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Performance Analysis on a New Design of Blade Shape for Savonius Wind Turbine

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ABSTRACT

Drag-type vertical axis wind turbine (VAWT) is well known as a potential and reliable in the development of a wind energy system. Its advantages attract world attention due to its simple geometry design and significantly cheaper to build compared to a horizontal axis wind turbine (HAWT). The present study will consider the essential geometry improvement of the Savonius rotor, where the profile of the blade was made in the form of a half-cylinder. Numerical simulation was conducted to study the effect of geometrical setup on the performance of the rotor in terms of the coefficient of power, coefficient of torque and power output. The model was designed according to the existing tested model by experimental work, except for the inner surface blade which uses an overlap ratio of 0.2. Different wind speeds of 6 m/s, 8 m/s and 10 m/s were used for the simulation to analyze the behaviour of properties of the new design blade. According to the results obtained, it shows that the power coefficient for the new design of the inner blade was increased by 20% compared to the previous design. The power output of the wind turbine reaches the maximum power in the middle of the tip speed ratio for all types of wind speeds. This is because the power coefficient will start to fall off after reaching the maximum electrical power produced. Besides, it is due to the limit of the blade performance which will keep the blade from rotating too fast and avoiding damage due to excessive force.

1. Introduction

Electricity has become one of the commodities in modern civilization. The uses of electricity are very wide regardless of any aspect of the job. The utilization of energy has given many benefits not only to humans but also to the development of a nation [1,2]. For over 200 years, the main source of energy generation is depending on fossil fuels. However, the huge demand for fossil fuels has led to

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global depletion. Therefore, dependence on the carbon economy as an international strategic economic development has declined. To overcome the situation, environmentally friendly types of energy known as renewable energy was introduced [3-5], which today, are the focus of the global strategy to be used as an alternative to fossil fuels. Solar, wind, wave, marine and bioenergy are among the most common types of renewable energy. Among the renewable energy sources, wind energy plays an important role in the future of the global economy and has grown rapidly throughout the world [6-9].

Based on data compiled in the Wind Technologies Market Report, wind energy consistently comes in at or below the going market rate for electricity [10,11]. Through the report, wind energy is considered one of the natural resources which are available nowadays to generate cheap power. However, to obtain the best use of this energy, there are a lot of complex and lengthy studies that need to be performed to develop the performance of the wind turbine system [12-14]. A wind turbine is a device that converts kinetic energy into mechanical energy to produce electricity. Generally, the turbine is connected to generators that use a turning motion of the shaft to rotate a rotor. The wind act as the mechanical power which moves the blade as it passed the turbine. The development and continuity of historic to modern technology over time and space had manufactured the existing wind turbine into two types of axis which is the vertical and horizontal axis. This axis describes the way how the turbine interconnects with an electrical network.

The present work aims to analyse the wind effect on the new design blade of the vertical axis wind turbine (VAWT) as well as to determine the efficiency of tip ratio, power, and torque coefficient of the new design of the blade. A numerical simulation will be conducted to determine the effect of the new blade design on the performance of the rotor in terms of the coefficient of power, coefficient of torque and power output. The model is designed according to the existing tested model by experimental work, except for the inner surface blade which is used an overlap ratio of 0.2. The comparison between numerical simulations and experimental work will present to compare and validate the numerical work. For this purpose, the simulation work will be performed by using ANSYS Fluent software.

The information gleaned from this research can be used to optimize Savonius rotor rotational mechanical electric generating and wind energy harvesting. Additionally, for various sizes of the turbine blade, it is possible to determine how well the Savonius rotor performs in terms of aerodynamic characteristics like torque, torque coefficient, power, and power coefficient.

1.1 Vertical Axis Wind Turbine

Technically, horizontal rotation works on a horizontal axis wind turbine (HWAT) while vertical rotation takes on a vertical axis wind turbine (VAWT). Research shows that HWAT can be categorized as significantly close to VAWT [15-18]. However, VAWT has high efficiency compared to HAWT because the tighter spacing of the counter-rotating turbine allows it to have or produce higher power densities. This can be proved by a result of a researcher who found that normally modern HWAT can produce about 2-3 W per square meter while VWAT shows high potential production of about 30 Watt per square meter [19, 20]. Other than that, the vertical axis wind turbine receives a better effect during the process of rotation of the blades. This is because the blades receive a fixed load due to the direction of inertial force and gravity that keeps them stable ever. It’s different from a horizontal axis wind turbine in which the direction of inertial force is subject to change so that the blade will suffer the alternating load and reduce the fatigue strength of the blade [21]. Furthermore, the horizontal wind axis wind turbine had difficulty in maintenance due to the position of the generator from the ground. This makes repairing and maintenance procedures hard to do.

