Investigation on Improving Performance by Varying Stagger Angle of Cylinder in Returning Position to Overlap Savonius Wind Turbine

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***Abstract*—Wind energy is an alternative energy driver in reducing the use of fossil energy. Investigations into Savonius wind turbines are crucial for improving turbine performance. The investigation of the performance is conducted by the overlap turbine (β) of 0.3 using experiments and numerical. The experimental study used a Savonius turbine model placed in the test section with a turbine diameter and height of 40 cm. The Savonius turbine adds a cylinder by varying γ of 45°, 55°, 65°, and 75° placed on the returning position namely upstream of returning. The parameters in this study are ds/D of 0.4, and S/d of 1.7 with varying wind celerity of 5 m/s, 6 m/s, and 7 m/s. Numerical studies were carried out to validate the experimental results using the Unsteady for Realizable k-ε turbulence model. The experimental study shows that the highest performance occurs at $\gamma = 55^o$ at wind celerity of 5 m/s with the highest Cp of 0.389 and an increase in turbine performance of 18.70% compared to the original savonius wind turbine. Numerical simulations show valid values and flow phenomena indicate the performance in streamline and pressure contour.**

***Keywords*—Savonius, overlap, cylinder, stagger angle, returning position, power coefficient**

I. Introduction

Wind energy contributes to electrical energy by blowing wind into a turbine which causes the turbine to rotate and then produces electricity. Wind celerity in Indonesia a range from 3 m/s to 6 m/s per year [1]. Articles related to the Savonius turbine have been highly developed and refined over the years with modifications such as change in the number of blades, turbine geometry, adding disturbances in the form of deflectors and cylinders on the reverse and forward sides. This will significantly improve turbine performance by strengthening it, particularly through the implementation of helical forms and geometries utilizing Myring. Turbine geometry is developed numerically and the development of helical geometry shows improved performance [2]. Performance improvements have been made considering the new blade shape, which was carried out using numerical simulations using ANSYS Fluent 15.0 with the turbulent model SST K-ω model. The power coefficient is shown to be greater than that of conventional blades with an increase of 20% [3].

The development of Myring successfully demonstrated the best performance at $n = 1$ with the best Cp achievement compared to other n [4]. The application of Myring for $n = 1$ was developed as a replacement for $n = 2$ (original Savonius) showing the highest Cp occurs at an overlap of 0.2 in about 62.83 % [5]. Myring has been modified by installing cylinders at a diameter ratio of 0.4 which produces the highest Cp and the performance enhance in about 42.88% [6]. Modification of the advancing side cylinder placement using formula of Myring $n = 1$ showed the highest performance at a diameter ratio of 0.4 [7]. Different treatments by rotating the cylinder had a positive impact on turbine performance. The highest performance was indicated at a diameter ratio of 0.4. The performance increase was approximately 66.193% compared to the original Savonius [8].

Savonius performance has been enhanced by a change of the number of blades, the addition of cylinders, deflectors, and the position of the cylinders. Changing the number of blades provides the best performance results

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with 2 blades and overlap ratio from 0.1 until 0.15 [9]. Blades that change their geometry in experiments with the best operating parameters provide variations in the number of blades from 2 to 4. The highest performance occurs with two blades compared to the others. Installation of end plates to rotor can increase performance compared to a single end plate. Two stages on a rotor have greater performance than a single stage [10]. The Savonius performance with overlap was also studied numerically, which can reduce negative torque. The net torque results in increased turbine performance and obtained the highest *Cp* value at overlap of 0.2 [11]. Numerical simulations on variations of turbine blade overlap have been validated experimentally with 3D simulations with the aim of finding the best validation [12].

Placing the cylinder upstream of the advancing side by varying cylinder stagger angle produces the highest performance at a stagger angle of 60° with a *Cp* of 0.4356 [13]. Performance can be improved by adding cylinders. The parameters to be varied are the cylinder diameter, cylinder spacing, and stagger angle located at the advancing side. Changes in cylinder diameter indicate the highest performance at a diameter ratio of 0.4. A larger diameter will cause a high velocity on surface near the advancing blade tip with reattached formation. The results indicate the highest at angle of stagger of 60° [14].

