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Performance Investigation of Vertical Axis Wind Turbine with Savonius Rotor using Computational Fluid Dynamics (CFD)

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ABSTRACT

The quest of clean and sustainable energy has grown rapidly all over the world in the recent years. Among the renewable energy resources available, wind energy is considered one of the reliable, environmentally friendly, green and fastest-growing source of electricity generation. This generation is accomplished through wind turbines. However, the efficiency of these wind turbines is still very limited and unsatisfactory. The primary goal of this study is to evaluate the performance of a Savonius rotor wind turbine in terms of aerodynamic characteristics, including torque, torque coefficient, and power coefficient. The design of Savonius wind turbine blades is varied and its effects is observed. The simulation models are developed using a modeling software known as Solidworks 2021 and then generated into Ansys Design Modeler 2021 R1 to define the fluid domain. In total, three distinct turbine blades are modelled while varying the diameter and height of the rotor. The simulation study is performed using FLUENT 2021 R21. A constant wind speed value of 9.2 m/s has been used throughout the simulation. The simulation was carried out using a transient time flow with a constant upstream wind speed. The results have shown that the power coefficient of all models increases with TSR and the highest efficiency is consensually obtained at almost a unity (0.9) TSR. Comparing the performance of all models, Model 2 generates the highest power coefficient followed by Model 3 and Model 1, respectively. In terms of power, torque and torque coefficient, nearly similar conclusion is drawn.

1. Introduction

The evolution of renewable energy has improved significantly over the previous decade. Currently, renewable energy is an alternative to non-renewable. Human activity now pollutes the atmosphere with carbon dioxide, greenhouse gases, and other pollutants. Using non-renewable energy has caused the atmosphere to blanket and trap heat. This includes increased storm frequency, drought, sea level rise, and extinction. Unlike non-renewable energy, most renewable energy sources

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emit little or no CO2. Even when including "life cycle" emissions of clean energy (for example, the emissions from each stage of a technology's life manufacturing, installation, operation, decommissioning), the global warming emissions associated with renewable energy are minimal [1]. Solar, hydro, wind, geothermal, tidal, and biomass energy are examples of renewable energy sources that can supply sustainable energy services using everyday available and indigenous resources. It seems hard to cover each country's huge electricity demand with renewable energy alone. Wind energy is a prominent renewable energy source that comes in a variety of sizes [2, 3].

Wind turbines harvest the kinetic energy of the wind to generate mechanical power. This mechanical force can be used for certain tasks, or a generator can be used to power dwellings. Wind turbines harness the power of moving air to power an electric generator. A wind turbine resembles a fan. Unlike fans, wind turbines use the wind to generate power [4]. Horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). Since horizontal axis wind turbines can generate more electricity from less wind, they have dominated the wind industry. Although heavier, horizontal axis wind turbines perform poorly in turbulent conditions. The vertical axis wind turbine is more compact and can accommodate reduced electrical demand. In modest wind projects in residential areas, vertical axis turbines are common. This wind turbine can produce well in turbulent wind conditions from any direction. Moreover, vertical axis wind turbines are the best choice for installations with variable wind conditions [5].

The Savonius wind turbine is a VAWT which was invented by Sigurd J. Savonius in 1922. Savonius Rotor wind turbines were first commercialized in the 1920s. Savonius wind turbines are propelled by drag. This wind turbine's aerodynamic efficiency is lower than other wind turbines like the Darrieus rotor. However, Savonius rotors are reliable and straightforward, with strong starting torque and no wind direction issues [6, 7]. Moreover, Savonius rotor has a simple structure and requires low operating speed. Savonius wind turbine converting wind energy to torque in a rotating shaft. This turbine is usually attached to the ground or rooftop which consists of several airfoils that are mounted vertically on a shaft or framework. According to Svetlana [8], the variation of the power coefficient under gusty wind conditions depends on the level of gustiness. This means, the highest the gustiness, the more stable the power coefficient. It is a good feature since the city is gusty and stable rotor operation is favorable. However, compared to the horizontal axis wind turbine (HAWT), the vertical axis wind turbine (VAWT) receives less attention (HAWTs). The design research is sparse, and the sources are unreliable. It is true, VAWTs cannot be compared to HAWTs, even though VAWTs have their advantages. The VAWTs rotor performance is lower than HAWTs, which shows that it needs to be enhanced to make the VAWTs type equal to HAWTs type.

