Blade Optimization of 300-Watt Vertical Axis Wind Turbine for Low Wind Speed Region

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Abstract— This study demonstrates the overall performance and efficiency of a 300-Watt conventional vertical axis wind turbine used for low wind speed regions. The study investigates the increasing of blade tangential velocity by adding a new blade attached to the main blade of the turbine. The new blades called secondary blades which will take the effect of increasing the tangential velocity and hence increasing the rated output power. The new contribution proposed in this study was taken into considerations the optimum position of the secondary blades. The position was taken to be in an overlap location with the main blades under two different configurations (forward and backward). A simulation analysis using ANSYS CFD was proposed in this study to evaluate the tangential velocity and the rotational speed of different cases for the modified vertical axis wind turbine. The range of wind velocities were 3 to 12 m/s in order to cover a reasonable range of wind speed. The variation of power and rotational speed was compared with the power and rotational speed calculated for the conventional wind turbine. The study illustrates the correlations of power and rotational speed of the modified vertical axis wind turbine. The increasing of tangential velocity and output power for the modified turbine under a minimum wind speed of 5 m/s were found to be 16.3% and 34% respectively.

Keywords— Wind Energy, Wind Turbine, Vertical Axis Wind Turbine, Low Wind Speed Regions

Introduction

Alternative energy has become very important in the last years due to the depletion of and high cost of fuel. Thus, free energy like solar and wind energies start to get high attention. This needs to improve wind energy conversion system which is transformed from small sized generation system to bigger sized system. Two main types of wind turbines are produced according to the axis of rotation, which are horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). The power gained from horizontal axis wind turbine is high compared with the power from the vertical axis wind turbine. However, the vertical axis wind turbine gives the interest to many researchers due to its advantages. These advantages are the cost and easiness of installing and maintenance, and also capture the wind from any direction without yawing.

There are some parameters that influence the performance of VAWT. One of the most important parameter is the blade of the wind turbine. The first indication about the blade design was conducted that it should be straight without any twisting with specific types of airfoils (Lee, Lee & Lim 2016). Therefore in order to increase the efficiency of small scale vertical axis wind turbine, an optimization of the conventional turbine could be presented in this study. The optimized design is presented for 300 watt with twisted blades of NACA4412, As the twisted blades reduce the oscillation and vibration of the turbine and gain more power (Shahizare *et al*. 2016). Streedbart and Singbji designed the first model of wind turbine with twisting blades in 1977 (Salih *et al.* 2015). The design was presented to estimate the aerodynamic effect of twisted blades on the load generated by the turbine. The results obtained from that study was validated with an experimental setup of an actual size of wind turbine and generator. The production of the torque in the vertical axis wind turbine can be done by two ways, either by lift force or drag force. As mentioned before, the Darrieus type of VAWT utilizes the lift force to produce the torque, while Savonius type of VAWT using the drag force in torque production (Martinez 2007).

Tip speed ratio is highly dependent parameter that influences the performance of the wind turbine. Tip speed ratio TSR is defined as the ratio between tangential velocity of the blade to the wind velocity acting on the blades of the wind turbine (Kang et al. 2012).

$$TSR = \frac{\omega R}{U} \tag{2.10}$$

Where; ω is defined as the rotational or angular velocity of the wind turbine, R is the rotational radius, and U is the wind velocity.

The optimal tip speed ratio of any wind turbine is in the range where maximum power coefficient could be obtained (Manyonge, Ochieng & Onyango 2012).

In vertical axis wind turbine, each blade can catch its own vortices and the once that generated by the other blade due to increasing in tip speed ratio. The increasing of tip speed ratio as a resultant of tangential velocity of the blades and/or rotational radius; this should lead to the fact that the angle of attack is increased as well. The effect of increasing or decreasing the tip speed ratio TSR on lift and drag forces is very important (Fukudome et al. 2006).