Another study on improving Svonius performance was conducted by adding deflectors as curtains. The placement of deflectors achieved a unique achievement that can increase the Cp of curtain 1 at θ of 60° for β of 15°, and α of 45° [15, 16]. Experiments on deflectors were able to improve performance by about 38.5% for well-arranged curtains [17]. The Cp values obtained in experimental studies in different wind tunnels with air ducts using deflectors [18] and performance in Cp increased by 15% to λ = 1.2 [19]. Experimental investigations were conducted by changing the overlap of the Savonius turbine with the aim of obtaining the power coefficient using overlap values of 0.15, 0.20, 0.25, and 0.30. The experimental results showed a suitable speed of 4 m/s at an overlap of 0.15, while wind speeds exceeding 4 m/s are recommended at an overlap of 0.30 [20, 21]. Experiments on truncated cylinders have increased *Cp* by 12.2% at S/D 1.4, and λ of 0.65 [22]. The effect of cylinder profile placed in upstream of the original Savonius with angle of stagger as a variable parameter and obtained the best performance at α of 60°. This increase reached 29.84% at λ of 0.9 [23]. The cylinder also increases the highest Savonius turbine performance at y/D = 0.75 with an increase of 22.267% [24].

From the above research, the placement of the cylinder on the upstream return blade has resulted in either an increase or decrease in Savonius performance. Investigating the performance of a Savonius turbine with an overlap of 0.3 resulted in the best performance. The contribution to the cylinder stagger angle (γ) also showed better results compared to no cylinder. By incorporating overlap variables, placing the cylinder in front of the return blade can improve Savonius turbine performance by varying the cylinder stagger angle (γ). Therefore, the study was conducted with experimental and numerical studies, where the experiment used a 2-blade Savonius with the cylinder position in the upstream side by varying wind celerity of 5 m/s, 6 m/s, and 7 m/s for conditions in Indonesia. This investigation aims to determine goals such as the power coefficient with changes in stagger angle (γ) of 45°, 55°, 65°, and 75°. In addition, a simulation study uses the Ansys 2025 R1 software to see the flow visualization across the Savonius turbine and cylinder.

II. Literature Review

Recent research on the Savonius turbine has progressed rapidly. Research has been conducted on modifying the blade shape, such as the helical one [2]. The new blade shape can increase performance by 20% [3].

The Myring shape has been developed and contributes the highest Cp increase in the Myring equation $n = 1$ [4–6]. Modified blades with a Myring shape, with a cylinder added next to the advancing blade, show that increasing the diameter improves Savonius performance. This is due to the nozzle effect between the advancing blade and the cylinder. Fluid acceleration on the cylinder side results in increased velocity and decreased pressure on the concave side of the advancing blade, thereby reducing negative torque. This increases total torque and automatically increases Savonius power [7]. Rotating the cylinder counterclockwise to the Savonius turbine rotation can improve turbine performance [8].

Modifications by overlapping the center of the Savonius turbine can improve Savonius turbine performance. The largest Cp value is at an overlap of 0.2 [11]. Numerical simulations on variations of turbine blade overlap have been validated experimentally with 3D simulations with the aim of finding the best validation [12]. Overlap can improve turbine performance by providing additional positive torque by helping direct the flow from the advancing concave side, which will add positive torque by directing the fluid flow to the returning concave side.

Numerically, the Betz limit for wind turbine is 16/27, or 59.3%. This value represents the maximum efficiency, also known as the wind turbine's power coefficient. This means that when a wind turbine is operating under optimal conditions, its efficiency will not exceed 59.3%. This study on the Savonius wind turbine will refer to the Betz limit standard.

Research on turbines with overlap on the turbine side has not been conducted, considering that overlap studies have demonstrated improved performance at 0.3 overlap. Therefore, this study will investigate the performance of a 0.3 overlap turbine with cylinder placement experimentally and numerically.

III. Experimental and Numerical Study

This research method uses experimental and numerical studies. Experiments measure the spin and torque of the turbine and calculate the power coefficient value. Meanwhile, numerical studies are conducted to observe the flow phenomena throughout the Savonius turbine that cannot be measured experimentally. This numerical study discusses flow phenomena such as velocity contours and pressure contours. This study uses a Savonius turbine by giving the overlap (β) of 0.3 and γ of 45°, 55°, 65°, and 75°.