The technologies in wind turbines began to improve year by year. The innovations keep on driving new improvements in the application of wind power. Wind power capacity has grown dramatically, and the turbines that generate it have become more powerful, efficient, and cost-effective for power producers [9]. Thus, over the years there were many efforts to enhance the aerodynamic performance to harvest more electrical energy from the wind including rotor design and robustness of the blade, adding another rotor such counter-rotating technique or adding more blades such as multi-stage or inner blades using both computational and experimental techniques [10-14].

Furthermore, the Savonius wind turbine's blade design contributes to its performance. The simple blade design of the Savonius wind turbine has its advantages. Adding fins to the Savonius wind turbine blades, altering the number of blades, and attaching external overlap have been studied to improve performance [15]. It was discovered that doubling the blade diameter of a Savonius wind turbine doubled the output [16]. The amount of wind caught increases with blade size. However, the power output does not increase accordingly.One of the advantages of Savonius wind turbines is that they can capture wind from any direction and rotate slowly. Its blades revolve because of the drag force pressing on them.

Currently, there are so many kinds of design of Savonius wind turbine. However, in this study, the design process for the Savonius-type wind turbine begins with preliminary sketching by referring to the previous study by Lee [17] and modify this design to improve its performance. Thus, the major purpose of this work is to maximize wind energy harvesting and rotational mechanical electric generation of Savonius rotors. The rotor blade is varied and the performance of each size is observed and compared in terms of maximum lift coefficient of three rotor sizes. The simulation is performed in 3D models using Fluent solver while achieving parameters such as lift, drag, and torque efficiency. Moreover, the performance of Savonius rotor in terms of aerodynamic characteristics such as torque, torque coefficient, power and power coefficient are compared with different sizes of the turbine blade.

2. Methods

2.1 Selection and Modelling of Blade

The models investigated in this study is Savonius wind turbine with three different sizes of the blade which is the first model with the height and diameter of 1 m and 0.4 m, the second model with the height and diameter of 0.75 m and 0.3 m, and the third model with the height and diameter of 0.5m and 0.2m, respectively. The design of the rotor consists of two blades. The height is changed to obtain the different diameters of the Savonius wind turbine. After the modelling phase is complete, the process continued to the next step, which is solving the model in the simulation software. Figure 1 shows a model design of the Savonius wind turbine blade and Table 1 shows the geometrical parameters of the three simulation models.

Table 1
Dimensional parameters of the models

No.	Name	Dimension	
		Diameter	Height
1	Model 1	40 cm	100 cm
2	Model 2	30 cm	75 cm
3	Model 3	20 cm	50 cm

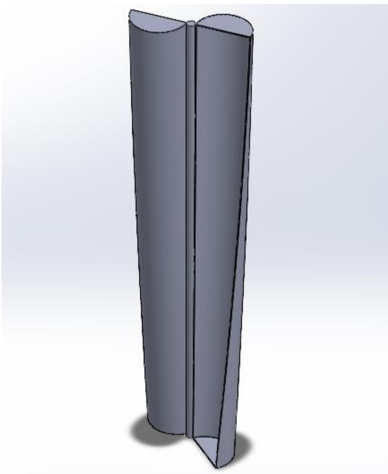

Fig. 1. Design of Savonius wind turbine model

2.2 Model Domain and Meshing

After importing the model into ANSYS, the square type of domain with a ratio of 12 and 32 between the square domain length and the rotor radius, as suggested from the previous study was sketched using Design Modeler. The setting of the domain is shown in Figure 2. The process of discretizing the computational domain to multiple numbers of cells or elements is called meshing. The number of cells for the mesh can be adjusted from the size of elements through the sizing option while implementing all triangles method for this study. The model's accuracy is also influenced by the work cells. The diagram below shows that increased meshing quality results in more exact flow solutions. As a result, creating the mesh is one of the most time-consuming and challenging components of the simulation. This is because improving mesh quality takes time and effort. Next, the adaptive sizing from the mesh sizing option is applied to get a more uniform mesh cell around the domain, as shown in Figure 3.

