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Numerical and Experimental Study on the Savonius Rotor Performance with The Gap Width Variations of Ventilation in Middle Blades

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Abstract. In previous research, the use of ventilation at 15° from the outer end of the blade Savonius was able to increase the efficiency of Savonius windmill. This study aims to determine how the influence of the fixed ventilation on middle of the blade towards a performance of the Savonius windmill. There are one model of the conventional Savonius windmill and three models of the ventilated Savonius windmill that simulated by CFD and tested in the wind tunnels. Simulation variabels used are variations for ventilation width and the rotation angle position of the rotor. Experimental variables were variations for the gap width of ventilation and wind speed. The ventilated Savonius with ventilation position in the middle of the rotor blades turns out to have the average power coefficient (C_p) lower than the conventional Savonius windmill. The wider the gap from the ventilation will further reduce the performance of the ventilated Savonius rotor. In this study, the SV65-10 model produced the worst performance. This power coefficient of the SV65-10 model is 29% lower than a conventional Savonius rotor..

Keywords: Savonius rotor, ventilation, power coefficient, wind speed, CFD Simulation.

1. Introduction

Indonesia is a tropical country and passed by equator. Indonesia has great wind energy potential but is only utilized 5.38% [1]. However, winds in Indonesia have characteristics such as: low wind speed 2 m/s - 6 m/s and fluctuating wind speed intensity [2]. The windmill that corresponds to the wind characteristic in Indonesia is Savonius's windmill. Savonius Windmill has simple construction, easy and inexpensive treatment. Unfortunately, Savonius's windmill has a low efficiency or power efficiency (C_p) of 15% [3].

Much research has been done to improve the efficiency of Savonius windmill. The performance of Savonius rotor has been studied by many researchers in order to determine the optimum design parameters of this rotor. Some of these studies have succeeded in improving the energy distribution of wind flow so that it is more effective in rotating the rotor of Savonius. The effect of blades overlap, blades spacing, number of blades, blades shapes and permanent ventilation on blades are among the main parameters that affect the effectiveness of wind energy and the performance of a Savonius wind



rotor. There is also research the curtain on the outer of rotor which also aims to further optimize the energy of wind flow in rotating the rotor Savonius.

For the dimensions of the blades overlap, there is not a consensus among the results obtained in published studies. Blackwell et al. [4] conclude that the optimum size for the blades overlap dimension is equivalent to a value between 10 and 15% of the chord size. Fujisawa [5] shows if the optimum size for the blades overlap is equal to 15% of the blades chord size and that is able to increase C_p almost 13% higher than the Savonius rotor without blades overlap. Menet, JL. [6] also has been investigated the various overlap ratios of Savonius rotors. The torque coefficient of the Savonius rotor, the best value of the overlap is 0.242. As for the verification of the influence of the blades spacing, most studies conclude that a null blades spacing gives the best performance of a Savonius wind rotor with a semicircular profile blades. For large blades spacing, the air does not satisfactorily focus on the concave portion of the returning blade, reducing the power of the turbine [7].

Alexander and Holownia [8], Ali, MH. [9], Saha et al. [10] carried out an experimental investigation on the performance improvement of the Savonius rotor by number of the semicircular profil blades. They reported that, the optimum number of blades is two for the Savonius rotor. N.H. Mahmoud et al. found that, two-bladed Savonius rotors have almost 50% higher peak power output than the three-bladed ones. As for, Saha and Rajkumar [11] have investigated the use of the twisted blade on Savonius windmill. Twisted geometry of the blade profile has a good performance as compared to the semicircular blade geometry. The results show if the twisted blade is able to increase $C_p = 2.95\%$ higher than the Savonius rotor with the semicircular blade. But in its application, the new modification of the blade such as the twisted blade is likely to make the shape of the Savonius blade more complicated and difficult to produce it.

