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A Study on the Performance of a 5 kW Scale VAWT with Omni-Directional Guide Vanes

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Key Words : CFD(전산유체역학), Omni-Directional Turbine(방향키터빈), VAWT(수직축 터빈), Wind Energy(풍력)

ABSTRACT

Vertical axis wind turbine, despite of its limit in power efficiency, the simplicity in structure and maintenance is a competitive factor that keeps this type of turbine in the game until nowadays. Continuous solutions have been given to handle its major weakness and the use of omni-directional guide vane is an considerable one. In this paper, a 5kkW scale Savonius-based wind turbine enhanced with such guide vane system was design and studied. Together with reasonable blade design, the wind turbine shows promising performance compared with basic design while maintaining its original advantages.

1. Introduction

For the current situation of our modern world, it is obviously seen that mankind has been continuously seeking for energy solutions to meets the not only the growing global demand, but also the environment conservation. Wind turbine, which has a significant long history of development, is still interested as a simple and reliable solution for such demands.

Of all known designs, vertical axis wind turbine (VAWT) has a notable feature, that is the advantage of being capable of catching the wind from all directions without a need to orient the blades.(1) Besides, another advantage is that the blade usually take the shape of simple geometry. Thus, the turbine operates in almost pure tension, it becomes relatively light and inexpensive to construct. The major disadvantage of VAWT is the relatively low power efficiency compared to horizontal designs. This is due to the fact that vertical orientation unwillingly divides the rotor blades into two groups. First group, the so-called “positive component”, consists of part of the blades which move in respect of wind direction, the second one consists of negative blade elements which move against the wind direction, consequently resist or limit the overall power output.

For decades, there are several methods invented for the reduction of negative effect in VAWTs. This paper introduce the design of a 5kW scale VAWT enhanced with stationary guide vanes which help orient the wind direction in a positive way to increase power output. The use of guide vane is not an innovative idea, however, with the combination of blade shape the VAWT design in this study shows promising impoved performance while maintains the economic fator in terms of structure and construction.

2. Design

The VAWT presented here is of Savonius-based style

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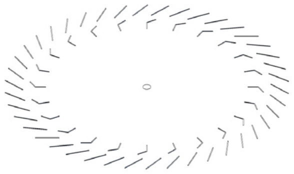
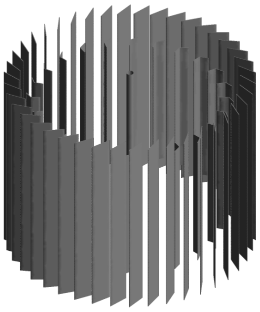


a) Sectional View



b) Full Model View

Fig. 1 Design of Omni-Directional VAWT

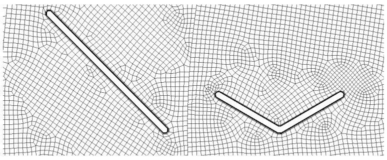
with several modifications (Fig. 1). Firsly, the blades are mounted at the periphery of the rotor, leaving a big empty space at the center (traditional design has the rotor interior mostly filled). Secondly, a large number of blades is used, and for this scale 24 blades are fitted. The purpose of this design is due to the fact that the most effective region for generating torque usually lies at far distance from the center. Thus, such arrangement is more beneficial for power generating while reduces the effect of resistance and blockage. The final modification is the use of omni-directional guide vane. As mentioned before, the main purpose of these vanes is to prevent turbine's rotor from generating negative effect. Moreover, the installation of guide vanes also enable seft-starting ability for the VAWT. In this design, 42 guide vanes are fitted.

For 5kW scale, device's sizing was calculated and given in Table 1. Since the guide vanes play flow orientation role, the blades are designed to match the direction of the air stream entering rotor. This is the most importance which directly influences the power output. In this work, three types of blade are analyzed. Fig. 2 shows the shapes of these blade designs, in turn named "V1", "V2" and "V3".