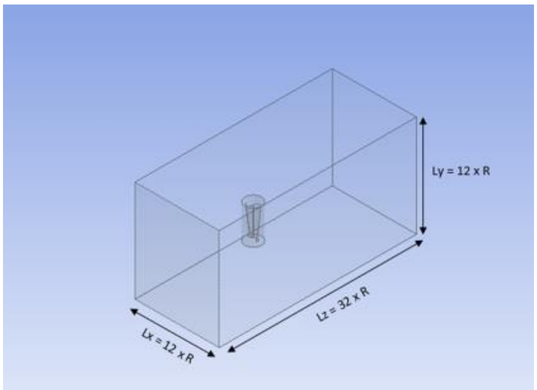

Fig. 2. Simulation domain

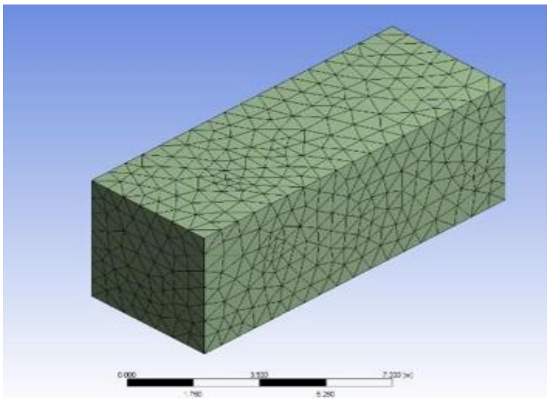

Fig. 3. Meshing for the whole simulation domain

2.3 Boundary Conditions and Flow Solver

This study consists of several boundary conditions, namely, inlet, outlet, boundaries wall, blade wall, and interface. The velocity inlet with steady distribution is applied at the inlet at the direction of the z-axis, and pressure outlet boundary conditions are assigned along the z-axis directly opposite to the velocity inlet boundary conditions. The wall boundary condition with a no-slip condition is applied to the blade wall, and the symmetrical wall boundary condition is assigned at the boundaries wall. For this study, there are two interfaces, which are interface-in and interface-out created around the blades separated by a certain distance. There is also a rotating and non-rotating interface where the magnitude and direction of the velocity can be applied to the rotating interface. The SIMPLE algorithm was used for the pressure-velocity coupling scheme for the solution method.

3. Results and Discussion
3.1 Model Validation

Before the simulation begins, there is one step that must be completed which is to compare the simulation results to those from the previous study. This ensures that the simulation method being used is reliable and accurate enough to be used for the remainder of the simulations. As a result, a validation process was carried out by transferring specific settings from the previous study to the current simulation settings to obtain the most comparable results possible. The power coefficient was calculated for this study using the simulation settings from the previous study, and the results were compared to those from ref. [17].

In Figure 4, the value of the power coefficient was plotted against the corresponding tip speed ratio (TSR) between current study results and previous study results using the same blade of the Savonius wind turbine. The graph shows that the trend between current and previous study results shows a similar trend from beginning to the end, which is promising and acceptable. The relative error was calculated to be around 18.60% on average.