A. Experimental Setup

This turbine research uses the original Savonius turbine and Savonius overlap turbine types. The Savonius turbine model has a height and diameter of 40 cm each with an overlap of 0.3 which is installed in front of the wind tunnel as revealed in Fig. 1, where (a) is for the original Savonius turbine and (b) is for the overlap Savonius turbine.

(a) (b)

Fig. 1. Savonius turbine: (a) Original Savonius and (b) Overlap Savonius.

The wind flow mechanism comes from a blower to flow fluid at varying wind celerity (U). Specifications have a diameter of 450 mm, 2850 RPM, a flow rate of 4413 CFM, a power of 2200 W, and a voltage of 220/240 V. The wind through the wind tunnel has a size of 30 cm × 30 cm. The wind tunnel outlet is installed with a honeycomb used to uniform the flow that will pass through the Savonius turbine. The wind from upstream will be disturbed by a cylinder with a ds/D of 0.4. The detailed experimental setup is represented as in Fig. 2.

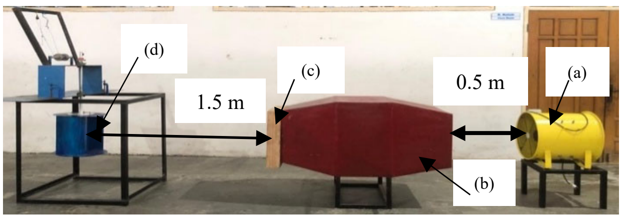

Fig. 2. Experimental arrangement: (a) Blower, (b) Wind Tunnel, (c) Honey Comb, and (d) Savonius Turbine.

The calculation involves parameters such as λ, *T*, *Ct* and *Cp* which are written in Eq. (1) until Eq. (4).

$$\lambda = \frac{U}{V} = \frac{\omega D}{2.V} \quad (1)$$

$$T = (m_1 - m_2) \cdot g \cdot \frac{(d_p + d_n)}{2} \quad (2)$$

$$Ct = \frac{4.T}{\rho \cdot A_s \cdot d \cdot U^2} \quad (3)$$

$$Cp = \frac{2\,P}{\rho \cdot A_s \cdot U^3} \quad (4)$$

where λ, T, ω, d, dp, dn, g, ρ, As, m_1, m_2, Cp, U, and P, are the tip speed ratio, the torque (N.m), the turbine rotation (rad/s), the Savonius turbine diameter (m), the pulley diameter (dp of 0.032 m), the nylon diameter (dn of 0.0015 m), the gravitational acceleration (9.81 m/s^2), the fluid density (1.225 kg/m^3), the turbine projection area (0.16 m^2), the high load (kg), the low load (kg), the power coefficient, the linear velocity (m/s), the power of turbine.

The rotation of the Savonius turbine will be measured using a tachometer, as shown in Fig. 3. The turbine torque calculation uses equation 2, recording the values of m_1 and m_2 in kg; these values will be used to determine the torque, as shown in Fig. 4.

Fig. 3. Tachometer.

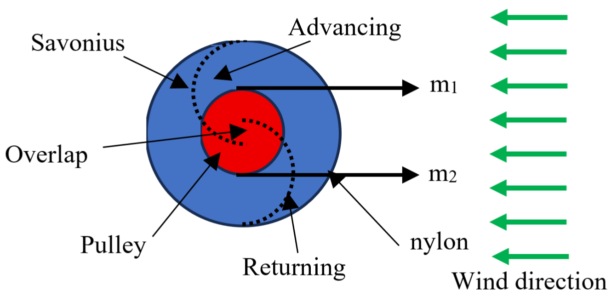

Fig. 4. Data collection scheme for torque calculation in top view.

The parameters studied in this research are changes in the stagger angle of the cylinder (γ) placed in front of the return blade, as shown in Fig. 5. The stagger angle is varied by γ = 45°, 55°, 65°, and 75°.

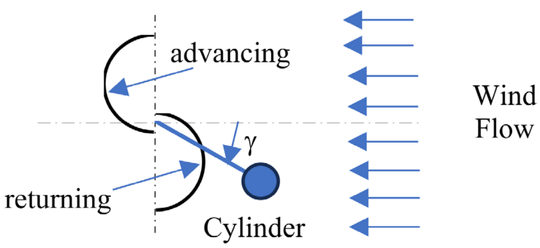

Fig. 5. Cylinder stagger angle (γ).