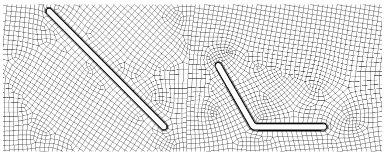
Due to the orientation of guide vanes, the air is directed into the rotating rotor with a tilted angle in most of the blades. Thus, the wind flow takes part in two aerodynamic motions expressed as direct inflow and rotating components. The magnitudes of wind speed and rotor revolution shall decide the combined velocity vector of an air particle passing through the turbine. The 3 blade designs are proposed aiming at effectively taking the air and absorbing its kinetic energy based on pre-described principle. Thus, flanging is applied for all three types but with different methods. Computational simulation is carried out for each design in order to understand the flow patterns and find out the most effective one.

Table 1 Design parameters

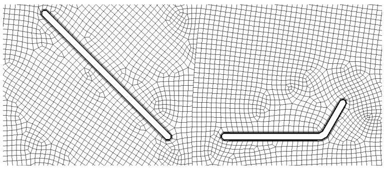
Design Power	5 kW
Rotor Diameter	9 m
Full Diameter	11 m
Number of Blade	24
Rotor Height	6 m
Number of Guide Vane	42
Blade Type	V1, V2, V3
Guide Vane Type	Plain Rectangular
Design Tilted Angle	45°
Design Wind Speed	10 m/s
TSR Range	0.2-0.5



a) V1 Blade



b) V2 Blade



c) V3 Blade

Fig. 2 Blade Designs

The application of guide vane and flanging blade also appeared in other's work, i.e. Chong et al. in 2014, where a similar VAWT was introduced. The authors uses guide vane to form a so-called power-augmented shroud and state that such design can increase the coefficient of torque and the coefficient of power.(2,3) However, those researchers use traditional

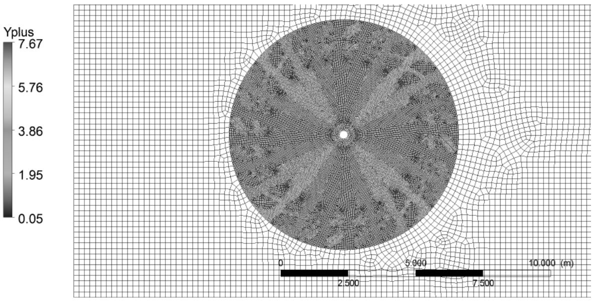


Fig. 3 Meshing and Mesh Quality of Computational Domain

airfoil style blade and applied flanging for the guide vanes in stead.

3. Computational Simulation

Computational Fluid Dynamics (CFD) has been being a reliable solution to solve fluid flow problem, especially for wind turbines. The solver used in this work is ANSYS CFX commercial code which is able to generate accurate simulation results for correctly defined problems. In order to do this, the turbine was modeled carefully using CAD tools and precisely meshed. The computational mesh is done with hexa only approach to assure the robustness of the domain. The mesh has high quality, dimensionless wall funtion value is within reliable range where maximum yplus is under 7.67 for the whole computational domain, while at near wall (blade, guide vane) region, this value is only about 0.05 (Fig. 3).

The computational domain is setup with one inlet and one outlet in rectangular shape in order to simulate the far field flow direction. Turbulence flow is solved by Shear Stress Transport (SST) model which is stable and has low rate of encountering computational errors. Most simulations are done in steady state analysis but some transient cases are also carried out to confirm the results' accuracy. To estimate turbine's performance at different conditions, the dimensionless speed called Tip-Speed Ratio (TRS, λ) is given as an input parameter.

$$\lambda = \frac{Velocity\,at\,Tip}{Free\,Stream\,Velocity} = \frac{R\omega}{U}$$

For these simulations, TSR is changed by changing rotor's rotational speed and free stream wind speed is maintained. The coresponding rotor revolutions for different TSR conditions are given in Table 2.