In this paper, the blade optimization of conventional vertical axis wind turbine with 300 Watt rated output power is done by adding new blades attached to its main blades with a special configuration called overlap for to locations (forward and backward). The concept was defined to have a special effect in aerodynamic behavior of the flow stream around and between the two blades. The study shows the simulation results using ANSYS CFD to evaluate the tangential velocity and the rotational speed for the modified vertical axis wind turbine with a wind speed ranges between (3m/s-12m/s).

I. METHODOLOGY OF STUDY

The research methodology used in this study is presented in Figure 1 to overcome the work done and the relationship between different parameters with their effects on the performance of optimized vertical axis wind turbine. In this part of study, only one configuration shall be discussed which is the overlap six blades vertical axis wind turbine with two different blade position (forward and backward).. The study was started in 2012 in Solar Energy Research Institute (SERI) / Universiti Kebangsaan Malaysia (UKM).

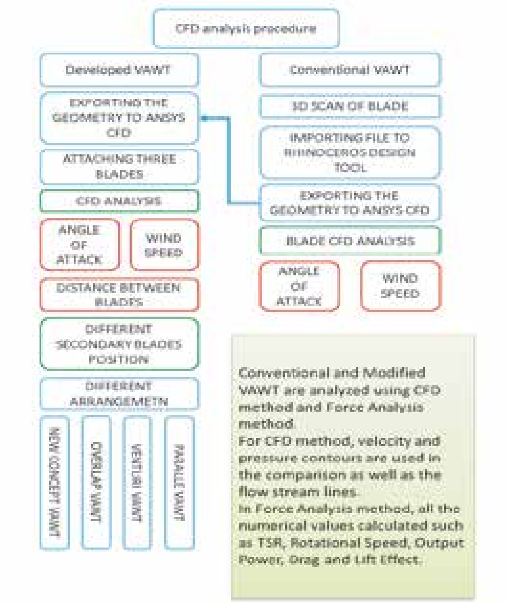

Figure 1: Research methodology of the study

The numerical investigation of both conventional and modified vertical axis wind turbine is presented. The first step was defined to analyze a 300 Watt conventional three blades vertical axis wind turbine designed and manufactured by (i-wind Sdn Bhd). The blade was scanned to convert the geometry file that could be read and modified by a specific modelling software called (Rhinoceros v.4). the scanning procedure consists of three-dimensional scan of one blade as shown in Figure 2. The output file of geometry was exported to the modelling software to clean it up and create a full-scale modelling of three blades vertical axis wind turbine and then the modified VAWT.

Figure 2: Three-dimensional scanning of blade

II. CFD ANALYSIS

In this study, simulation analysis using CFD ANSYS is presented for both the conventional and modified vertical axis wind turbine with airfoil section of NACA4412. The modified design of the turbine is called overlap. overlap geometry analysis presented is the configuration in which the secondary blade added and attached to the main blade by overlap form. The distance between center to center of main and secondary blades is conducted at 10 cm. Two different overlap configurations were presented, forward and backward overlap. The position of the secondary blade could classify this configuration whether it is forward or backward. As shown in Figure 3.

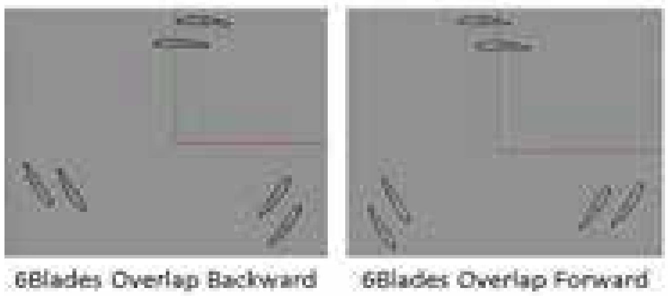

Figure 3: Geometry configuration of OVERLAP forward and backward

III. GOVERNING EQUATIONS

Navier-Stocks equation is well known as the governing equation used in the computational fluid dynamics analysis. It could be defined as a set of equations in which there is no exact answer or solution. The assumptions of the solution governing this type of equations are that the fluid is considered as Newtonian, where the flow could be explained by the following sets of equations.