Another problem encountered in introducing this technology is the unstable of wind speed, fluctuations in urban conditions and the direction of wind flow almost constant change. In 1922, the Finnish engineer, S.J. Savonius invented a new type of wind turbine which consists of two half-semi-circular parts shaped [22]. The invention of the wind turbine known as the Savonius wind turbine attracted many researchers to study and improve the performance of this device due to its features such as ease of design and installation, low maintenance as well as possessing only a few mechanical parts [23,24]. The VAWT have two kinds of application which are the simplest type Savonius rotor and the complex type Darrieus rotor. Savonius rotor is driven by drag-type configuration force while the Darrieus rotor was driven by lift-type configuration force. The operation of the Savonius rotor depends on the difference in drag force when the wind strikes both the concave and convex sides of the semi-spherical blades. The flow energy utilization of the Savonius rotor is low so it is not used for high power applications. The drag configuration of VAWT has low efficiency due to its low running speed which the value of the corresponding power coefficient reaches only 50% of one of the best-running horizontal axis wind turbines [25].

This is essentially caused by the low aerodynamic performance of the rotor and the difference between drag forces on the paddles. This reason makes the Savonius rotor have high productivity but low technicality as a wind machine device. This proves why the Savonius rotor type is often used for water-pumping purposes instead of generating electricity [26]. Hence due to this problem, the previous researcher concluded that the change of blade shape can have real impacts on the performance of the turbine itself. Blade geometry and configuration are crucial parts of determining the performance of wind capturing to improve power generation [27,28]. Many studies had been done on the shape of conventional Savonius such as adjusting overlap ratio and aspect ratio using other types of drag based VWAT such as helical [29]. Therefore, the aims of this research are essential to investigate the wind effect based on the new design blade shape numerically. Followed by the investigation, this study also will compare the performance of the new design blade shape between experimental and simulation results on the power coefficient, torque coefficient and tip ratio.

1.2 Savonius Wind Turbine Performance

The most important output that is interesting to determine from the study of Savonius wind turbines is the effect of the geometric parameters to improve the performance of wind turbines. For that, the calculation of the maximum power coefficient, C_p and the maximum torque coefficient, C_T needs to be performed. Besides that, the other parameter that needs to be considered for the analysis is the tip speed ratio, which is the parameter used to express the power coefficient in terms of the angular velocity of the blade, ω and upstream wind velocity. The real torque extracted because of a numerical test on the total theoretical torque expected from the airflow towards the turbine mathematically can represent the torque coefficient as in Eq. 1, where T is the torque of the turbine, R is a rotor radius, U represent the wind velocity and A is the swept area of the turbine.

$$\text{Power Coefficient}, C_p = \frac{\text{Output (Power Turbine, } P_{turbine})}{\text{Input (Power Available, } P_{available})} \tag{1}$$

On the other hand, the power coefficient of the power extracted can be shown in the mathematical relation because a numerical simulation tested on the total theoretical power expected from the airflow towards the turbine represented can be expressed in the following equations.

$$\text{Power Coefficient}, C_p = \frac{\text{Output (Power Turbine, } P_{turbine})}{\text{Input (Power Available, } P_{available})} \tag{2}$$

$$P_{turbine} = \frac{2\pi \text{NT}}{60} T\omega = V * I \tag{3}$$

$$P_{available} = \frac{1}{2}\rho A U^3 \tag{4}$$

From the equations, *T* is the rotational torque, *N* is the revolution per minute (*rpm*), and *ω* is the motor rotating speed (*rad/s*). The power of the turbine also can be present in terms of the voltage output of the DC generator, *V* (*volt*) and the current output of the DC generator, *I* (*Amp*). The power coefficient can be represented in terms of torque, as in 5 while where the λ in 6 is a tip speed ratio (*TSR*).

$$C_P = C_T \lambda \tag{5}$$
$$\lambda = \frac{\omega R}{U} \tag{6}$$

2. Numerical Model and Methodology

The development of the proposed wind turbine model is decided based on previous experimental studies. Since it is developed to study the rotor efficiency and make a comparison between simulation and experimental results, the dimension of the model is being followed precisely with the real experimental model. As vertical axis wind turbine is suitable at low wind speeds area, hence the simulation has been performing at the average low wind speeds which are 6, 8 and 10 m/s. Literarily the new design blade shape will give high efficiency compared to the classical blade shape at the same low wind speeds. Therefore, CFD simulation will be tested on the new design blade shape to evaluate the data to see the percentage difference between previous experimental work and proposed numerical simulation work.