Golecha et al. [12], Altan [13], Mohamed et al [14] investigated the use of the curtain in front of the convex side of the Savonius blade. They have been testing the use of directional curtain to prevent the negative torque on the blade Savonius. The curtain also is able to direct the wind toward the concave side of the Savonius rotor blade. The aim of this work is to determine the optimum configuration of Savonius rotor which gives the higher performance. The Altan's results showed that the best position of the curtains could increase C_p of Savonius rotor approximately 38.5%. The use of obstacle plate by Mohamed is able to increase the performance of Savonius windmills up to 27%. On the development of further research, Mohamed et al. and Altan et al. investigated a study of computational numerical simulations to optimize the geometry of the Savonius windmill with the curtain on the outer of rotor. From Mohamed's results, the performance of Savonius windmill increased of at least 30% for $0.3 < TSR < 1.4$. Results of the Golecha's research conclude that the deflector plate at its optimal position increases the coefficient of the power by 50% for a single-stage modified Savonius rotor. Unfortunately, the use of the wind curtains that permanently outside the Savonius rotor is very difficult to apply in the field because the wind coming from any direction, unlike the testing in a wind tunnel.

Permanent ventilation of the blades is also one of the main parameters that can improve the effectiveness of wind energy and the performance of Savonius wind rotor. Savonius rotor with ventilated blades is the latest innovation to improve the efficiency of the Savonius windmill. The idea of permanent ventilation on Savonius blade was discovered by Rudi Hariyanto, et al. (2016). The symmetry axis of the ventilation long side placed right at 15° from the outer end of the blade Savonius. Rudi H., et al. [15] have also compared experimental results with numerical results. Maximum efficiency of ventilated Savonius is 25% better than conventional Savonius. Ventilation on the blade are also able to eliminate a critical position at 165° rotation angle of the conventional Savonius rotor.

This paper will also present a performance analysis of Savonius with ventilated blades but for ventilation position in the middle of the rotor blades. . Research the Savonius rotor with ventilation position in the middle of the rotor blades has not been investigated before. In this study, we investigated the influence of the clearance width of ventilation and variations in wind speed to rotor performance. The performance analysis of all rotor models use CFD simulation and eksperimental testing. Further, the experimental results are compared with the conventional Savonius rotor and CFD simulation.

2. Experimental Methods

2.1 Spesification of Models

Fig. 1 illustrates geometry of Savonius rotor with ventilation position in the middle of the rotor blades. Geometry of the permanent ventilation on the blades also like the research previously [15] but the axis of symmetry of the ventilation long side placed right at 65° from the outer end of the blade Savonius. The long side of the ventilation further pushed towards the blade so as to form a gap where the clearance width can be varied. The following is geometry of the ventilated Savonius rotor that used in this study:

- Disk diameter of rotor (D) = 200 mm
- The rotor height of the rotor (H) = D
- The diameter of the blades (d) = $0,5.D$
- The width of overlap (e) = $0.2.d$
- The diameter stainless steel shaft (d_s) = $0,03.d$
- The gap width of ventilation (s) = $(0.02 - 0.1).d$.
- Lenght of ventilation (h) = $0,7.H$

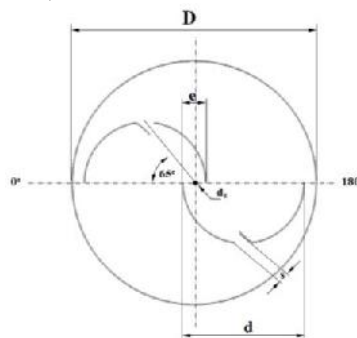
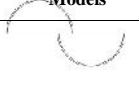


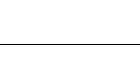


Figure 1. Cross-section 2D models of the ventilated rotor Savonius

Table 1 shows four models studied and its codification. Four models are one model the conventional Savonius rotor and three models the ventilated Savonius rotor. The variables that varied from the ventilation on the blade is the clearance width of ventilation. All models are made from the same material like the research previously.

