Aerodynamic Performance Analysis of Vertical Axis Wind Turbine (VAWT) Darrieus Type H-Rotor using Computational Fluid Dynamics (CFD) Approach

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Abstract: The recent renewable energy grows significantly concerning on people awareness of the negative effect toward environment. Based on the advantages that should be offer by Vertical Axis Wind Turbine (VAWT) becomes an interested object to be observed. Especially VAWT Darrieus, H-Rotor type. Not only known has simple structure but also has higher efficiency than Savonius. Airfoil Profile becomes substantial because its aerodynamic effects which run on the Darigus turbine. Numerous previous studies observed that the use of asymmetric airfoil gives advantage toward Darrieus turbine efficiency. In this case, this research focuses on the influence of cambered airfoil toward the maximum position to the turbine performance. The Investigation is observed using Computational Fluid Dynamic (CFD) which is two dimensions Darrieus turbine type H-Rotor turbine model is simulated in transients current condition. In result, the simulation as power coefficient presented the best turbine performance is conducted by airfoil with the maximum camber position close to the trailing edge. While the variation on the chord length gives a solidity ratio of 0.6 as the best value between the above and below.

1 INTRODUCTION

Globalisation now days demanded by hygienic availability and low-cost resource. Therefore, regarding human awareness about the negative impact of conservative energy resource caused renewable technology conversion become vital. In this case, Wind Energy Conversion System (WECS) is the most built and developed. The furthermost WECS technology is Horizontal Axis Wind Turbine (HAWT). It has higher efficiency than the other kind of Vertical Axis Wind Turbine (VAWT). Even though, it offer another advantage such as the simplest structure. Moreover, VAWT able to run at any course of the wind and to provide another benefit such a minimum noise, stable in wind turbulence condition, integrate with another building and give easiness in its generator, gearbox and bearing application (Ahmadi-Baloutaki, 2015).

There are two differences major in VAWT implementation, those are: Saviours which is the interaction of the wind turbine utilizing drag force and Darrieus which is using lift force of aerodynamic effect, the second VAWT is the common one to use as wind turbine electricity (Manwell et al., 2010). Which is in this case blade design is important to gain the effect of aerodynamic due to airfoil design. Airfoil is particular form of geometry design to gain lift force and to minimize increasing drag force.

In fluid currency, airfoil lift force is occurred because the differences of upper and lower surface pressure. It caused by angle of attack and camber (**?**). Airfoil symmetry often used in darrieus turbine to minimize the negative torque during single rotor rotation. The other hand, airfoil with camber increasing the lift force at the zero attack angle and functioning at higher maximum torque, but at the second half of rotation it always occurred negative torque. According to the study by Sengupta et al. (2016), Bausas and Danao (2015), asymmetrical airfoil is giving the improvement to the whole of rotor performance. Qamar and Janajreh (2017) researched the rotor performance with NACA 4512 and NACA 7512 asymmetrical airfoil. The result is airfoil with moderate camber has better performance.

The purpose of this research is to identify the influence of maximum camber at 4 digit NACA conventional airfoil. The chosen type of airfoil is NACA 4312, 4512 dan 4712 which is the second digit of vari-

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ation delivers the maximum camber's value toward chord line airfoil. The best performing airfoil will be further investigated to see the effects of the variation of solidity ratio. Computational Fluid Dynamic (CFD) two dimensions method is used to obtain the optimal coefficient power value.

2 BASIC THEORY

2.1 Wind Energy

Energy inside of wind stream is a kinetic energy. This energy is converted to mechanic energy in wind turbine system. Kinetic energy at a certain wind mass (m) which moving at (u) speed can be identified as equation below:

$$E = \frac{1}{2}mu^2 \quad (1)$$

If the turbine cross section area is A, where the air passes through it at the velocity u, then there is a displacement of volume V per time unit, therefore:

$$V = uA \quad (2)$$

Meanwhile, mass current at ρ air density clarified in below equation:

$$m = \rho uA \quad (3)$$

Energy which contained in wind P can be identified as substitute Equation 3 to Equation 1 as turn out to be this equation :

$$m = \rho uA \quad (4)$$

As P is power that contained in the wind, u is wind speed and air density ρ. The amount of air density on sea surface is 1.225 kg/m^3.

2.2 Tip Speed Ratio

Tip Speed Ratio (γ) is comparison between tip blade speed and wind speed that get through it (Hemami, 2005).

$$\gamma = \frac{\omega R}{u} \quad (5)$$

Which is ω as the rotation speed of turbine, R is the length of the turbine radius.