A schematic diagram of the vertical axis wind turbine is shown in Figure 1. The design of the barrel rotor is quite simple. It takes a basic idea which is behind the two-blade is a half-cylinder shape. The barrel does not meet at the axis which is set a gap apart to create an overlap. The overlap ratio of the rotor is the effective geometry parameter in the performance improvement, and the overlap ratio used in this model is equal to 0.2 with the rotor height ratio to the diameter, H/D = 1.0. In addition, the rotor diameter and the blade thickness are 200 mm and 4 mm respectively, with the addition of the endplates up and down of the rotor, the optimum measurement of the endplate is 1.1D times the rotor diameter. The geometric parameter for the Savonius wind turbine modelled for this study is summarized in Table 1.

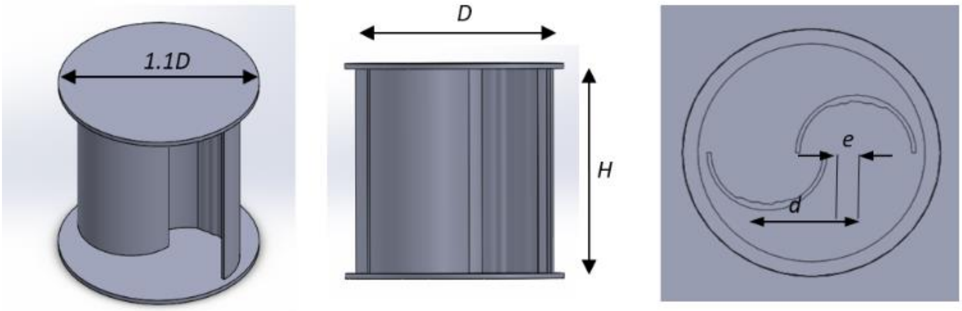


Fig. 1. Model of Savonius vertical axis wind turbine

Table 1
Geometric parameter for Savonius wind turbine

Parameter	Value
Rotor diameter, *D*	200 mm
End plate diameter	220 mm
Height of blade, *H*	200 mm
Overlap ratio	0.2
Blade chord length	112.5 mm
Wind speed, *U*	6, 8, 10 m/s
Aspect ratio, *H/D*	1
No. of stage and blade	1 and 2

3.1 Meshing and Boundary Conditions

The model of the wind turbine is started by setting up the domain where it will act as a tunnel to allow fluid flow. Rectangular with the dimension of 600 mm x 600 mm x 1200 mm has been chosen. The surface of the domain is then named according to their function which is the inlet, outlet, and boundary wall, which are set for boundary conditions for this study. The boundary condition velocity inlet is imposed upstream of the blade at 3D from the blade axis and takes the same area of the wind tunnel as presented in experimental work. The remaining upstream area is taken as a pressure inlet. The boundary condition downstream of the blade is set as a pressure outlet. The wall of the flow domain is taken at 1D from the rotational axis where a pressure outlet boundary condition is imposed and the change of any parameters φ to x or y-directions is equal to 0. Figure 2 shows the computational domain and boundary conditions.