Table 1. The Savonius rotor models and its codification

No	Type Windmill	The Clearance Width of Ventilation (s)	Cross-sectional 2D Models	Codification
1	Conventional Savonius	-		SC
2	Ventilanted Savonius	$0,02*d$		SV65-02
3	Ventilanted Savonius	$0,05*d$		SV65-05
4	Ventilanted Savonius	$0,1*d$		SV65-10

2.2 Numerical model description

Numerical model in this study use Computational Fluid Dynamics (CFD) - Fluent. CFD simulation is used to obtain the flow behavior prediction, the vector velocity, fluid flow profile and pressure. Simulations performed on rotor angular position from 0° to 180° with a change position every 15° to the direction the wind is coming. Set- up boundary conditions used in CFD simulation is the inlet $v = 5 \text{ m/s}$ (constant), outlet: pressure outlet = 101325 Pa (constant). The boundary conditions that used for all simulations are same as the simulation study of Rudi H. et al. [16]. Solution method includes the scheme: semi- (simple), the momentum: order upwind second. In the fluid flow analysis, the convergence criterion use to solve the Navier-Stokes equation by iteration. Then the selected report of result is the force and moment value.

The complete two-dimensional computational model includes an inner of rectangle containing the rotor model. The computational domain of the rectangle is taken as $0.5 \text{ m} \times 0.5 \text{ m}$. The next step in the simulation effort is the generation of the computational mesh. Sizing of mesh use advanced size function on: curvature and proximate. Thus, two fluid mesh sections are clearly noticeable. First, adjacent to the rotor blades, very small elements to capture the very sharp velocity gradients at the blade surface and second, the relatively bigger elements in the outer surrounding of the turbine model. Fig. 2 show if the grid node density utilized in the rotor blade domain was higher than in the other domains.

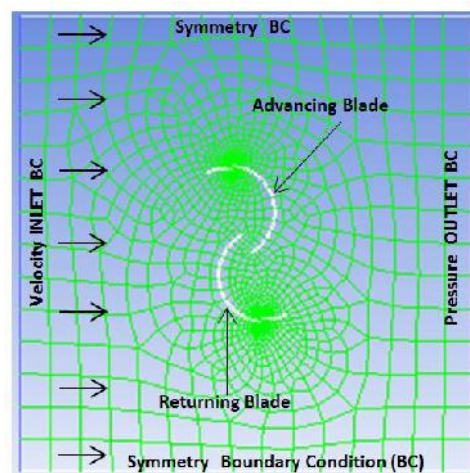


Figure 2. Grid generation around blade of the rotor model

This analysis, the following assumptions are made to select the model and the solver: Basically, the flow field around a blade of rotor model is highly turbulent like a result of research from Rudi H. et al. Thus, the main features of turbulence must be considered while choosing the computational technique to solve of a turbulent flow over the rotor model. Therefore, the selection of the turbulence model plays an important role for obtaining the desired computational results. Fluent simulation program for Savonius rotor can use the k-turbulence models standard. K- turbulence model of the standard has been able to provide an accurate simulation results.

Transport Standard Model equation for (k-) are as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (1)$$

and

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_b + C_{3\varepsilon} G_k) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \quad (2)$$

Where:

- G_b is the generation of turbulence kinetic energy due to buoyancy
- Y_M is the contribution of fluctuating dilatation in compressible turbulence with the overall dissipation levels, calculated as described in the Securities Compressibility in k -
- C_1 , C_2 and constant C_3 each valued 1.44, 1.92, and 0.09.
- σ_k and σ_ε turbulent Prandtl numbers for k and ε each worth 1 and 1.3.

2.3 Eksperimental Methods

There were two methods of testing in this study:

1. The first test is testing the performance of the models in the wind tunnel with variations in wind speed of 1-7 m/s. Testing data that taken is rotor rotation (rpm).
2. The second test is testing the torque of the rotor with a small dynamometer. Testing data that taken are variations of rotor rotation (n) to get the braking load (F) against the shaft of rotor. The controlled variable is the wind speed constant at 5 m/s. Then the testing data are used to calculate tip speed ratio (TSR), torque coefficient (C_t) and power coefficient (C_p) as follows:

- TSR is calculated from

$$TSR = \frac{U}{v} = \frac{\omega \cdot R}{v} = \frac{2\pi n R}{60 \cdot v} \quad (3)$$

Where: R is radius of rotor (m), v is wind speed (m/s), n is rotation of rotor (rpm).