TABLE I. ANALYSIS OF UNCERTAINTY

Variables	Symbol	Uncertainty (%)
Density	ρ	0.316
Angular velocity	ω	0.71
Torque	T	0.5006
Area	A	0.35
Turbine diameter	D	0.25
Power coefficient	Cp	1.88

Experimental studies will measure the parameters, and the quality of the measurement data will be validated against the measurement uncertainty. Analysis of uncertainty have been presented in Table I. The experimental uncertainty will pertain to parameters such as density, angular velocity, torque, area, diameter, and power coefficient. The uncertainty analysis on the power coefficient shows a value of 1.88% which means that the measurement certainty in the experiment is 98.12% for parameter of *Cp*.

B. Numerical Simulation

The numerical simulation begins by creating a geometry with boundary conditions as represented in Fig. 6. This numerical simulation follows boundary conditions by means of 3D, where the inlet (velocity inlet), tunnel (symmetry), Savonius turbine (rotating zone), Stationary zone, Outlet (pressure outlet). The simulation was carried out using the sliding mesh method.

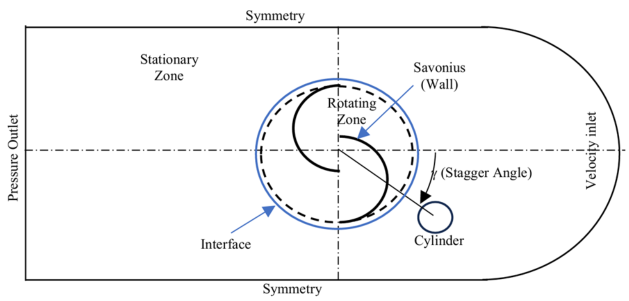

Fig. 6. Boundary conditions.

Numerical analysis using 3D simulation with Realizable Realizable *k-ε* turbulent model with unstructured meshing (tetrahedral) and meshing around turbine and cylinder is shown in Fig. 7.

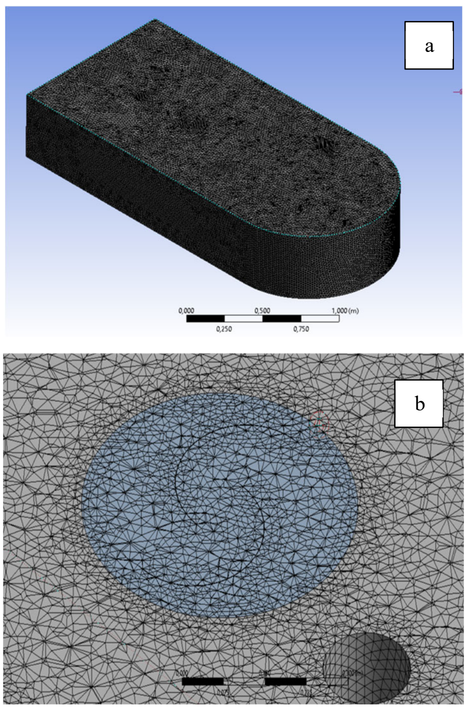

Fig. 7. Meshing: (a) Overall and (b) near blade and cylinder.

The initial stage involves calculating Number of Time Step (NTS) and Time Step Size (TSS) to determine the values required for grid independence and to validate results against experimental data. The NTS and TSS values are calculated from several data, such as RPM conversion to ω in rad/s, Tip Speed Ratio (λ) value, wind celerity, and Savonius turbine diameter. Grid independence uses 3λ values from the experimental data. NTS and TSS for grid independence are shown in Table II.

TABLE II. NTS AND TSS FOR GRID INDEPENDENCE

TSR Exp.	*v* (m/s)	*D* (m)	*ω* (rad/s)	*n* (RPM)	NTS	TSS
0.47	5	0.4	11.6286	111.04	3998	0.0150
0.80	5	0.4	20.1143	192.08	6915	0.0087
0.96	5	0.4	23.8857	228.09	8211	0.0073

Grid independence uses the result of the best variation from experiments, namely stagger angle variation of 55° at $\lambda = 0.8$ represented in Fig. 8. The simulation was varied by meshing size (0.02 m, 0.0175 m, and 0.015 m) until the simulation Coefficient of Power (*Cp*) results were close to previous experiments. Simulation results for grid independence for a stagger angle of 55° at $\lambda = 0.8$ are shown in Table III.