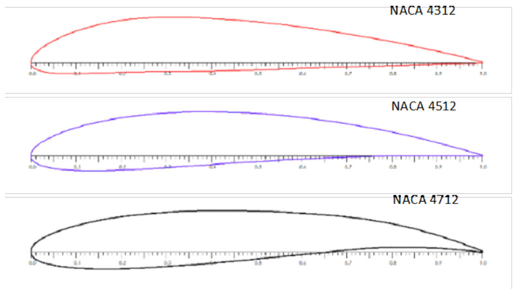

Figure 1: Airfoil NACA 4312, 4512 and 4712

2.3 Power Coefficient

The capability of wind turbine to convert wind energy to mechanic energy called coefficient power (Cp) that written as equation below:

$$Cp = \frac{Pmechanic}{Pwind} \quad (6)$$

$$Cp = \frac{\omega T}{\frac{1}{2}\rho Au^3} \quad (7)$$

P mechanic is mechanic power and P wind is wind power. Meanwhile T is torque which consist at coefficient equation moment (Cm):

$$Cm = \frac{T}{\frac{1}{2}\rho ARu^2} \quad (8)$$

3 RESEARCH METODOLOGY

3.1 Examine Variable

The purpose of this research is to analyse the characteristic of VAWT 3 blades that use 4 digit NACA airfoil. First digit showing maximum camber. Second digit showing the position of maximum camber according the leading edge. Last two digits showing maximum thickness of the airfoil. Those parameters will be examined is the maximum position of camber on the airfoil of NACA 4312, 4512 and 4712 as show in the figures below:

The tree airfoils have the same maximum thickness and the same maximum camber value, each represented by the first digit and the last two digits in the four number digit code of NACA airfoil. This aim is to obtain the lift coefficient (C_l) which does not have a significant difference between the examined of three airfoils. So, the overall rotor performance can be analyzed from the effect of the camber position. The

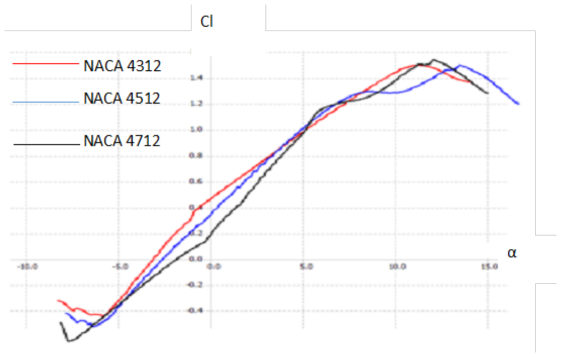

Figure 2: Curve of Cl vs Alpha for Airfoil NACA 4312, 4512, 4712

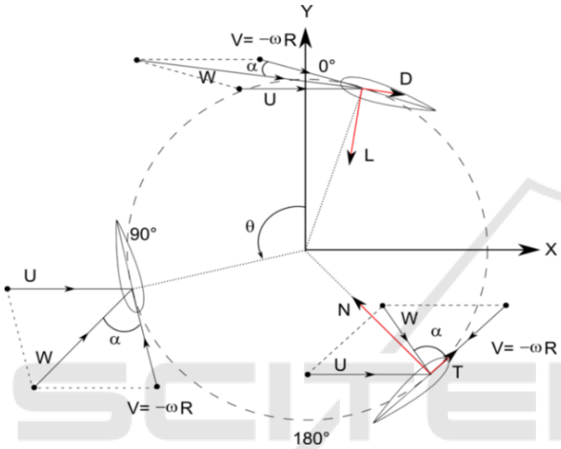

Figure 3: Aerodynamic force on Darrieus turbine

polar simulation of the three airfoils has been simulated using QBlade software. This software is integrated with the XFOIL, the program used to simulate the subsonic flow around airfoil and may be able to predict the performance of airfoil till the last second before stall (Marten and Wendler, 2013). This simulation comes with the result of C_l with the variation of angel of attack (α), as shows in the Figure 2.

