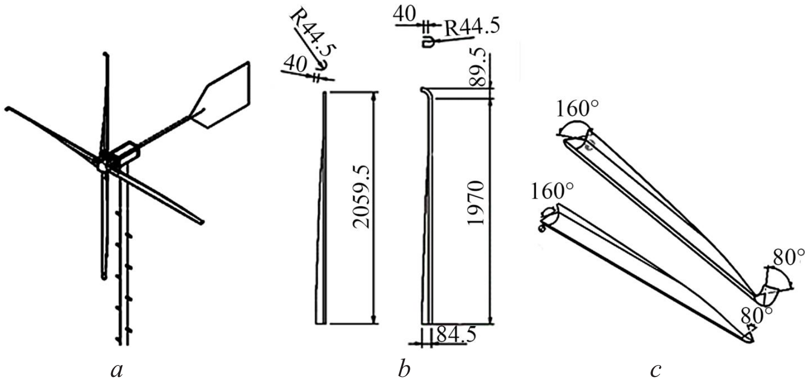


Fig. 6. The PVC pipe propeller wind turbine model: *a* – Wind turbine installation; *b* – Elbow Tip and without Elbow Tip front view; *c* – Elbow Tip and without Elbow Tip isometric view

DOE (design of experiment) is comprised of statistical and mathematical techniques for optimization process development and improvement, which utilizes the experiement design, regression analysis, and variance analysis. In this case, the response variable Torque «T» (y) is affected by two independent variables: Angle of attack «α» or (x_1) and wind speed «V» or (x_2). The significance effect of those independent variables (x_1, x_2) that lead to maximum torque (and working stress) can be obtained from an appropriate model formulation. Variance and regression analyses can be used to estimate regression coefficients in the quadratic polynomial model and to generate an uncertainty measure in the coefficients [20].

3. Results and discussion

The geometry design of the propeller pipe wind turbine was tested using CFD simulations to produce data to be analyzed using Minitab 19 software. This simulation study analysis method used the Regression and ANOVA. It has two independent variables consisting of wind speed and angle of attack. Likewise, the aerodynamic study of turbine performance also uses variable wind speed and angle of attack. With the DOE method, it can be seen the effect of the independent variable on the dependent variable, as well as the effect of the interaction between the two independent variables on the dependent variable is the turbine power torque (T).

Fig. 7 shows the position of the maximum torque affected by the angle of attack and wind speed at a plot position between 15–30 degrees. While the results of the DoE factorial analysis according to the ANOVA table and the coefficients of the regression equation show that the angle of attack variable is 15° and 3° at a wind speed of 7 m/s which contributes to producing quite a large torque. The determinant coefficient (R^2) in the regression equation model is able to explain 99.9 % suitability, which means this simulation test has high fidelity criteria.

Fig. 10 shows an increase in torque of 200 % after the tip of the propeller blade is equipped with an elbow tip at speeds of 5 m/s to 7 m/s using α = 15° and α = 30°. While the use of α = 45° does not produce a significant increase in torque value at a speed of 7 m/s. The innovation of adding an elbow tip to the outer radius of the propeller blade creates stagnation of flow on the concave side of the elbow pipe surface causing a momentum change phenomenon. The momentum force generated at the elbow tip as shown in **Fig. 8** is a novelty in the design of a horizontal turbine propeller pipe that can be used as a reference to increase turbine torque in the category of simple applied technology. It can be seen in **Fig. 8** that the pressure escalation centered on the elbow tip zone is able to increase the torque up to 200 % compared to the propeller blade without the elbow tip as shown in

Torque Radar Chart (**Fig. 9, *a*, *b***). While in **Fig. 9, *c***, it can be seen that at α = 45° and wind speed of 7 m/s the propeller blade cannot optimally produce a change in momentum at the elbow tip. In this condition, the torque value is almost the same for both the PVC propeller pipe using the elbow tip and without the elbow tip. In addition, at α = 45° the blade projection swap area is too large in the hub zone so that producing drag forces opposite with momentum forces at the elbow tip, in this condition causes the torque become low. **Fig. 10** illustrations the behavior of fluid flow around the propeller hub shows the occurrence of a vortex at a wind speed of 7 m/s causing the flow to spread and not focus into the concave wall of the PVC pipe that leads radially to the elbow tip through the surface of pipe in order producing momentum forces. The elbow tip zone has a less pressure impact that reduce the torque of the blade.

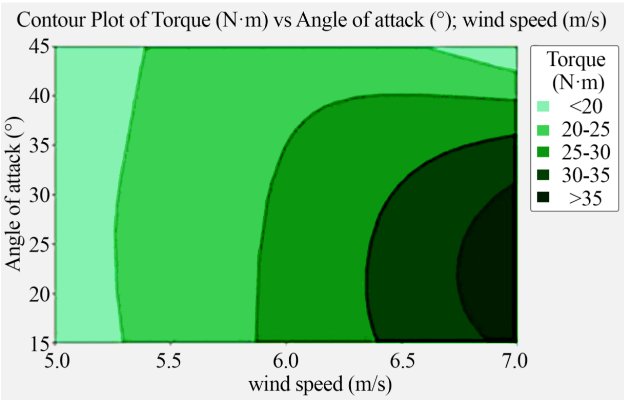


Fig. 7. Contour plot of Torque versus Angle of attack (α) and wind speed (v)