TABLE III. THE RESULT OF GRID INDEPENDENCE FOR $\gamma = 55^o$ AT $\lambda = 0.8$

Mesh	*Cp* Num.	*Cp* Exp.	Nodes	Element	Error (%)
1	0.363	0.389	126,743	651,850	6.59
2	0.377	0.389	126,878	652,370	3.17
3	0.376	0.389	254,964	1,335,686	3.34

Table III shows that the simulation Coefficient of Power (*Cp*) result that is closest to the experimental *Cp* result in mesh 2. Therefore, the mesh used for the next simulation is mesh 2 with a size of 0.0175 m and error 3.17%.

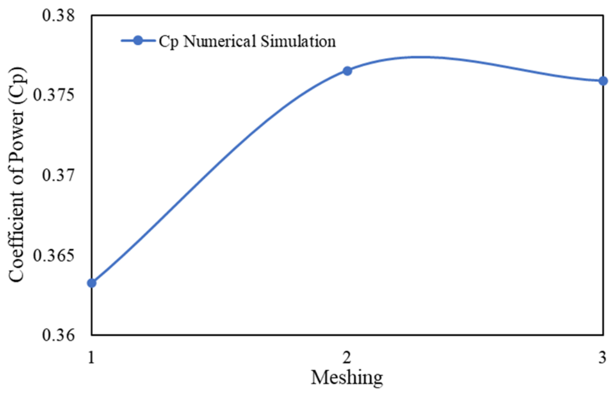

Fig. 8. Grid Independence of Coefficient of Power (*Cp*) with respect to meshing size for $\gamma = 55°$ at $\lambda = 0.8$.

Model validation is useful for observing the deviation between simulation and experiment. Model validation was performed on a Savonius overlap wind turbine by installing a cylinder in front of the return blade at a stagger angle of 55°. The results of Cp curve against λ from the experimental results were used as a reference for the model validation process in numerical simulations. The model can be said to be valid if the shape of the Cp-λ curves from the simulation results are close to or have a trend line that is not far from the experimental results. Numerical simulations were performed at 3 values of λ, namely 0.47; 0.8; and 0.96 using mesh 2 (element size 0.0175 m). Model validation can be seen in Table IV.

TABLE IV. VALIDATION FOR γ OF 55° MESH 0.0175

λ	Cp Num.	Cp Exp.	% err.	Num-Exp
0.47	0.2631	0.2775	5.202	0.0144
0.80	0.3766	0.3889	3.170	0.0123

The next numerical simulation uses 5 variations of λ that have been determined with the data shown in Table V. The software input data using λ of 0.4, 0.6, 0.8, 1.0, and 1.2.

TABLE V. THE VALUE OF NTS AND TSS

λ	v (m/s)	D (m)	ω (rad/s)	n (RPM)	NTS	TSS
0.4	5	0.4	10	95.49	3438	0.0175
0.6	5	0.4	15	143.24	5157	0.0116
0.8	5	0.4	20	190.99	6875	0.0087
1.0	5	0.4	25	238.73	8594	0.0070
1.2	5	0.4	30	286.48	10313	0.0058

IV. RESULT AND DISCUSSION

The research involves experimental and numerical studies, where the experiments will produce quantitative analysis to determine the power coefficient. Numerical studies are used to analyze phenomena that cannot be observed experimentally. Observations of flow phenomena across the Savonius turbine will corroborate the experimental results by observing the captured velocity streamline, pressure contour, and pressure distribution.

A. Performance

The experimental result of the power coefficient with respect to λ on a Savonius overlap wind turbine by adding a cylinder with change of stagger angle (γ) of 45°, 55°, 65°, and 75° placed in upstream returning area at U = 5 m/s is showed in Fig. 9.

The curve shows that a larger λ value will increase the Cp, but a certain λ value will decrease the Cp because it has reached its peak, this is in line with the decreasing turbine spin. This is in accordance with the power coefficient formula as a function of the quadratic equation of the Savonius turbine rotation.

The power coefficient respect to λ at a wind celerity of 5 m/s is represented in Fig. 9. At a wind celerity of 5 m/s, the Savonius overlap wind turbine by putting a cylinder in upstream side of the returning causes performance enhancement at a stagger angle of 55° with the highest Cp of 0.389 at λ = 0.805. This indicates that there is agreement with research [23], where the best stagger angle occurs at 60°.