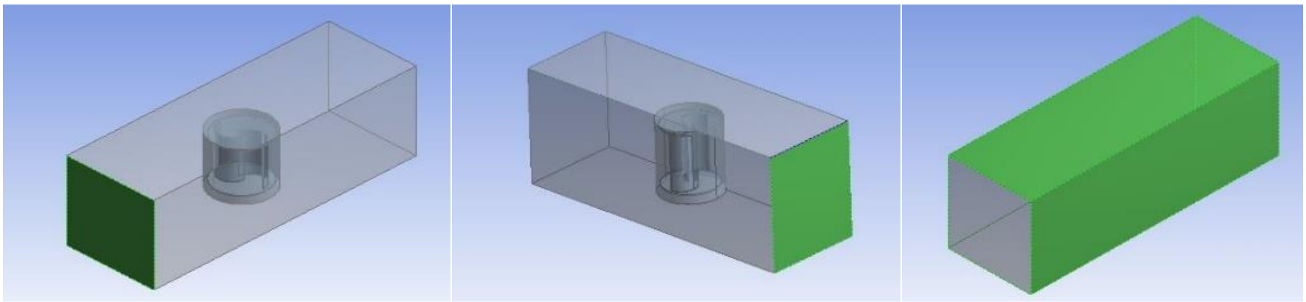
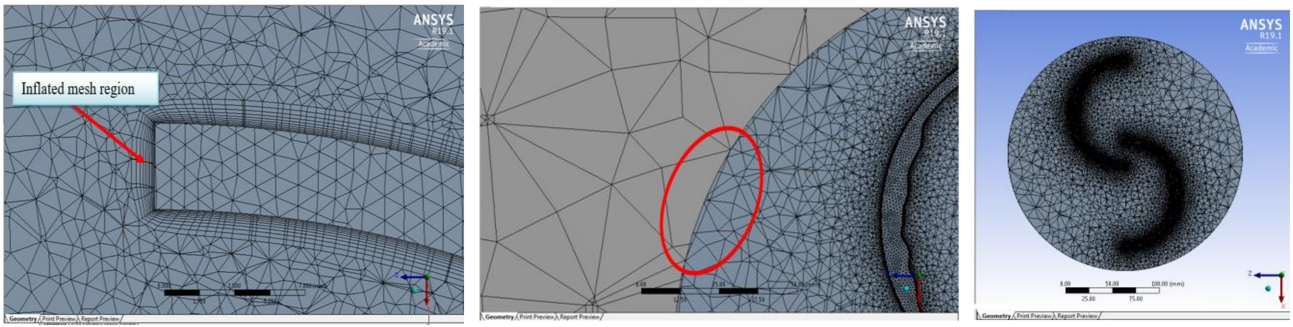

Inlet: Velocity inlet, 6,8,10 m/s
Outlet: Pressure outlet
Wall: Pressure outlet

Fig. 2. Computational domain and boundary condition

The domain is divided into two parts, a fixed part with coarse unstructured and a rotating part with a fine unstructured grid. The two parts are separated by an interface. The fine grids for rotating parts are used with an addition of inflation up to 10 layers. The inflation gives the element a high aspect ratio around the curve shape so that the geometry looks like a compact solid. Hence, the calculation in this simulation will be more precise. Different mesh sizes will prevent the nodes to cross the interface due to not matching nodes, as shown in Figure 3.



Inflation around the blade Different mesh sizes for two parts Fine mesh for rotating part

Fig. 3. Meshing for the simulation work

3.1 Grid Independent Test

A grid-independent test had been conducted to fix the grid sensitivity of the study to determine the acceptable mesh size and several elements that do not greatly influence it. The suitable mesh sizing is achieved by the level of adaptation of re-meshing into a smaller size of the element. The reliable element sizes chosen depend on the least relative error of output torque gained by applying the following equation.

$$\text{Relative error, \%} = \frac{\text{Absolute error}}{\text{Experimental value (torque)}} \times 100\% \tag{7}$$

where the absolute error is the difference between simulation torque and experimental torque.

The result of the grid-independent test was shown in Table 2. From the results, a 0.9 mm element size had been chosen due to the least relative error compared to the other. Hence, it had been considered the most reliable and suitable element size.

Table 2
Grit independent test

Element size	No. of nodes	No. of elements	Skewness	Simulation torque (Nm)	Absolute error (%)	Relative error (%)
15	628691	1839141	0.89	0.0674780	0.014	0.027
7	628914	1840927	0.85	0.0622108	0.009	0.017
2	1208892	3411718	0.85	0.0609899	0.008	0.015
0.9	5307504	15004101	0.88	0.0546911	0.002	0.003

3. Results

The results of the numerical simulation of the Savonius wind turbine based on the new shape of the design blade will be discussed in this section. The performance of the wind turbine can be determined by using the data from the torque output (*Nm*), torque coefficient, C_T, power coefficient, C_P, tip speed ratio (*TSR*) and power output (watt). All the data obtained during the simulation was calculated to get the results for the new design of the wind turbine. The simulation results were also validated with the experimental work to make sure that the simulation results have a good agreement with the experimental work, hence giving high confidence in the simulation results obtained. The results for velocity, pressure, and flow behaviour also will be presented in this section.