The continuity of mass:

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho\, V) = 0 \qquad (1)$$

The continuity of momentum:

X – momentum:

$$\frac{\partial (\rho u)}{\partial t} + \nabla . (\rho u V) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \qquad (2)$$

Y – momentum:

$$\frac{\partial(\rho v)}{\partial t} + \nabla.(\rho v V) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \quad (3)$$

Z – momentum:

$$\frac{\partial(\rho w)}{\partial t} + \nabla.(\rho w V) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \quad (4)$$

The continuity of energy:

$$\rho \frac{\partial}{\partial t}\left(e + \frac{v^2}{2}\right) = pq + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) - \frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z} \quad (5)$$

In vertical axis wind turbine simulation, the governing solution consists of continuity and momentum equations. Rynolds average Navier Stocks approach are considered for turbulence occurs during the rotation of the wind turbine. It is important when using CFD method to know that the performance prediction of vertical axis wind turbine requires large domain and this domain should include the sliding mesh method. Both large domain analysis and sliding mesh solution should be defined with time (transient mode) to overcome all the steady and unsteady performance of the wind turbine especially during rotation.

IV. SIMULATION MODEL

The 3D modeling of the wind turbine was generated using a special modeling software, then exported to Ansys Design Modeler as shown in figure 4

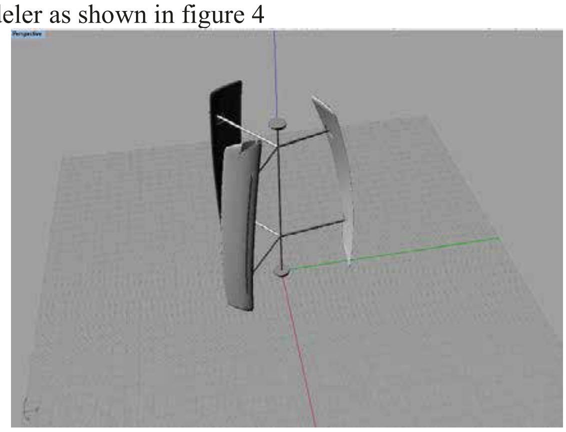

Figure 4: Three-dimensional drawing of conventional VAWT

Firstly, the conventional vertical axis wind turbine was simulated to monitor the performance and rotational speed as well as the effect of tip speed ratio TSR. In order to simplify the solution analysis and hence the blades are all having the same profile; the simulation is taken to be in two-dimensional modeling. This could reduce the time of analysis, as well as reducing the total numbers of simulation procedures since the solution is depending on transient mode and not a steady state. For the generation of NACA4412 airfoils in ANSYS, the geometry first was imported in Ansys Design Modeler to create the rotating domain as shown in figure 5. The rotating domain then surrounded by a fixed domain in order to enhance the sliding mesh technique as shown in figure 6.

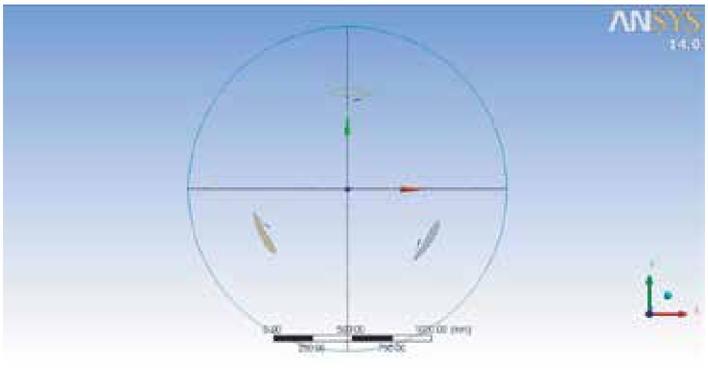

Figure 5: Two-dimensional geometry imported by Ansys Design Modeler with rotating domain