At other stagger angles, it shows a decrease in performance compared to the Savonius overlap no cylinder or the original Savonius turbine. This is caused by the interaction of fluid flow through the cylinder and the Savonius turbine which will make the turbine performance less than optimal because there will increase pressure at the returning side so that drag difference between the advancing and the returning area becomes smaller which will decrease the turbine performance. The Cp enhancement of turbine at U = 5 m/s is shown in Table VI.

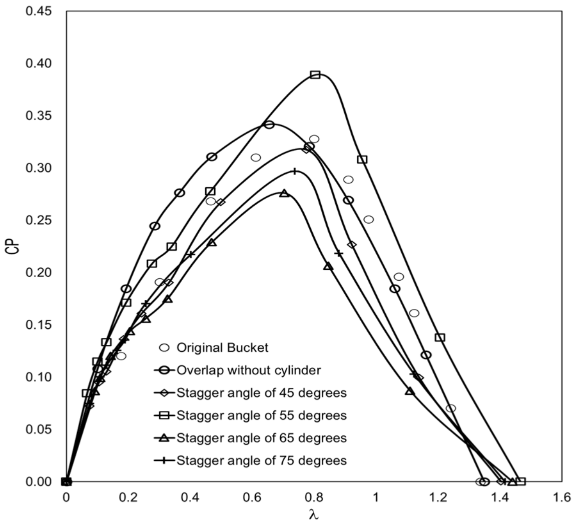

Fig. 9. Cp against λ for 5 m/s.

TABLE VI. Cp FOR U = 5 m/s

Parameters	λ	Cp	Improvement (%)	Result
Original Bucket	0.800	0.328	0	0
without cylinder	0.654	0.342	4.26	Increase
γ of 45°	0.775	0.317	−3.14	Decrease
γ of 55°	0.805	0.389	18.7	Increase
γ of 65°	0.704	0.276	−15.78	Decrease
γ of 75°	0.738	0.297	−9.42	Decrease

The power coefficient will increase with increasing λ value and the Cp value reach peak at a certain λ which will decrease the Cp value. This indicates that power coefficient is a quadratic function of λ.

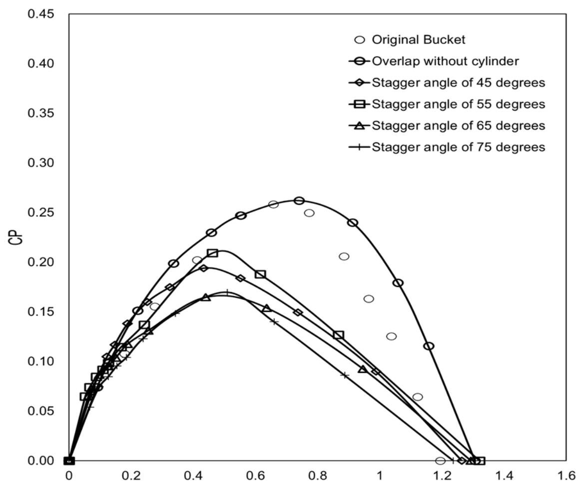

Fig. 10. Cp against λ for 6 m/s.

The power coefficient against λ at wind celerity of 6 m/s by varying the stagger angle represented as in Fig. 10. Analysis of the power coefficient against λ at a wind celerity of 6 m/s on the overlapping Savonius turbine with the cylinder positioned upstream of the returning blade has an impact on reducing performance compared to the overlapping Savonius without cylinder or called the original Savonius turbine. This is due to the fluid interaction between the cylinder and the overlapping savonius turbine which will make the turbine less than optimal because on the return blade side it causes an increase pressure so that drag force experiences a difference between the advanced blade and the returning blade side is smaller so that the turbine performance decreases.

While at all of stagger angle of the cylinders experienced a decrease in performance compared to those without them. This indicates that the cylinders negatively impact the performance of the Savonius turbine, and indeed, the high wind celerity of 6 m/s is not suitable for use in Savonius turbines. The results of the percentage increase in performance at a wind celerity of 6 m/s are shown in Table VII.