Table 2 Simulation Cases

TSR	0.2	0.3	0.4	0.5
Corresponding RPM	4.244	6.366	8.488	10.61

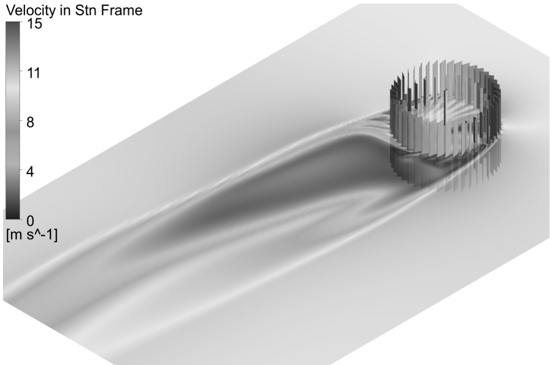


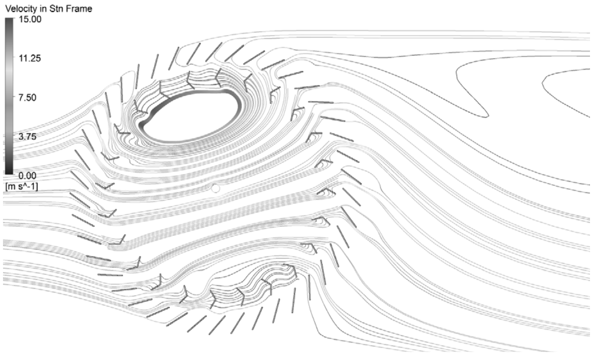
Fig. 4 Flow Visualizaton for V2 Design at TSR 0.2

4. Results and Discussions

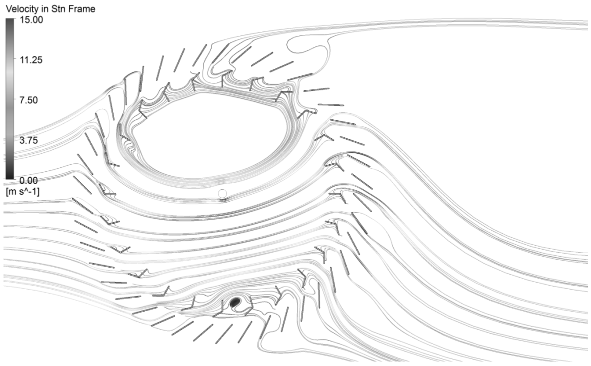
4.1 Flow Patterns

Fig. 4 illustrates an example vizualization of air flow passed through the turbine, the model in the figure is V2 design operating at TSR 0.2. The figure presents the cut plane of relative water velocity (velocity in rotating frame) which distributes over the guide vanes, blades and hub. It is clearly seen that the contrast in color expains the effect resulted from the application of omni-directional guide vane. The rotor is set to turn counter-clockwise, so the flow tends to move in a spline-like pattern. This is due to the guiding effect of the vanes, also it means the air is oriented to pass the blades in a more effective way.

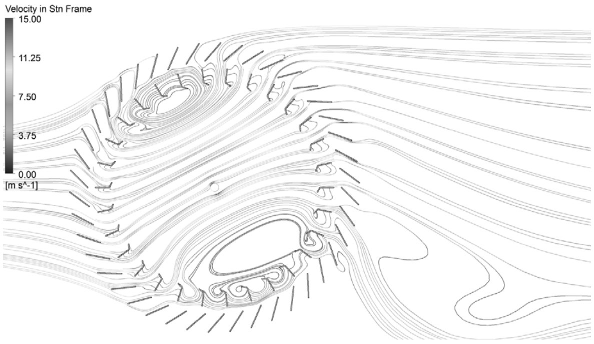
Detailed wake patterns for each blade designs are show in Fig. 5. The illustrations present these their simulation results in the same condition (at TSR 0.3). According to these patterns, there is a significant difference between V2 design and the rest. The difference is that the streamlines have smoother shape and are well developed over the field. These streamlines are also tend to move along with the rotating direction (from left to right) in counter-clockwise, means that the flow was guided effectively.



a) V1 Blade



b) V2 Blade



c) V3 Blade

Fig. 5 Wake Patterns at TSR 0.3

For V1 design, the streamline patterns are also resonable but seems to be separated into two regions (upper and lower components) as in traditional VAWT (negative and positive components). For V3 design, such effect also presents. Besides, there are many local vortexes and collisions inside the rotor region. This may considerably influence the device's aerodynamic performance.

4.2 Power Efficiency

Power performances of the designed VAWTs are evaluated by power coefficient CP which is calculated for each design and summarized in Fig. 6. where CP is expressed as a function of TSR. The similar expression is shown in Fig. 7 but the ouput is put in dimensional value.