- The power coefficient C_p can be determined from the following equations:

$$C_p = \frac{P_m}{P_w} \quad (4)$$

Where P_m is the mechanical power and P_w is the wind power.

The mechanical power can be calculated from

$$P_m = T \cdot \omega \quad (5)$$

The wind power can be calculated from

$$P_w = \frac{1}{2} \rho A v^3 \quad (6)$$

Where A is the projected area of the rotor in (m²)

3. Results and Discussion

3.1 Rotation Comparative of the rotor model

Experimental results justify the simulation results. The ventilation on the middle of Savonius's blade actually degrades the performance of the windmill. Figure 3 shows if the increasing ventilation width on the SV65 model causing lower rotor rotation. The average decrease in rotation of the SV65 2, SV65 5 and SV65 10 models is 3%, 9% and 23% compared to conventional Savonius rotation for all variations of wind speed.

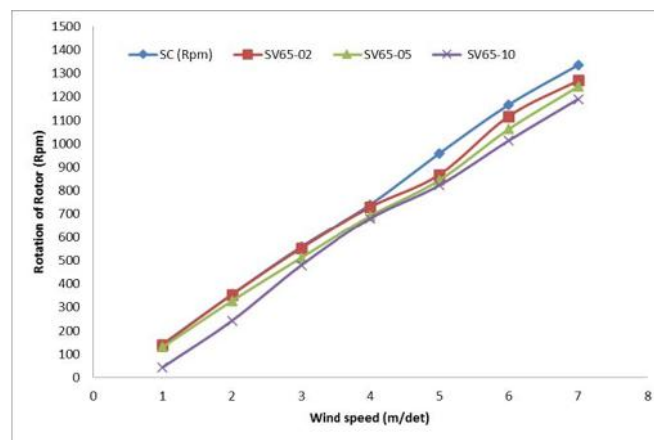


Figure 3. The rotation of Savonius rotor models

3.2 Power coefficient ratio analysis (C_p)

Figure 4 shows if the SV65 2, SV65 5 and SV65 10 models only produce 85%, 74% and 71% efficiency (C_p) compared to conventional Savonius C_p values. C_p experimental results are similar to static torque from the simulation results. Torque is directly proportional to useful power. Thus, the lower of the torque that produced by the rotor causes the lower of the C_p value of a rotor model.

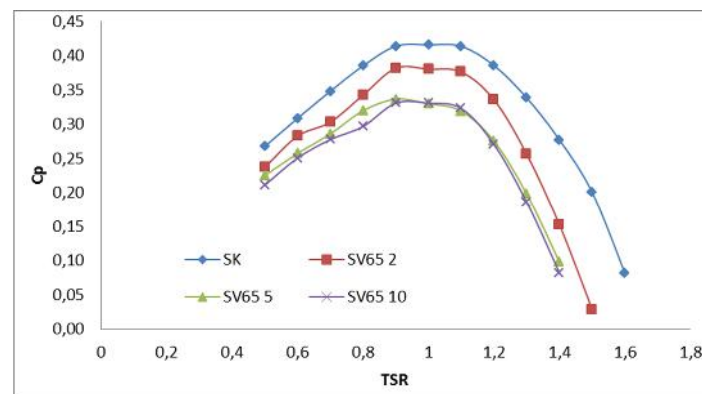


Figure 4. The value of the conventional SV65 and Savonius rotor coefficient (C_p)

3.3 Static torque of Model SV65

Figure 5 shows if permanent ventilation at the center of the blade has lowered the performance of Savonius's rotor. The larger of the ventilation gap causes the resulting static torque to be lower. The SV65 2, 65 5 and 65 10 models are only capable of generating static torque of 62%, 53% and 39% respectively compared to conventional Savonius torque. One cause is the formation of negative torque at 165° turning angle. This means that at this angle, the rotor tends to reverse and greatly affects the low total torque of the SV65 model. The SV65 2, 65 5 and 65 10 models are only capable of producing static torque of 62%, 53% and 39% compared to the torque of conventional Savonius. One of the causes is the formation

of negative torque at a rotary angle of 165° . Negative torque values that occur are (-46) to (-83). This means that at this angle, the rotor tends to reverse and has a large effect on the low total torque value of the SV65 model.