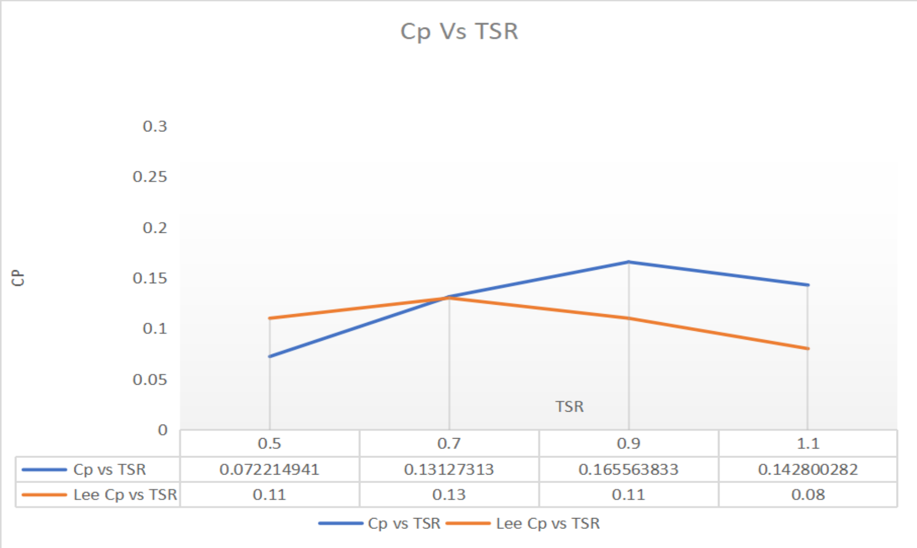

Fig. 4. The comparison between current and previous results

3.2 Comparison of Torque and Torque Coefficient

Primarily in a wind turbine, the performance of the wind turbine is usually determined by aerodynamic characteristics such as the torque, torque coefficient, power, and power coefficient. Torque also can be referred to as the moment of a force. Torque is a force that acts perpendicular to the axis of the rotating blade. The value of torque was obtained through the ANSYS Fluent software. The torque and torque coefficient comparisons between three models of Savonius wind turbine are presented as in Figure 5 and Figure 6.

By referring to the comparison graph in Figure 5, the pattern of the graph for all models is the same. The value is constant from TSR 0.5 to 0.9, and the torque decreases from TSR 0.9 to 1.1. Model 3 has the highest torque value, which is 0.5920 at TSR 0.5, followed by model 2, which is 0.3002 at TSR 0.5, and the last one is model 1 with the torque of 0.0753 at TSR 0.5 blade, which could affect the starting capability of the wind turbine, which is not covered in the current study.

Moreover, the relation between torque coefficient and the tip-speed ratio is depicted in the Figure 6. By referring to the comparison graph, the pattern of graph for Models 2 and 3 are the same where the graph pattern is constant from TSR 0.5 to 0.9 and then decreasing from TSR 0.9 to 1.1. The graph pattern for model 1 is different from other models since the pattern decreases from TSR 0.5 to 0.7, constant at TSR 0.7 to 0.9, and then decreases again from TSR 0.9 to 1.1.