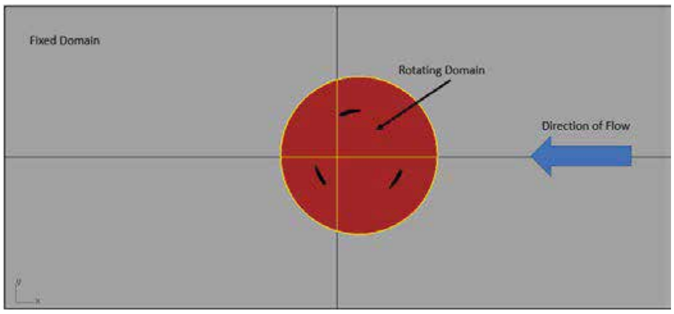

Figure 6 Two-dimensional geometry showing rotating domain surrounded by fixed domain

The modified vertical axis wind turbine M-VAWT consists of three main blades representing the conventional vertical axis wind turbine with three secondary blades attached to each blade in an overlap configuration.

V. MESH GENERATION

Sliding mesh technique is used to investigate the performance of i-wind vertical axis wind turbine and the proposed VAWT. In order to obtain high accuracy and output efficiency utilizing CFD simulation, transient time step solution method is also predicted. Reynolds – Average Navier – Stokes (RANS) Equations was considered as the most popular simulation technique used in fluid flow especially in the investigation of wind turbine. RANS method is used in this study where it is based on Navier-Stokes equations that describes the conservation of momentum. To simulate the domain, the geometry has been created using Design Modeler with three major steps; 1) create the solid structure (i.e. blades), 2) generate the domain, 3) Boolean the blades inside the domain. Figure 7 shows the meshing technique of two-dimensional fixed and rotating domains.

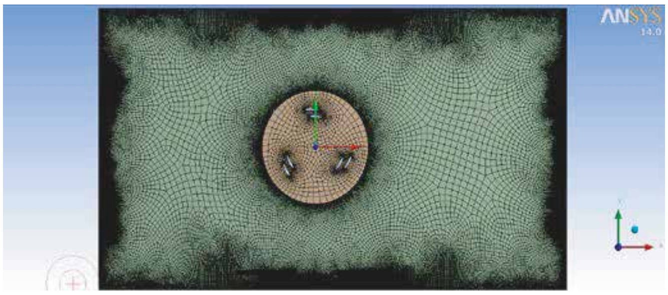

Figure 7: Two-dimensional sliding mesh method of 6 blades overlap configuration

Figure 8 below represents the sliding mesh interface between the fixed and rotating domains where the cells are created and generated more around the blades and in the contact area of interface.

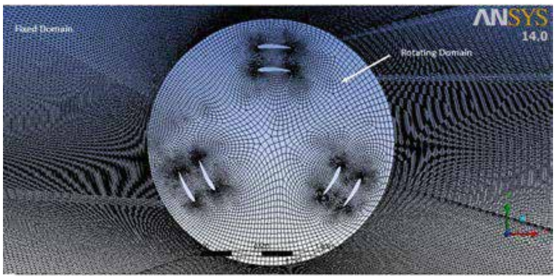

Figure 8: Sliding mesh interface showing fixed and rotating domains

VI. RESULTS AND DISCUSSION

Two different arrangements were proposed in this configuration, overlap forward and overlap backward. The forwarded overlap occurs where the secondary blade is located above the main blade in parallel position but is overlapping it with a certain distance. The same description for the backward overlap concept in which the secondary blade is located above the main blade with a back shifting. The tangential velocity profile of both main and secondary blades for forward overlap vertical axis wind turbine is presented in figure 9. The range of velocities for the secondary blade were recorded to be 2.73 to 2.95 m/s. This was considered as a good enhancement for the main tangential velocity, but the profile of the velocity is totally different than the main tangential velocity profile as presented in figure 10.