3.1 Torque and Power Coefficient

The new shape of the design blade was simulated under different wind speed settings to determine the torque for each condition. The information on the torque can be used to calculate the power generated by the wind turbine for the new design of the wind blade. The simulation results for three different settings of wind speeds were used to study the wind power behaviour for the new model at each wind speed. Figure 4 shows the relationship between the generated simulation turbine and the tip speed ratio of the new model and the old model of the Savonius wind turbine (experimental results), which contributed to the new Savonius wind turbine raising the positive momentum due to the increased of the pressure on the concave side of the concave.

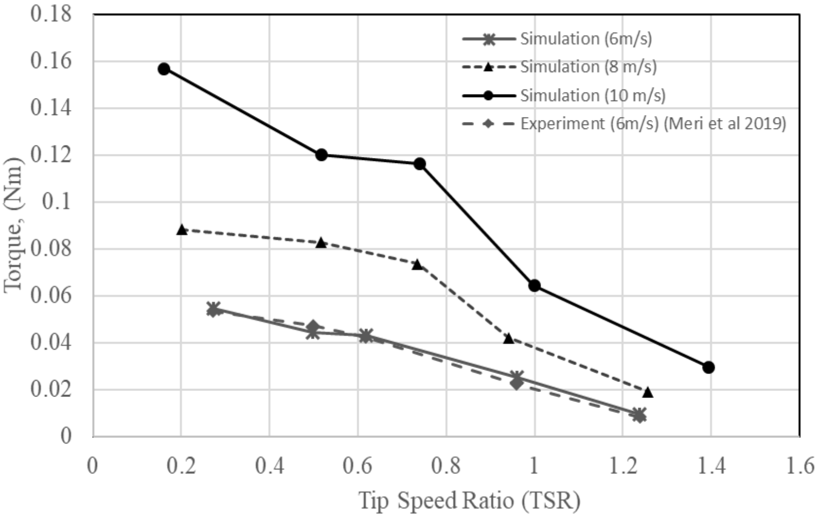


Fig. 4. Torque obtained by simulation work

The data for torque with revolution per minute (RPM) of the Savonius wind turbine (rotational speed) of the new model simulation was used to calculate the torque and power coefficient at each case of wind speed. For comparing the efficiency of the new design blade of the Savonius wind turbine, the torque coefficient and power coefficient are plotted for each wind velocity which represents the vertical axis with the tip speed ratio at the horizontal axis with the classical elliptical wind turbine Savonius at the wind speed 6 m/s as shown in Figures 5 and 6. The maximum coefficient of the new model is about 0.30 to 0.32 at simulated wind speed, 6 m/s, 8 m/s and 10 m/s. The new model contributed to the efficiency of the performance, where the percentage of increase in the coefficient of power was up to 20% compared to the classical elliptical Savonius wind turbine.

The power output of a wind turbine depends on the blade size and the wind speeds through the rotor. The curved blade design can capture the wind force efficiently compared to the flat blade design. As the velocity of the wind increases, it will produce more power due to the stronger wind allowing the blade to rotate faster. The highest electrical power production will occur at the maximum power coefficient. However, the power coefficient will start to fall off after reaching the maximum electrical power produced. This is due to the electrical power production will remain constant while the wind speed keeps increasing.