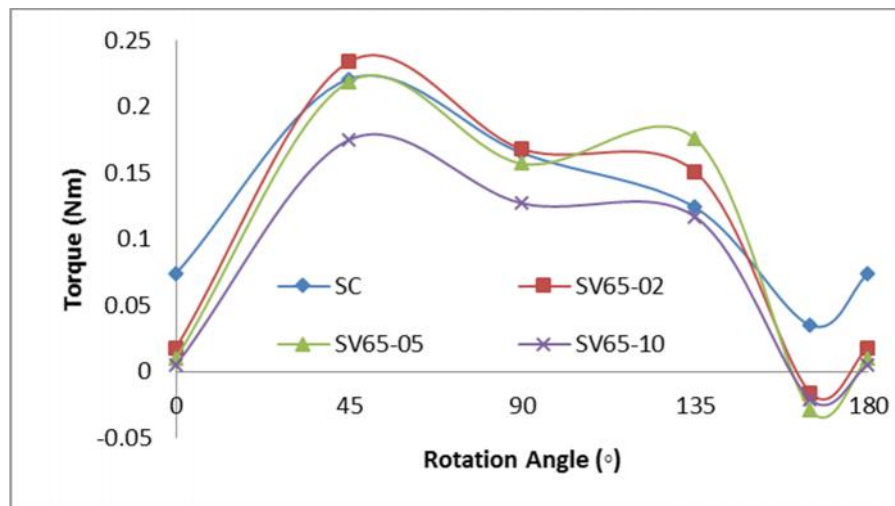


Figure 5. Effect of ventilation in middle blade to torque

Figure 5 also shows if the SV65 model is only able to produce the highest static torque at a 135° rotating angle. The torque values of the SV65 2 and SV65 5 models are 122% and 142% higher than the torque of the SC model. At a 135° rotation angle, the ventilation position against the x-axis forms an angle of 20° . This shows if ventilation of SV65 models are able to advance the lifting force of the wind so that the wind is able to rotate the rotor at the rotation angle 135° .

3.4 Airflow analysis on the concave surface of the Savonius blades

Viewed from the airflow profile, ventilation in the center of the blade is unable to shift the center of the driving force that acting on the blade. Figure 6 shows if the center of the driving force on the two blades between the conventional Savonius and the SV65 model is the same position at every rotation angle. Thus, the ability of the rotor to convert the wind velocity into pressure on the concave surface of the blade that will determine the performance of the rotor models. For example at a 135° rotation angle, the red color on the concave surface (number 1) of the SV65 2 and SV65 5 models looks wider than the conventional Savonius. This indicates if the wind pressure or positive force on the concave surface of the blade of both the SV65 2 model and the SV65 5 model is larger than the conventional Savonius. If the gap of ventilation is widened to 10% of the blade diameter (d) as the SV65 10 model, the red color on the concave surface of the blade appears to be smaller than the conventional Savonius. The reason is that some of the wind directly breaks through from the ventilation slot and without having time to hit the concave surface of the blade. So the wider the ventilation gap will result in the greater loss of the wind energy.

The larger ventilation slot of the SV65 model causes the greater loss of wind energy causing less static torque.