3.2 Geomatry Model

The aim of this research is to analyse Darrieus wind turbine Straight Bladed with the 3 blades. The aerodynamics force of this turbine may be seen in the Figure 3

The geometry created must be represented the physical problems, therefore it is important to compare the result of the model with the experimental data. The model which is used as the standard of validation may be seen in the Table 1. Solidity ratio is $\sigma = Nc/R$ with the maximum value 0.5 based on the recommendation of Ahmadi-Baloutaki (2015). The initial Azimuthal position is accounted from angular

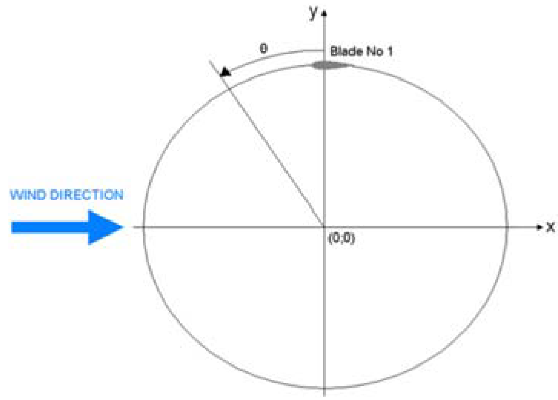

Figure 4: Azimuthal coordinate of blade number 1 [9]

Table 1: Dimension of validation model [9-10].

D_{rotor}[mm]	1030
H_{rotor}[mm]	1414
n [-]	3
Profil Airfoil	NACA 0021
As [m2]	1.45642
Chord lengh (c) [mm]	85.8
σ [-]	0.5

coordinate of the first blade, in the half of chord to be exact. The motion of positive azimuthal is obtained since the blades start to move counter clockwise, as show in the Figure 4 below :

3.3 Numerical Model

C-shape Domain is chosen to modeled the computational domain. The boundary condition and the size is defined based on Figure 5 where as the red colour is inlet, blue is outlet, black is the symmetry, green is the rotor, the purple is the stationary area or silent area. The orange is blade area, this motion is based on the rotor motion and the last is gray which is as the airfoil.

After creating the geometry, mesh and determina-

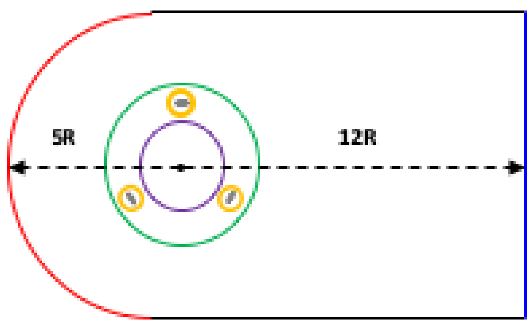

Figure 5: Boundary layers set up

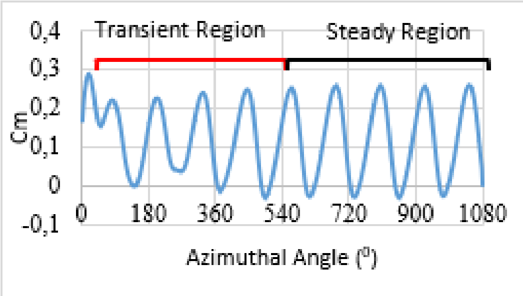

Figure 6: The moment coefficient curve (Cm) as a function of azimuth angle (θ)

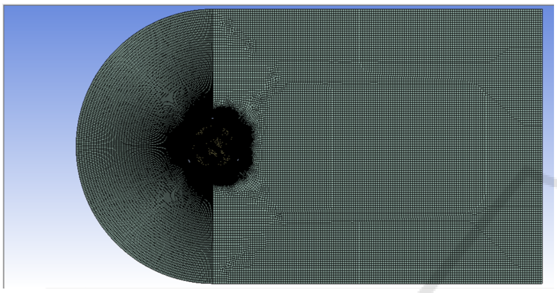

Figure 7: Mesh discretization of whole domain

tion of the boundary condition, the next step is to create the certain parameter. To obtain the result of each tip speed ratio (TSR), the variation of angular is given with the constant wind velocity at 9 m/s. Computation is done in each 20 of rotor rotation. The total rotation of rotor is simulated as 10800 or 3 full circle. Moment coefficient (*Cm*) gains from the overall value of moment in last rotation of 3600. This case is done to gain the stable result as shown in the Figure 6. Simulation has been calculated using ANSYS Fluent software in transient flow conditions. Sliding mesh technique is used to modeled a rotating turbine. The realizable K-ε turbulence model has been applied to the solver setup. Convergency is set with overall equation 10-4 and maximum of iteration is 80.