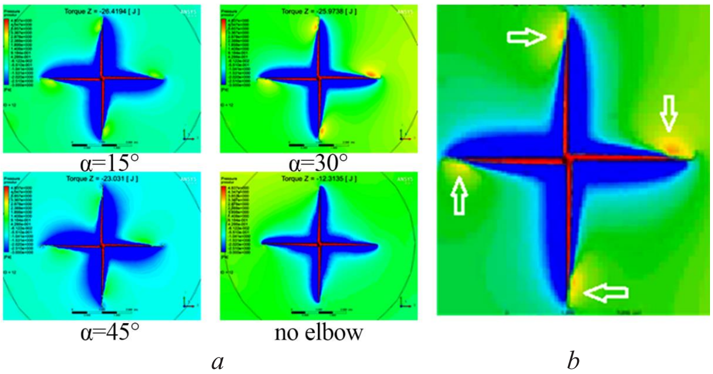
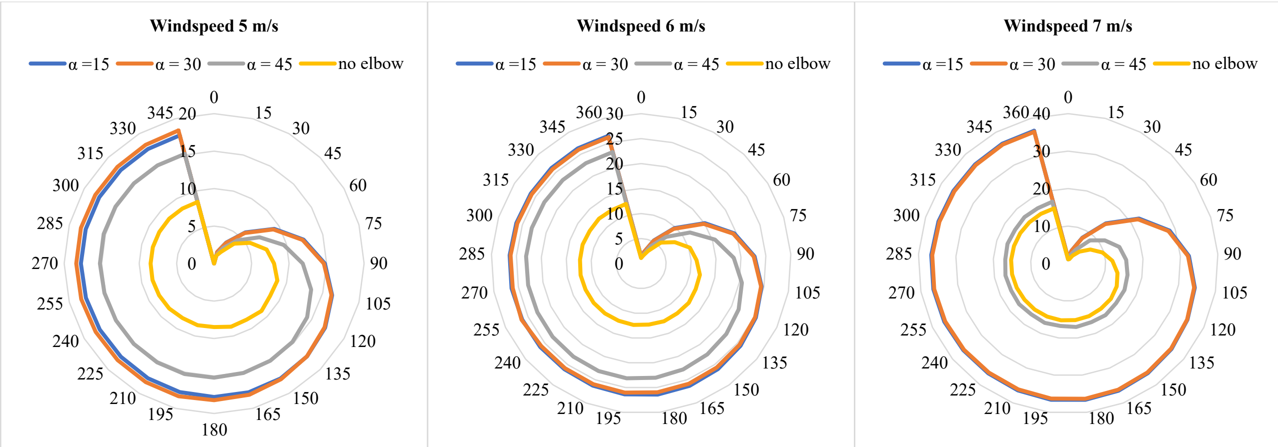


Fig. 8. Momentum Forces due to stagnant flow on the elbow tip in outer radius of propeller with any set condition: *a* – angle of attack of α = 15°, α = 30°, α = 45°, and no elbow; *b* – detailed elbow tip effect to create high pressure

By using PVC pipe material to build propeller wind turbines has proven to be quite strong in simulation test with Solidwork software and experimental testing in wind tunnel laboratories up to speed 8 m/s [20]. Using material PVC to build Propeller turbine has benefit and easy copied by using readily available material in store which is feasible and affordable to applied as simple technology. Based on experimentally researched Vicky and Kamdi also using PVC blade has much better power capacity which at low wind speed can be able to propelled the wind turbine [12, 13].

Generally, HAWT explores lift force only through a certain angle of attack on the blade flap, while this new pipe propeller turbine is equipped with an elbow at the outer radius of the pipe blade which has a concave surface facing the direction of the wind which able to generate both drag force and also lift force to increase turbine torque. The innovation of adding an elbow tip to the HAWT pipe propeller is a solution as well as a novelty in this research. The results of this study can be applied to the general public who want to develop this new HAWT PVC pipe propeller design because it is easy to get these materials at building stores.



a *b* *c*

Fig. 9. Torque Radar Chart using variable of wind speed (v) and Angle of Attack (α): *a* – wind speed of 5 m/s; *b* – wind speed of 6 m/s; *c* – wind speed of 7 m/s

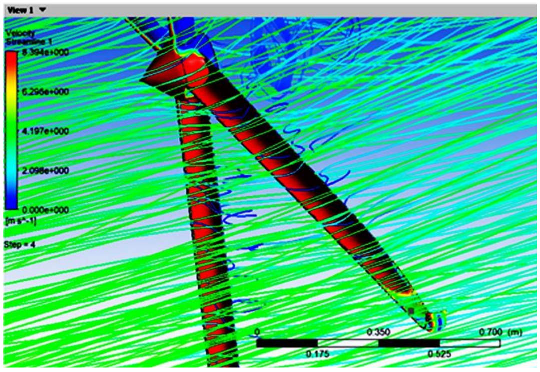


Fig. 10. Stream line at wind speed 7 m/s and 45° angle of attack shows creating the vortex around hub region cause decreasing torque

4. Conclusions

The conclusion of this research is that addition elbow tip at the end of outer radius PVC Pipe Horizontal Axis Wind Turbine Propeller with using 15° and 30° angle of attack could increasing torque about 200 % than without the elbow tip. But using 45° angle of attack although additional with elbow tip at the end of outer radius propeller could not effectively increasing the torque although the wind speed reached on 7 m/s.

The innovation of adding an elbow tip to the outer radius of the propeller blade able to create stagnation of flow on the concave side of the elbow pipe surface creating a momentum change phenomenon. Creating new model propeller blade using PVC pipe with elbow tip is a novelty in the design of a horizontal wind turbine that can be used as a reference to increase turbine torque in the category of simple applied technology.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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