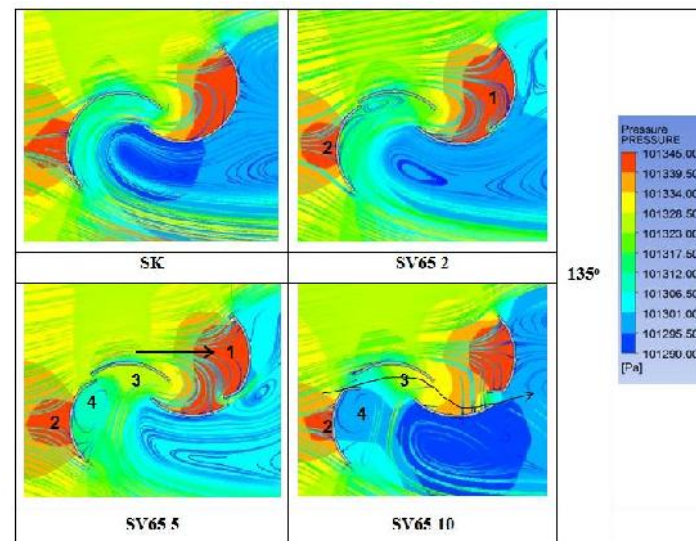


Figure 6. Comparison of simulated air pressure and airflow profiles between SV65 and Savonius Conventional at turn angle 135°

As for a review of the pressure or negative force acting on the convex surface of the blade, the negative force on the SV65 model is smaller than that of the conventional Savonius (number 2). The ventilation position in the center of the blade causes some of the mass flow rate of the wind to be sucked into the concave portion of the blade. This will reduce the wind pressure on the convex surface of the blade. The widening ventilation of the SV65 model causes the negative force of the wind to be lower. This is indicated by the less red color on the convex side of the blade.

The area at number 3 confirms if the width of the ventilation gap and mass flow rate of wind that sucked through ventilation gap is directly proportional. But the airflow on the inside of the blade goes directly to the ventilation gap of the partner's blade. This causes the air in the area of number 4 also get sucked so that the pressure becomes smaller. As a result of the SV65 10 model, the pressure difference between the convex surface of the blade and the inside becomes enlarged, or it may be said that the inside of the convex side of the blade (area4) loses energy to against the negative forces that acting on the convex surface of the blade. This causes the static torque value of the SV65 10 at a 135° rotation angle to be lower than that of the conventional Savonius.

Static torque of SV65 model at $165^\circ - 180^\circ$ rotation angle is very low. Even at a 165° rotation angle is negative. This means that energy loss of airflow is very large. Figure 6 shows if at 165° and 0° rotation angles, the vortex that formed on the concave surface of the advancing blade is wider and has more vortex flow lines than the conventional Savonius (shown by numbers 1 and 2). The ventilation position in the middle of the blade also pulls the vortex until the vortex position shifts close to the surface of the blade wall. The wider the gap of ventilation causes the wider vortex circle that formed and cover almost the entire surface of the blade. Vortex causes pressure of area in front of the blade to be very low. As a result all the kinetic energy of the wind is sucked by the vortex without having to hit the concave wall of the blade. This causes the torque to be negative at a 165° rotary angle and is extremely low at 0° .

As for the associated wind flow losses occurring at 45° and 90° rotating angles are caused by some direct wind passing through the ventilation gaps without hitting the concave wall of the blade. The larger the blade gaps then causes more wind to pass through the ventilation vents and the greater the lost wind energy. Figure 8 shows the airflow line passing through the ventilation openings. This causes the air pressure behind the SV65 blade (number 3) to be larger than the conventional Savonius blade. This also causes the pressure difference between the porous surface of the SV65 blade with the back of the blade to become smaller. The decrease in the pressure difference causes a decrease in the value of the positive driving force. This means that at both rotation angles, SV65 model is heavier to rotate than conventional Savonius model. Therefore the static torque value of the SV65 model on both rotation angles are also smaller than the conventional Savonius.