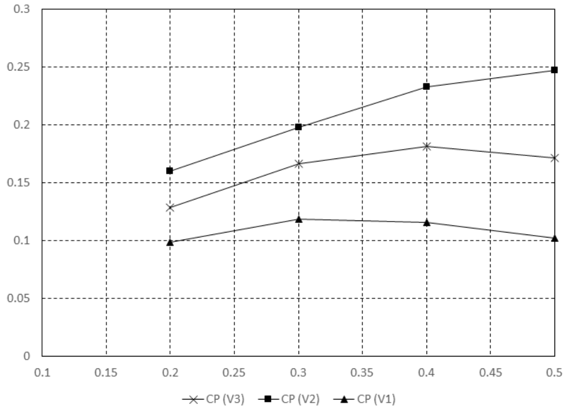


Fig. 6 Power Efficiency vs TSR Curves

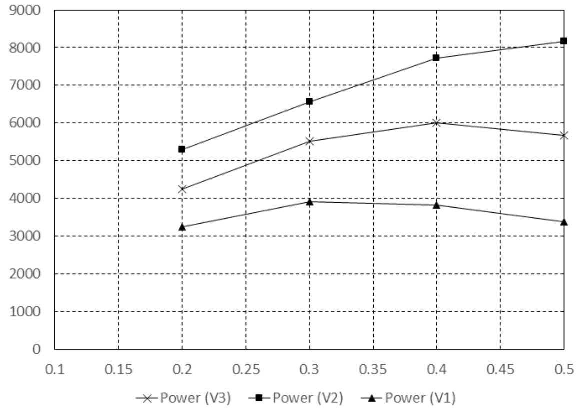


Fig. 7 Power Output vs TSR Curves

As seen in flow analysis section, the V2 design shows the highest power efficiency of all, and throughout the TSR range. Moreover, the curve's trend is in increasing state, thus within the scope of this work, the performance of V2 design is not yet estimated fully. Unexpected, The poorest one is V1 design, V3 blade's performance is acceptable but has no positive trending. However, all of three designs have CP abobe 0.1 value, which is often the limit of Savonius-based turbine. Recently, Kadam et al. did a thorough work to review the performance of this type of turbine but most of his tests results in maximum CP around 0.1.(5)

According to the results, the V1 and V3 designs have optimum operating points at TSR 0.3, while V2 design can work efficiently at high TSR up to 0.5 or even higher. At this point, the device's efficiency reaches almost 25% which is considered high so far.

For given initial conditions, the required power output is 5kW. Except the V1 design, the other two are both able to capture that amount of energy. While V3 design can get the required energy at high TSR only, V2 design satisfies the requirement at all TSRs.

The major reason for the efficiency difference is the flanging style. For V2 design, there is a clear open for air to get out after contacting with the blade and continue to pass through the hub, then get in the blades at the rear. Hence, air energy is transferred perfectly without or with least resistance. Despite the fact that V1 design only differs from V2 design in blade's angle of attack, such positioning creates a blockage on the flow and consequently there are energy losses. V3 design has the same flaw but the flanging part is shorter. All in all, by applying the omni-directional guide vane with the V2 blade, the Savonius-based VAWT's performance is improved significantly.

5. Conclusions

This paper introduces a computational evaluation of a VAWT enhanced with omni-directional guide vane which focus on finding possible solutions to increase power efficiency. In summary, the following conclusions are given.

1) The proposed design of VAWT generally has high power efficiency for its type. Especially, the V2 blade design show promising performance with maximum CP up to 25%.
2) The application of omni-directional guide vane plays the key role in the improvement of power performance by means of effectivel distribution of wind stream..
3) The sizing and structure of the analyzed VAWT satisfied the power requirement while maintaining the advantage of simplicity in both construction, design and maintenance..

The VAWTin this paper is computational model and its capability has not been fully comprehended yet since various factors were excluded, i.e. number of blades, number of guide vanes, tilted angle, blade angle of attack, sizing.... These problems should be investigated and taken into account in future work to discover the optimal design for Savonius-based VAWT. The results of this study help contributing to the present development of wind turbine as the potential method of tidal energy conversion to serve the future demand of renewable energy.

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