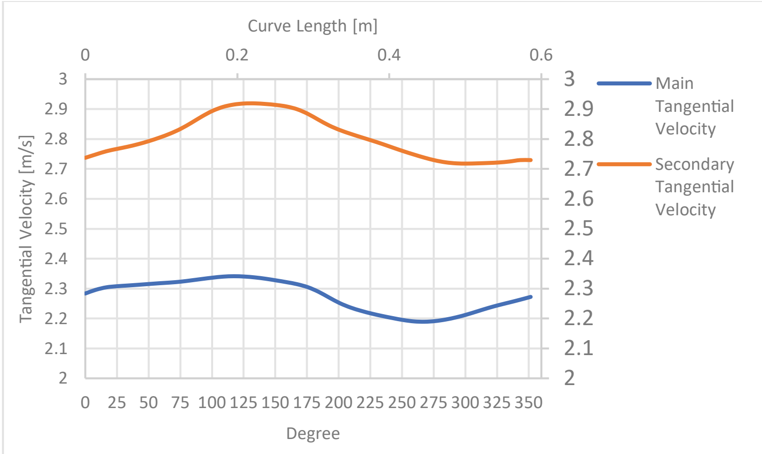

Figure 9 Tangential velocity profile of main and secondary blades of six blades overlap forward modified vertical axis wind turbine

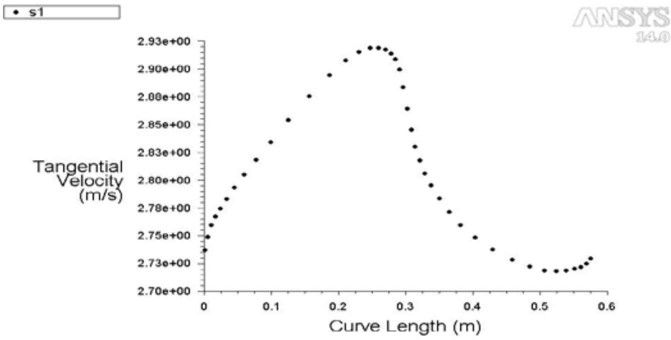

Figure 10 Secondary blade tangential velocity of overlap forward modified VAWT

For the other concept of overlap configuration, the range of tangential velocity profile of secondary blade in the backward arrangement was found to be 2.68 to 2.90 m/s as presented in figure 4.38.

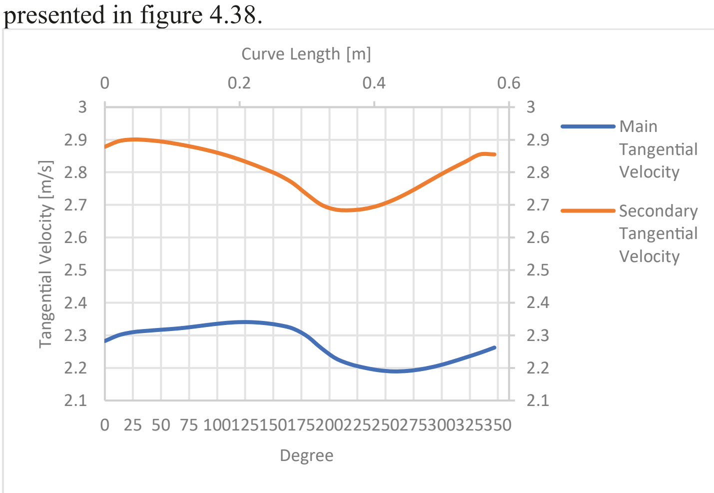

Figure 11 Tangential velocity profile of main and secondary blades of six blades overlap backward modified vertical axis wind turbine

From the analysis of the velocity contour for the six blades overlap backward configuration and the tangential velocity profile of the secondary bade; it is found that the secondary blade does not follow the same profile of the main blade tangential velocity. Figure 11 represents the tangential velocity profile of secondary blade recorded for full rotation of overlap backward concept of modified vertical axis wind turbine.