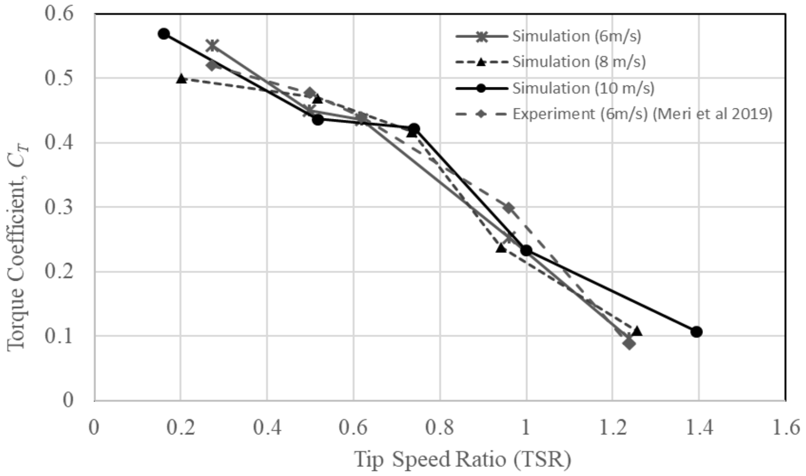


Fig. 5. Torque coefficient, C_T by simulation work

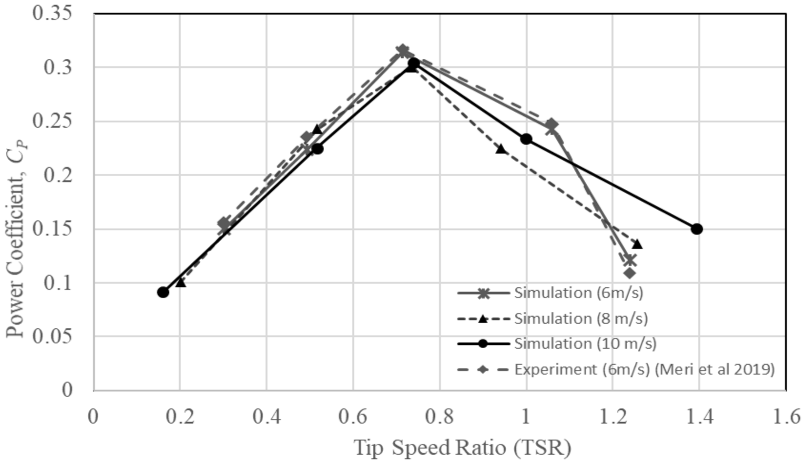


Fig. 6. Power coefficient, C_P by simulation work

3.2 Pressure and Velocity

The flow pattern of the rotational blade can be analyzed at a pre-processing result which shows the flow pattern at any condition. In this section, the plotting surface of velocity and pressure visualization will be discussed. Figure 7 shows the velocity contour result in particular wind spend and angular velocity. The velocity contour preview starts with 6 m/s wind speed with 16 rad/s followed by 8 m/s wind speed with 55 rad/s and 10 m/s wind speed with 105 rad/s. Generally, the velocity distribution for all wind speeds has the same gradient around the blade. A concave blade that takes force from the wind inlet is facing the high velocity at the returning blade while the convex part which blocks the area from inlet wind speed is facing the reduction velocity during the rotational condition. High rotation gives a high-velocity gradient around the blade.

Figure 8 shows the streamline and velocity vector obtained from the simulation of the flow around the new design of the Savonius wind turbine blade. This streamline gives a more realistic visualization where it showed that the effect of stirring flow occurs at the blade. By observing the inner side of the blade, we can see that the streamline indicated with a light blue that represents nearly 3 m/s velocity changed to green colour as it passed through the blade and continue with an actual inlet velocity of 6 m/s. For the velocity vector, it is seen that the blade is facing a rotational condition as the vector is rotated around the blade. The velocity vector shows the direction of the movement around the blade and the fluid domain. The velocity vector that gives bright red colour shows that the region is facing high velocity same goes for velocity contour distribution. Both figures of vector prove that the blade is rotating on the *y*-axis, and it showed that the velocity and pressure distribution effect when the rotation of the blade is animated using the number of time steps from the beginning until complete 1 revolution.

