Effects of Solidity on Aerodynamic Performance of H-Type Vertical Axis Wind Turbine

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Abstract. In order to study the effects of solidity on aerodynamic performance of H-type vertical axis wind turbine (H-VAWT), the mechanical model of H-VAWT was established, numerical investigations were implemented for the different solidity by changing the radius, chord length and blade number. As the result shows, the H-VAWT with a lower solidity will obtain the maximum $C_p$ at a high tip speed ratio and the maximum value will be larger, while the H-VAWT with a higher solidity has better starting performance but the value of $C_p$ is smaller. For small H-VAWT, the suitable solidity range is 0.2~1.28; for large H-VAWT, the suitable solidity range is 0.2~0.6. The effects of changing the radius and blade number on aerodynamic performance are almost the same, the effect of changing the chord length on aerodynamic performance is different from the above two methods and the value of $C_p$ increases with the increase of the solidity. Changing the chord length can increase the peak value of wind energy utilization rate, while the increase of the blade number will reduce the peak value of wind energy utilization rate.

1. Introduction

Energy is a base of social economic development, is the driving force for the progress of economic social, and is closely related to human life and living environment. Coal, oil, natural gas and other fossil energy lasted for nearly 200 years of the 19th and 20th century to the progress and development of human civilization. Wind energy is a kind of clean and renewable energy, its application is more and more mature. Although, compared to the Horizontal Axis Wind Turbine (HAWT), the wind energy utilization coefficient of the Vertical Axis Wind Turbine which converts wind energy into electrical energy (VAWT) is a bit low, but the VAWT, especially H-VAWT (Straight Bladed Vertical Axis Wind Turbine), received extensive attention and high value of the researchers from all over the world and became a research hotspot in the field of wind power development, which because of its rotor rotation has nothing to do with the wind, small vibration, low noise, good environment, high safety, simple structure, easy installation and maintenance and so on. Utilization rate of wind energy is the important index to judge the aerodynamic performance of wind turbine, and the solidity is closely related to the utilization rate of wind power, so the design of solidity is important. Many scholars abroad have carried on the thorough research: Shengmao Li and Yan Li, by changing the NACA0012 and NACA0018 blade chord length and blade number of H-VAWT, and concluded that the maximum power coefficient will be got under low tip speed ratio of high solidity, but the maximum power...
The coefficient will decrease to low solidity of H-VAWT. In the meanwhile, the article points out that even the same solidity, the performance of the H-VAWT will be greatly influenced by different combining forms of the blade number and chord length [1].

In the literature of Jay Paul Wilhelm, he put forward a control strategy which can change the solidity of CC-VAWT, the strategy relies on the wind speed, and the paper points out that there will be 22% of the increase of the power efficiency [2].

Simhan (1985), Kirke and Lazauskas (1985) pointed out that the self-starting of H-VAWT which by reducing the radius instead of increasing the chord length didn't play an improvement role as increasing chord length.

Mojtaba Ahmadi Baloutak and others pointed out that the minimum solidity is 0.1 and the maximum solidity is less than 1 which were an appoint in the design of wind turbine; by contrast analysis, most of the literature agree that H-VAWT has an optimal aerodynamic performance when $0.2 < \sigma < 0.6$ [3].

Although, there were abundant researches on solidity of H-type vertical axis wind turbine, but the results may not be generalizable and there is no overall consideration of blade number, radius and the influence of chord length to wind energy utilization. Based on the CFD numerical simulation, the paper research the relation among the blade number, radius, chord length to the aerodynamic performance of H-type vertical axis wind turbine which under the low tip speed ratio. Furthermore, study the influence of the solidity to wind power utilization, to provide the reference for the design of H type vertical axis wind turbines.

2. The solving methods and geometric model

2.1. The solving methods
There are many methods and theory is used to predict the performance of VAWT and simulate the flow field. Such as momentum theory model, the vortex model, the waterfall model, the panel method and CFD method [4-10]. Biadgo et al. performed the numerical simulation for NACA 0012 VAWT and found that the analytical model, double-multiple stream tube model (DMST), overestimated the maximum power coefficient ($C_p$), compared to CFD results [11]. McLaren et al. developed a URANS (unsteady RANS) model for a high solidity H-type Darrieus VAWT and observed that the maximum thrust occurred at the TSR of 1.6 [12]; the study of Lanzafame explained, for 2D CFD simulation of H-Darrieus VAWT, the transition shear stress transport (SST) turbulence model leads to better agreement with the experimental data than the fully turbulent model [13]. Based on the URANS and $k$-$\omega$ SST turbulence model, H-VAWT unsteady three-dimensional flow field is simulated in this paper by the Ansys-fluent software.