3.4 Discretization of Numerical Model

The meshing strategy is created base on existent domain, which is the area has direct attraction to the airfoil must be gained the detail mesh. In this model the mesh is resulted around 140.000 cell. Samples of 2D mesh discretization of tested models shown in Figure 7 and Figure 8.

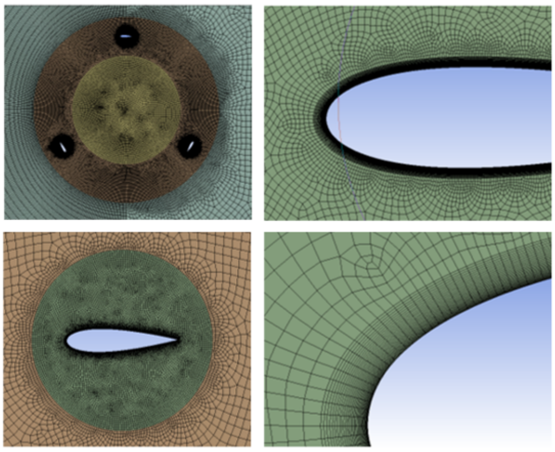

Figure 8: Mesh discretization of rotational domain and airfoil

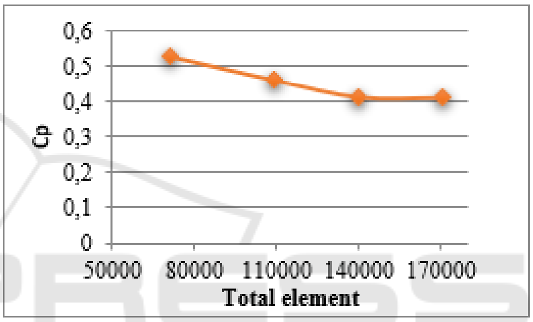

Figure 9: The coefecient power (Cp) as a function of total mesh

4 RESULT AND DISCUSSION

4.1 Study of Mesh Sensitivity

The strategy in making mesh is one of important point in CFD simulation. Generally the more finer of mesh, the result will be gained will be better. Somehow the time consuming of the simulation will be longer. In this study, the simulation based on validation model with TSR = 3.3 where the *Cp* result from the experimental data is compared with simulation result. The amount of the mesh for the first simulation is 80.000 cell, then it increases by 30.000 cell. The result of 170.000 cell is still in enhancement, but the result of 140000 simulation sel and 170000 only have small different. The result of mesh sensitivity study is in the Figure 9.

4.2 Validation

The present CFD simulation is proven to be able to show the same behaviour compared to experimental

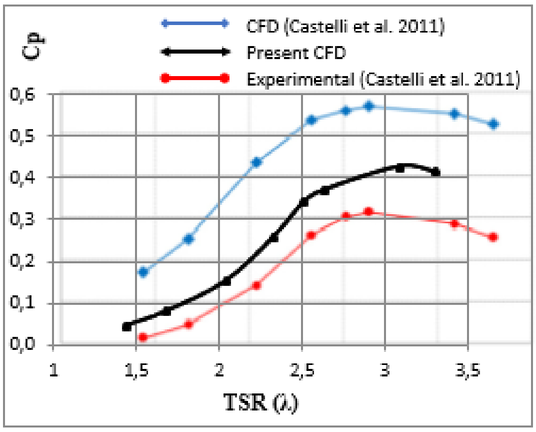

Figure 10: Validation CFD model to be compared with experimental and the previous CFD data (Raciti Castelli et al., 2011)

data. Even CFD simulation shows a little higher result, this is because of 2-Dimension that is used by the CFD, where the effect of 3D such as vortex interaction and tip vortice which influence tip loses cannot be catch by 2D model (Subramanian et al., 2017).

In 2D the influence of singularity (source or vortex) only around cross each segment. However, in the 3-Dimension modelling which is used singularity distribution (source or vortex) in panel. Therefore, the influence is not only happen between the panel but also it happens in all sides of panel. Trough this effect it influence the result of modelling (Chan, 1990).

4.3 Effect of Airfoil Variation

The simulation result as coefficient moment counted as equation 5, 7 and 8 to gain the result of the power coefficient as the representation of Darrieus rotor performance. For every rotor within differences of airfoil profile is simulated in each Tip Speed Ratio (TSR). Here are the chosen TSR: 2; 3; 3.5; 4 and 5. The dimension and the size of the rotor are keep using model validation data as Table 1.