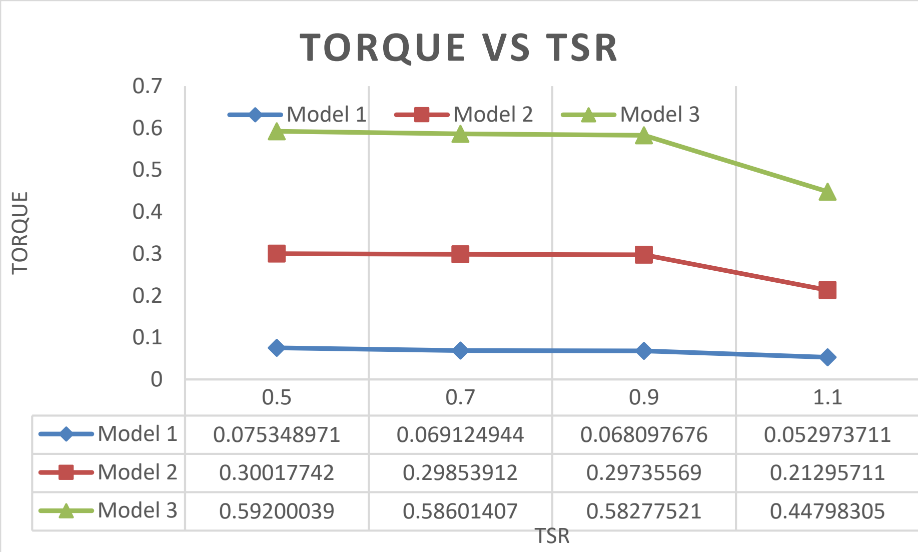

Fig. 5. Torque against the tip-speed ratio for all three model

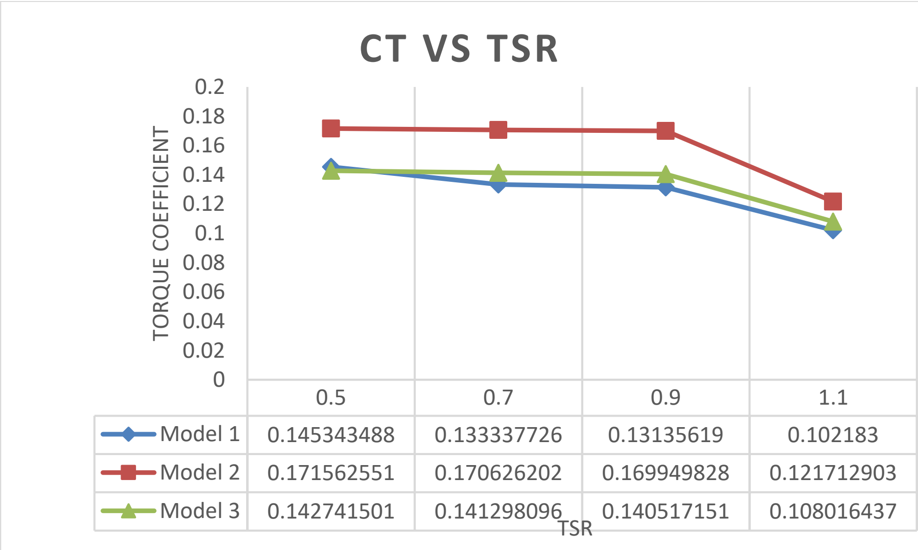

Fig. 6. Torque coefficient against TSR comparison for 3 model

3.3 Comparison of Power and Power Coefficient

Figure 7 depicts the relationship between power and tip-speed ratio. The highest power generated by all models is 24.13 W. Followed by 22.67W, 18.87W and 13.62W, respectively. All these values are obtained by the Model 3 simulation. Model 3 at the point of (TSR=0.7, 0.9) shows an enhanced performance percentage of 38.54% and 27.87%. Besides, model 2 has improved by 39.08% and 28.10% at TSR of 0.7 and 0.9, respectively, followed by model 1, which has an increment performance percentage of 28.24% and 26.74% at TSR of 0.7 and 0.9. By comparing the peak value of Cp for all models, the difference of 31.99% by model 3 and model 2, while the percentage of model 2 and model 1 is 65.63%.

Furthermore, the Savonius rotor's operation is determined by the lift and drag forces acting on the blades. The amount of these forces can be influenced by factors such as blade angle and blade shape. As a result, each rotor configuration has a unique power coefficient. The Cp of each model is compared for this purpose. Figure 8 depicts the results of 3 models after analysed and plotted, where *Cp* is a function of TSR. Figure 8 clearly shows that model 2 with a height of 0.75m and a diameter of

0.3m has the best performance in terms of Cp, followed by model 3 with a height of 1.0m and a diameter of 0.4m, and model 1 with a height of 0.5m and a diameter of 0.2m. Model 2 at the point of (TSR=0.7, 0.9) shows an enhanced performance percentage of 39.16% and 28.14%. Besides, model 3 has improved by 38.52% and 27.91% at TSR of 0.7 and 0.9, respectively, followed by model 1, which has an increment performance percentage of 28.33% and 26.69% at TSR of 0.7 and 0.9. By comparing the peak value of Cp for all models, the difference of 18.96% by model 2 and model 3, while the percentage of model 2 and model 1 is 25.62%.