2.2. Geometric model
To compare the calculated results and experimental results, The geometric parameters of three-dimensional physical model for calculation is based on literature [14], namely the airfoil is NACA0015 airfoil, blade chord length is 0.4 m, blade height is 3 m, blades number is three, rotation diameter is 2.5 m, the experiment is in wind tunnel which at the test section of 9 m * 9 m (the wind tunnel, is the National Research Council Canada in Ottawa, Canada's 9 m * 9 m wind tunnel). Figure 1 is the Geometric model and boundary conditions.
2.3. Comparison between CFD and experimental data

In order to verify the accuracy of the numerical results, figure 2 shows the comparison of numerical and experimental results, the horizontal axis represents the tip speed ratio (TSR) $\lambda$, the vertical axis represents the power coefficient $C_p$. Although the comparison of numerical and experimental results has a slight discrepancy, numerical results are significantly consistent with experimental results. Therefore the numerical calculation can investigate the performance of the VAWT.
3. Effect on H–VAWT aerodynamic performance by changing blade number

It can be seen from figure 3 that:

1. Under low tip speed ratio, increased blade number can get higher $C_p$ values, and namely the wind energy conversion rate is higher. Therefore, a higher solidity makes for the wind turbine self-starting under low tip speed ratio. But, the peak value of the higher solidity wind turbine reached under the low tip speed ratio is less than the smaller solidity wind turbine.

2. For the higher solidity H-VAWT, the $C_p$-$\lambda$ curve will have a relatively sharp crest, that is to say, the high efficiency range of the H-VAWT is relatively narrow, which is a significant disadvantage when the wind speed change was bigger.

3. H-VAWT will get better aerodynamic performance when the solidity is between 0.32~1.28; H-VAWT has an optimal aerodynamic performance when $0.2<\sigma<0.6$

4. Effect on H–VAWT aerodynamic performance by changing Chord length or radius

The solidity is determined by three factors: blade number, chord length and rotational radius. For getting a more comprehensive exploration of the influence of solidity on H–VAWT aerodynamic performance, this section calculated the change of solidity by changing other two factors (blade length and rotational radius), and then compared with the results which by changing the blade number, the calculation results are shown in figure 4:
Figure 4. The result of three methods of changing the solidity

It can be seen from the above results that the influence to the wind turbine aerodynamic performance is almost the same by changing the rotational radius and blade number to change solidity. But the result is not the same by changing the chord length to change solidity. The main reason is the Reynolds number is related to the synthetic speed and chord length. In the same solidity and tip speed ratio, changing the chord length will change the local Reynolds number of the blade, while changing the radius and the blade number will not change the blade's Reynolds number. In the case of a high solidity, changing the blade chord length will improve the performance of the wind turbine; in the small solidity, changing the blade chord will make the wind turbine performance decline faster. When the solidity is small, the $C_p$ peak of the H-VAWT obtained by changing the chord length of the blade is smaller than the $C_p$ peak obtained by changing the radius and the blade number, while when the solidity is high, the $C_p$ peak of the H-VAWT obtained by changing the chord length of the blade is larger than the $C_p$ peak obtained by changing the radius and the blade number.

5. Conclusion

(1) To small scale wind turbines, the suitable scope of solidity is 0.2~1.28, to large scale wind turbines, the suitable scope of solidity is 0.2~0.6.

(2) When the solidity is small, the $C_p$ peak of the H-VAWT obtained by changing the chord length of the blade is smaller than the $C_p$ peak obtained by changing the radius and the blade number, this is because the the Reynolds number and the reduction frequency obtained by changing the chord length is less than the latter two methods. When the tip speed ratio is high ($\lambda>2$), the $C_p-\lambda$ curve obtained by changing the radius is close to the $C_p-\lambda$ curve obtained by changing the chord length; when the tip speed ratio is low ($\lambda<2$), the $C_p-\lambda$ curve obtained by changing the radius is close to the $C_p-\lambda$ curve obtained by changing the blade number.

(3) The chord length changes can improve the peak of the wind energy utilization, while increase the blade number can reduce the peak of the wind energy utilization.
(4) Under the same tip speed ratio, the effect of changing the chord length on the aerodynamic performance of H-VAWT is completely different from that of the other two methods; with the increase of chord length, the aerodynamic performance of VAWT increases faster.

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