CFD simulation shows various of Darrieus curve performance at lower TSR. But, on the upper TSR 4 mostly has the same result. Figure 11 shows that the airfoil profile of NACA 4712 has the higher maximum result of coefficient power than another profile.

Interstingly, the NACA 4712 airfoil also has the widest curve, which means the best operating range. The profile of NACA 4312 has the lower performance. Whereas, the NACA 4512 with the maximum camber position in the middle of the airfoil coincidentally gives a symmetrical *Cp*-TSR curve. The Maximum *Cp* is at TSR 3.5 with an almost equal gradient rise and drop curve. Those three examined air-

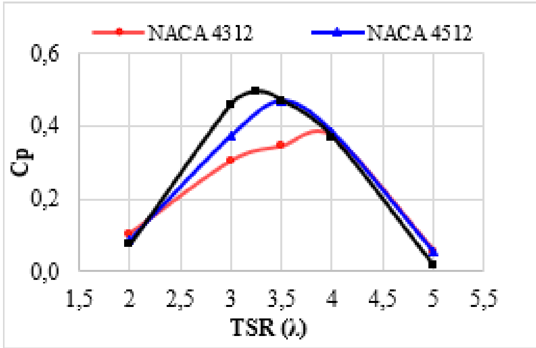

Figure 11: Cp vs TSR Curve at arotor Darrieus with airfoil variation

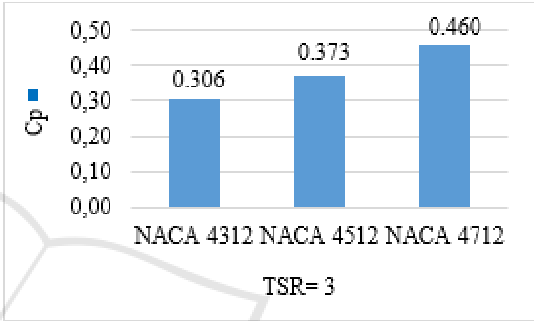

Figure 12: Maximum Cp for each airfoil

foils have the same power coefficient values at TSR 4, whereas the differences are contrasting at *Cp* values seen in TSR 3. Based on the results showed clearly the position of camber gave the significant change toward the whole Darrieus rotor performance.

By shifting the camber's position toward the trailing edge then the maximum *Cp* is increased and the TSR operation ranged becomes wider. Figure 12 showed the maximum value of *Cp* for each airfoil profile, while, each values of *Cp* airfoil through TSR 3 is showed in Figure 13.

Further review were held on TSR 3 in it compared the instantaneous of coefficient moment through az-

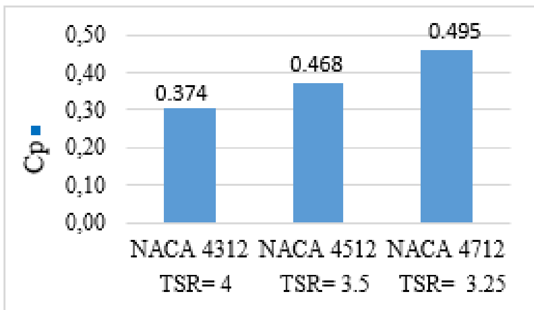

Figure 13: Cp for each airfoil on TSR=3

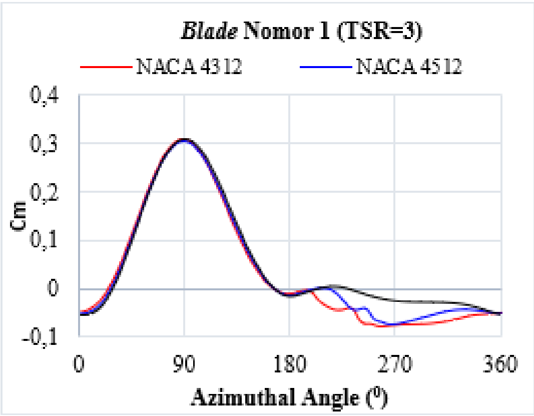

Figure 14: Cm vs Azimuthal angle for NACA 4312, 4512 and 4712 (TSR= 3)