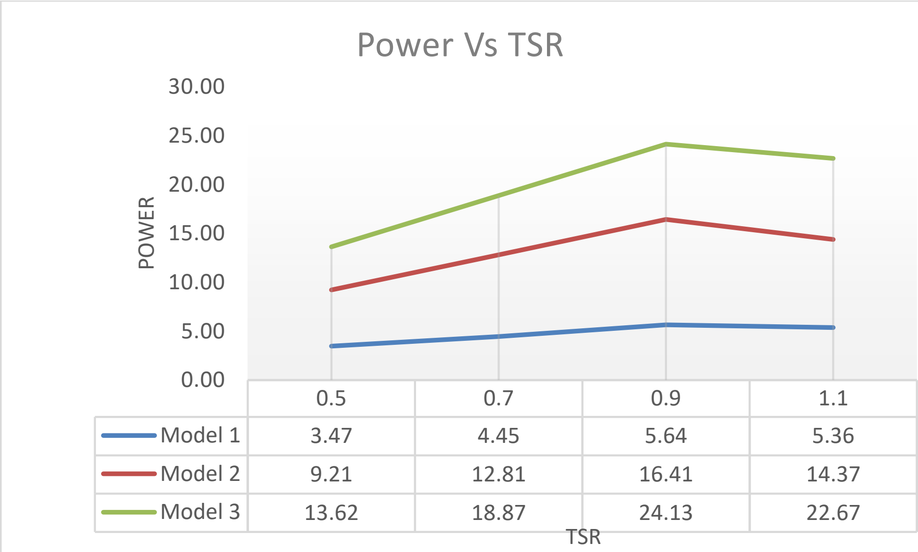

Fig. 7. Power against TSR comparison for 3 models

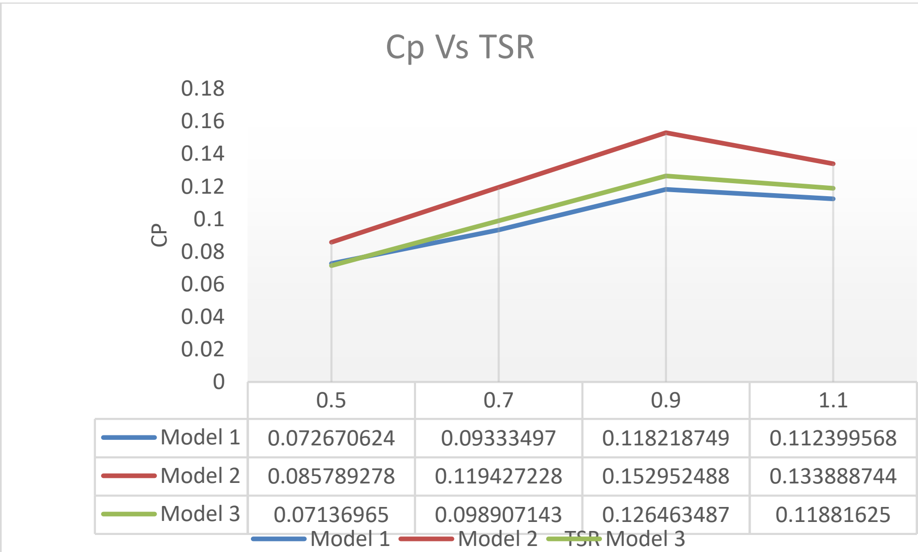

Fig. 8. Comparison of Cp against TSR for 3 Model

3.4 Velocity and Pressure Distributions

It is significant to show the velocity and pressure distributions around the rotor blade while studying fluid flow properties during simulations. Thus, the velocity and pressure distributions are shown in Figure 9 and Figure 10, respectively. The velocity distributions at the leading edge of the blades are low due to stagnation phenomenon when the blade encounter the wind while creating some vortex building up inside the rotor, as shown in Figure 9. In terms of pressure distribution, since pressure drop across the blade wall is minimal, there are no significant differences in the pressure distribution contour outcome. The average pressure across the blade wall, however, varied. The rotor's spin causes the wind around it to rotate. It helps reduce the incoming wind velocity on the returning blade, which affects rotor performance due to the resistance generated between the blade surface and the incoming air, as shown in Figure 10. The low velocity around the blade causes a high pressure on the convex side of the returning blade. Low-pressure zones are visible at the leading edge of the blade, where the wind is strongest. Its size and shape have shifted. Savonius rotors spin due to the pressure drag force. The force varies with the blade angle. So, the blades' various geometries are