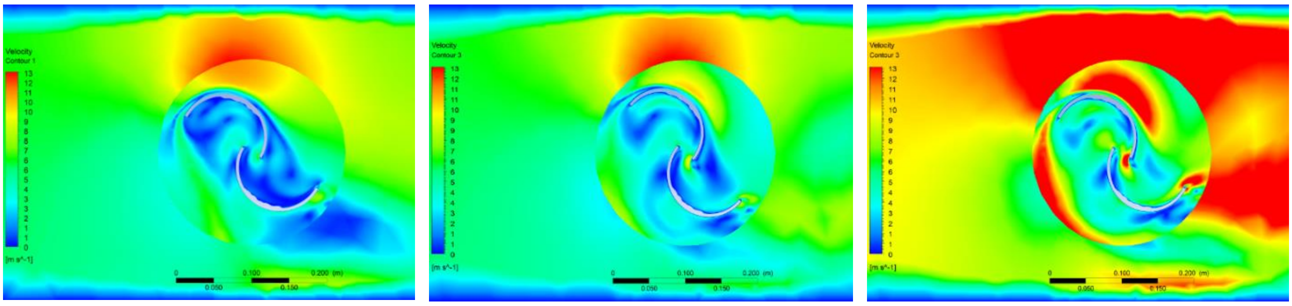

6 m/s 8 m/s 10 m/s

Fig. 7. Velocity contour at 6 m/s, 8 m/s and 10 m/s wind speed

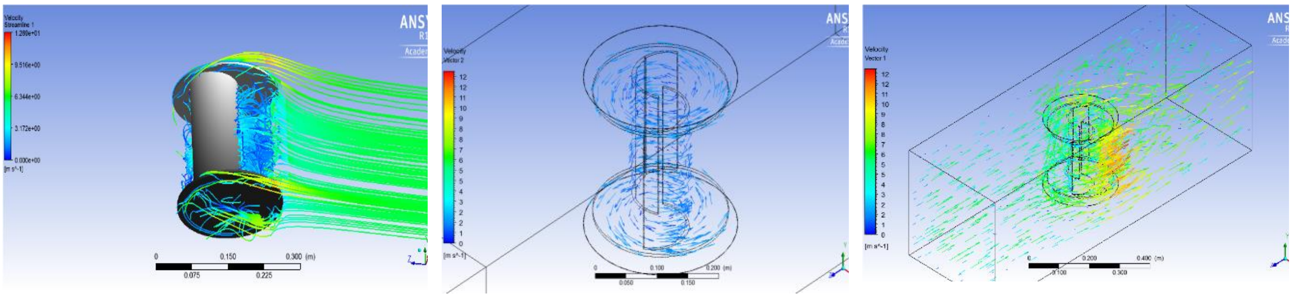

Streamline Velocity vector around the blade Velocity vector in the fluid domain

Fig. 8. Velocity vector and streamline

The pressure contour shows a high-pressure gradient with red colour at the concave surface of the blade. As the wind speed is increasing, the effect of the pressure gradient also increases. By observing both velocity and pressure contour, the high-velocity region occurs at the convex returning blade, due to the inertia effect generated by returning blade swept movement while the pressure contour has the lowest pressure at the same location. This phenomenon coincides with a theoretical study where high velocity will produce low pressure.

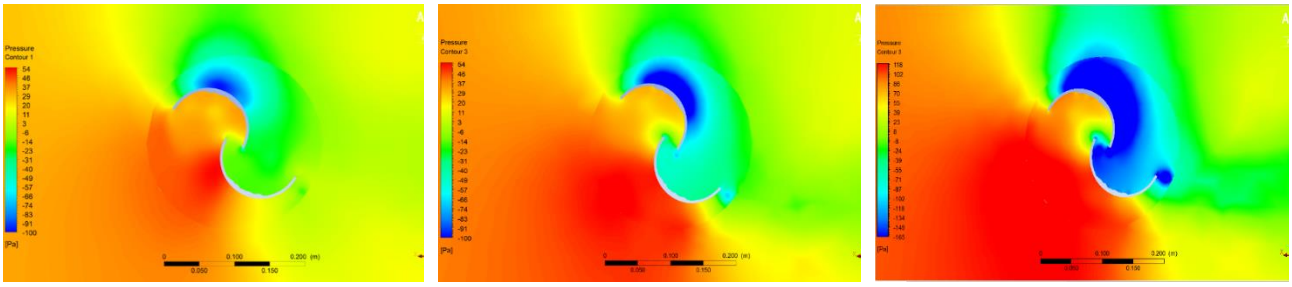

6 m/s 8 m/s 10 m/s

Fig. 9. Pressure contour for 6 m/s, 8 m/s and 10 m/s wind speed

4. Conclusions

In this study, a CFD approach had been used to determine the performance of the Savonius wind turbine based on the new design blade shape. The simulation analysis was conducted by using the transient method which was computed at each time of the quantity. For wind turbine cases, the value for each time is calculated based on each angle of the blade rotation. The k-e turbulence models are used for this solution because they can predict well near the boundary wall. The result obtained from the simulation study was compared to the experimental result which gives a good agreement for the torque coefficient and power coefficient. For the objective to investigate the effect of the wind speed on the performance of the new design blade, the results show that the performance of the Savonius wind turbine based on the new design blade shape had increased its power coefficient up to 20% with tip speed ratio of 0.71 compared to classical elliptical Savonius wind turbine. The different wind speeds produced a different revolution per minute of the rotation, hence increasing the power output of a Savonius wind turbine.

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