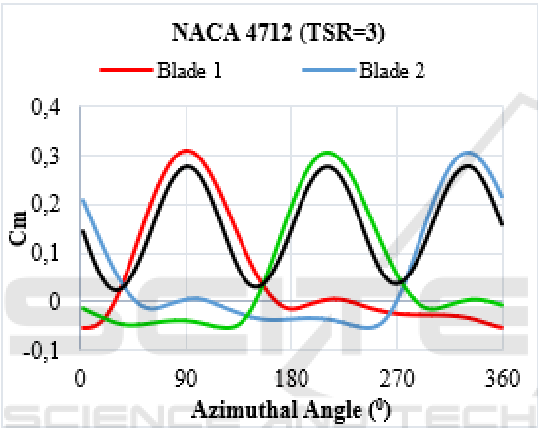

Figure 15: Moment coefficient of NACA 4712 at TSR= 3 on all blade

imuthal angle on blade 1 as showed in Figure 14. The *Cm* has almost the same value while the three kinds of airfoils leading the first half of the rotation. But, while the second half rotation; the negative variation moment significantly occurred. Which blade profile of NACA 4312 produced the highest negative moment. Whereas, the smallest is NACA 4712. Although the second half of the azimuthal angle position always generates a negative torque, however the impact of 3 blades as a whole always generates positive torque as shown in Figure 15.

4.4 Effect of Solidity Ratio

In the previous section it was found that the NACA 4712 profile has many advantages than another tested profile. So, those profile is simulated with chord length variations. Based on this variation, the value of solidity ratio (σ) also changed. This ratio is determined by the number of blades (n), chord length (c)

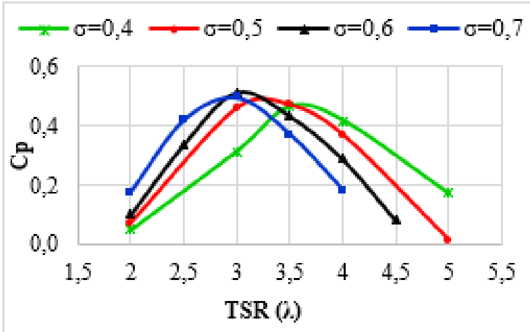

Figure 16: Cp vs TSR for each σ

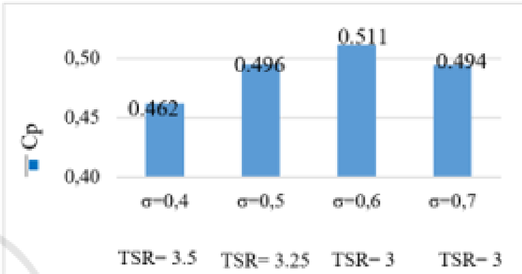

Figure 17: Maximum Cp with variation σ

and radius length (R) with the following equation:

$$\sigma = \frac{nc}{R} \tag{9}$$

The examined solidity ratio is in the range of values 0.4 to 0.7. The simulation result curve of Cp-TSR is showed in Figure 16.

The simulation results show that the maximum Cp value of 0.511 is owned by VAWT for a solidity ratio of 0.6. Whereas, the Cp-TSR curve with solidity ratio upper and lower of 0.6 has smaller Cp value. The difference in solidity ratio also has an effect on turbine range operation. Where, a high solidity has Cp value at a low TSR range. While the solidity decreasing the Cp-TSR curve shifted to the right. This case also worked on the maximum value of the Cp. Which is the solidity ratio 0.7 has maximum Cp in TSR = 3. Within, if the solidity ratio is reduced, the Cp maximum will also move to higher TSR. More details are presented in Figure 17 below.

4.5 Conclusion and Suggestion

Numerical analysis with 2-Dimensional Computational Fluid Dynamic (CFD) approach have been used in this research. The result has been taken is quite valid to know the characteristics of Vertical Axis Wind Turbine, Darrieus type, even though the results are slightly larger than experimental data.

The simulation results on the airfoil asymmetrical variation gave the significant differences in Darrieus rotor performance. To bring the maximum camber position to trailing edge then the Cp maximum is increased. The examined airfoil profile NACA 4712 gave the best result and the highest maximum Cp result as best result is 0.495 toward TSR 3.25.

The result of Cp-TSR curve shape also has the best result; because the wide curve means have good operation of the speed range. The worst rotor showed by NACA 4312. The investigation on TSR 3 has shown that the examined variation performance of three airfoils is spread caused by the difference of negative value as long as half second of azimuth angle position. While the variation of solidity ratio by changing the chord length found that the maximum value of the highest Cp obtained in solidity ratio 0.6 is by value 0.51.

The maximum camber position change has been shown to provide improved aerodynamic performance. The changeover of Cp-TSR curve looked consistent and united. The variable of this work is eligible for the further research combining with other related variable.

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