exposed to the wind. In this way, each configuration has its own drag force. Thus, the rotor's average torque varies with blade position and rotation speed. A blue spot inside the inner blade of the returning blade represents a low wind velocity. Notably, the shape of this zone changed with the blade arc angle.

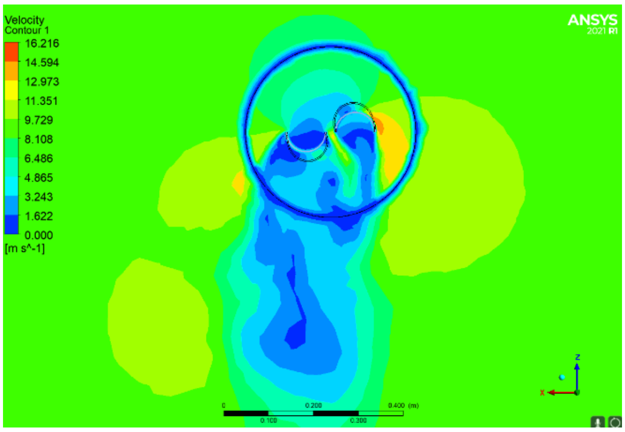

Fig. 9. Velocity distribution of Model 1

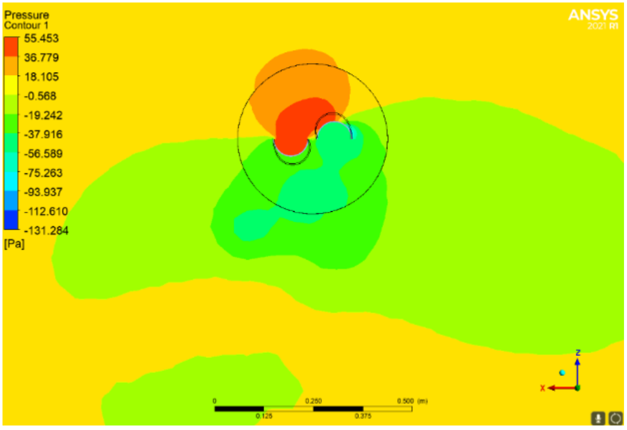

Fig. 10. Pressure distribution of Model 1

4. Conclusion

In this study, the efficiency of the Savonius Rotor wind turbine model was numerically evaluated by using with various blade sizes at 9.2 m/s. The main objective was achieved by testing the performance of Savonius wind turbine and comparing the torque and power output of various rotor sizes at constant wind speed. The results have shown that the power coefficient of all models increases with TSR and the highest efficiency is consensually obtained at almost a unity (0.9) TSR. Comparing the performance of all models, Model 2 with 0.75 m height and 0.3 m diameter produced the highest power coefficient compared to the other two Savonius wind turbine models, followed by Model 3 and Model 1, respectively. In terms of power, torque and torque coefficient, nearly similar conclusion is drawn. However, the power and power coefficient increase from low TSR until the optimal TSR, while torque and torque coefficient are higher at low TSR and decreases as the TSR increase.

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