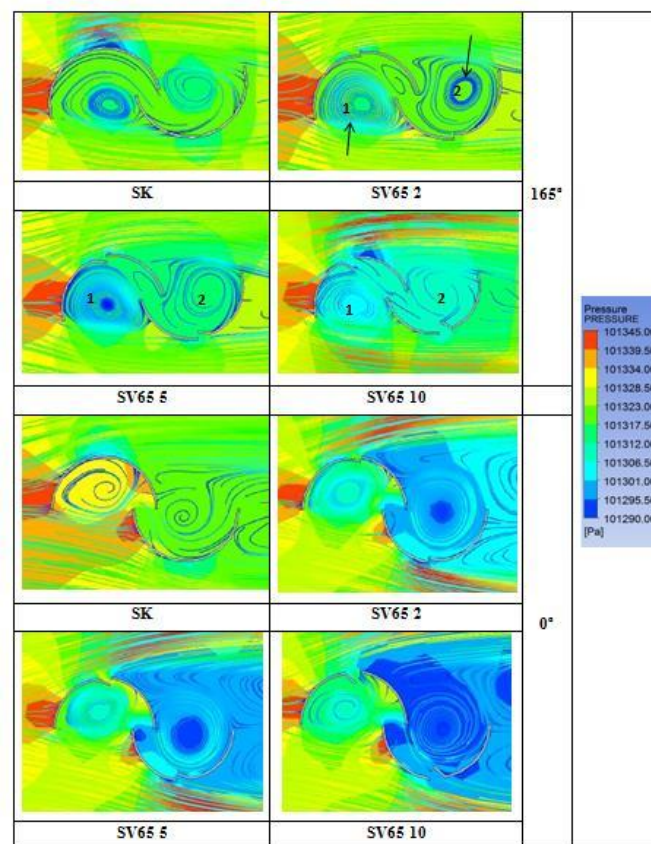


Figure 7. Comparison of simulated air pressure and airflow profiles between SV65 and Savonius Conventional at 165° dan 0° rotating angles

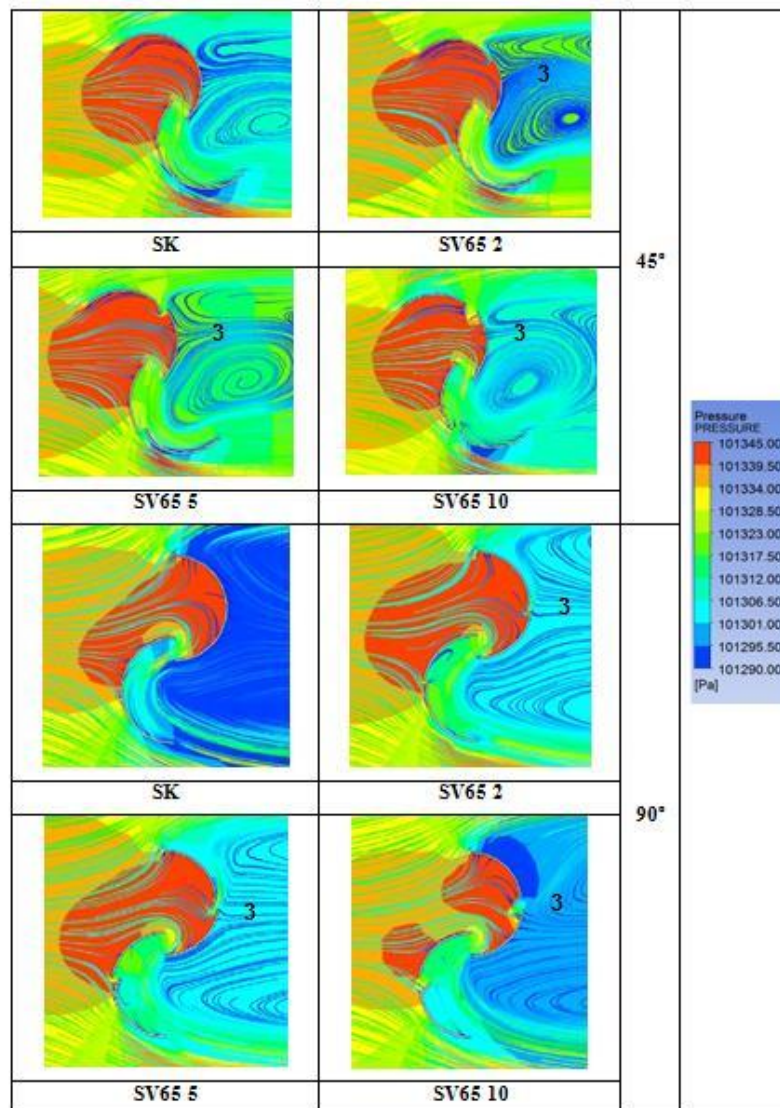


Figure 8. Comparison of simulated air pressure and airflow profiles between SV65 and Savonius Conventional at 45° dan 90° rotating angles