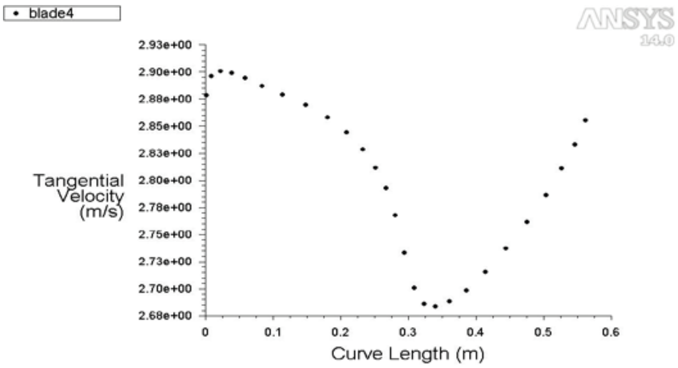

Figure 12 Secondary blade tangential velocity of overlap backward modified VAWT

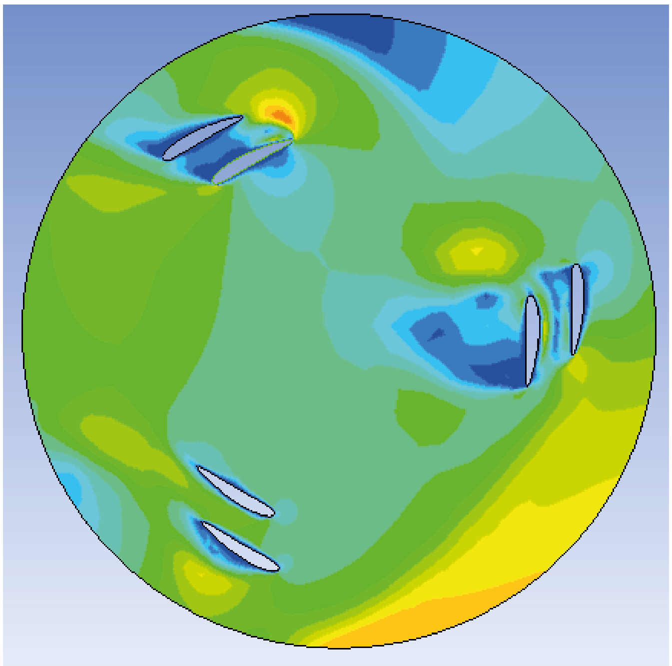

Figure 13 Velocity contour of modified VAWT with overlap forward

VII. CONCLUSION

From the study and investigation of conventional vertical axis wind turbine and the proposed design configurations (overlap forward and overlap backward), it can be concluded that adding a secondary blade attached to the main blade as in the presented configuration will enhance the performance of conventional vertical axis wind turbine.

This could improve the tangential velocity and the rotational speed which leads to increase the torque of the turbine and as a result increasing the output power by 34% at wind velocity of 5m/s.

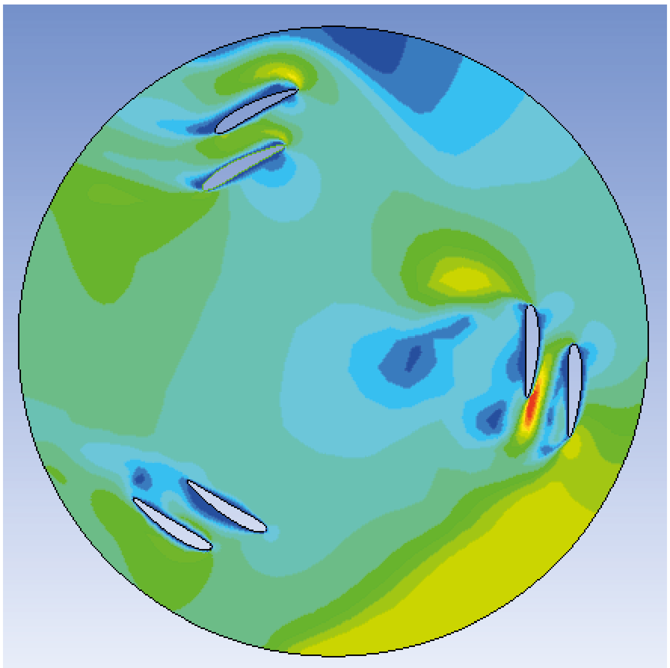

Figure 14 Velocity contour of modified VAWT with overlap backward

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