3.5 Vortex Comparison In Front Of The Blade Concave Surfaces

The concave surface of the blades is the most important part of Savonius rotor for producing a positive torque. However, at a certain angle of rotation, in front of the concave surface of the blade occurs a vortex that an adverse for the rotor rotation. Figure 7 showed if the vortex is formed in front of the concave surface of the blades. Vortex will absorb some of the kinetic energy of the wind. This causes the pressure acting on the concave surface of the blade to be low

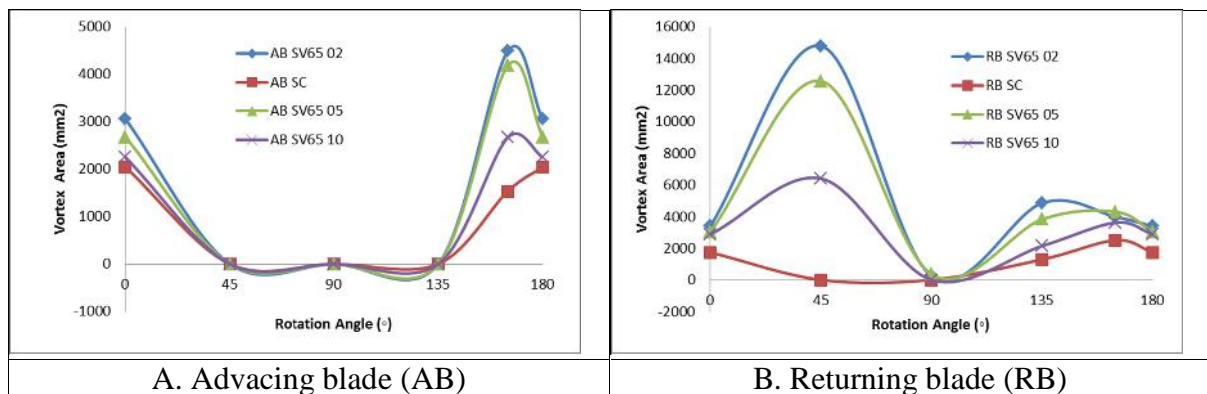


Figure 9: Vortex area in front of the concave surface on advancing and returning blades

Gambar 9 memperlihatkan jika at the rotating angle of 165° - 180° , the ventilation on the SV65 blades justru menyebabkan terbentuknya luas vortek in front of the concave surface of the advancing blade yang lebih besar dibanding pada sudu Savonius konvensional. The larger the area of the vortex then the greater the pressure difference that occurs between the center of the vortex to the outside of the circular vortex.. So the loss of kinetic energy due to it is absorbed vortex also getting bigger. Vortex will absorb some of the kinetic energy of the wind. This causes the pressure acting on the concave surface of the SV65 blade to be negatif. Dengan demikian torsi statis pada sudut putar 165° ini juga bernilai negatif.

Ventilasi di tengah sudu juga menumbuhkan vortek yang sangat besar didepan concave surface dari returning blade dan posisinya lebih dekat dengan convex surface dari advancing blade pada sudut putar 45° dan 135° terutama pada model SV65 2 dan SV65 5. Hisapan dari vortek mampu membuat advancing blade berputar lebih cepat dan menghasilkan torsi lebih besar dibanding model SC.

4. Conclusions

The simulation and eksperimental results show that if the use of ventilation in the middle on the rotor blades actually decreases the performance of Savonius windmill. The wider the gap of the ventilation causes the rotation and the efficiency of the rotor to become smaller. From simulation results, the static torque that produced by the SV65 model is less than 55% compared to the conventional Savonius model. From eksperimental results, C_p of ventilated Savonius is less than 85% compared to C_p of the conventional Savonius at a wind speed of 5 m/s.

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