TABLE VII. *CP* FOR *U* = 6 m/s

Parameters	λ	*Cp*	Improvement (%)	Result
Original Bucket	0.657	0.258	0	0
without cylinder	0.740	0.262	1.50	Increase
γ of 45°	0.433	0.194	−24.91	Decrease
γ of 55°	0.461	0.209	−18.98	Decrease
γ of 65°	0.440	0.164	−36.28	Decrease
γ of 75°	0.510	0.170	−34.29	Decrease

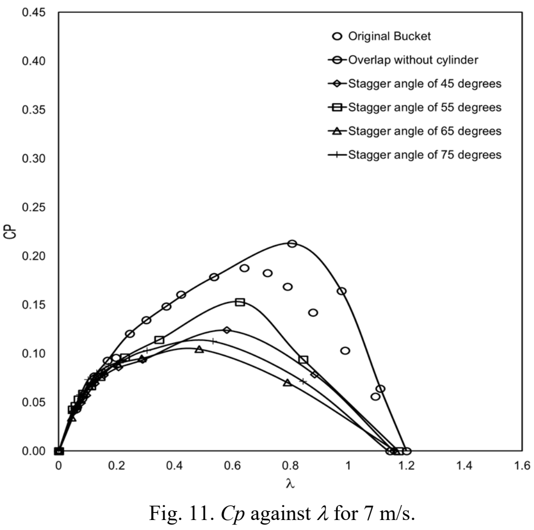

Fig. 11. *Cp* against λ for 7 m/s.

The graph of power coefficient against λ at a wind celerity of 7 m/s is represented in Fig. 11. Increasing the tip speed ratio (λ) will increase the value of the Coefficient of power (*Cp*), but at a certain λ, the Cp value will reach a peak and the Cp value decreases with increasing λ value. At a wind celerity of 7 m/s, the Savonius overlap wind turbine with a cylinder located on the upstream side of the returning blade experiences a decrease in performance compared to overlap Savonius turbine without a cylinder or the original Savonius turbine. This is due to the interaction of fluid flow passing through the cylinder and the Savonius overlap Savonius which will have an impact on not optimal performance on the returning blade side, there will be an increase in pressure so that drag force difference between the advancing side and returning sides becomes smaller and the turbine performance decreases.

A wind celerity of 7 m/s also negatively impacts the performance of the Savonius turbine. This behavior is similar to that observed at a wind celerity of 6 m/s, meaning the Savonius turbine is not suitable at 7 m/s. The results of the percentage increase in performance at a wind celerity of 7 m/s are shown in Table VIII.

TABLE VIII. *CP* FOR *U* = 7 M/S

Parameters	λ	*Cp*	Improvement (%)	Result
Original Bucket	0.641	0.188	0	0
without cylinder	0.805	0.213	13.32	Increase
γ of 45°	0.581	0.124	−34.07	Decrease
γ of 55°	0.626	0.153	−18.61	Decrease
γ of 65°	0.485	0.104	−44.37	Decrease
γ of 75°	0.533	0.112	−40.14	Decrease

An interesting phenomenon occurs in the performance of Savonius wind turbines at very high wind speeds. When rotating rapidly, the turbine blades can form a configuration resembling a solid cylinder for the upstream airflow. Under these conditions, the Savonius turbine is unable to efficiently capture the wind's kinetic energy, and the blades partially obstruct the flow from upstream to downstream. This phenomenon increases turbulence and reduces overall efficiency.

B. Numerical Simulation Result

These characteristics are fluid flow phenomena that are difficult to observe through experiments, so numerical studies are needed to prove these phenomena with CFD approach. Observations from numerical simulations by looking at flow patterns such as streamline contours, pressure contours, and torque coefficients as a function of the inner blade rotation (°). The flow phenomenon in the Savonius turbine is taken at the best performance condition for U = 5 m/s (case: blade angles (θ) of 0°, 50°, and 100°), analysis of variations in the stagger angle with overlap (stagger angles (γ): 45°, 55°, and 65°). The analysis includes streamlines and pressure contours.

1) Flow phenomena at velocity streamline

The flow characteristics are analyzed against the velocity streamlines capture and strengthen analysis on pressure contours. The visualizations obtained will be the basis for analysis of several factors that affect the Savonius turbine performance. The velocity streamlines and pressure contours are analyzed at the best Coefficient of Power (*Cp*) value from all variations of the overlapping Savonius turbine by varying the blade angle by 0°, 50°, and 100° at a wind celerity of 5 m/s.

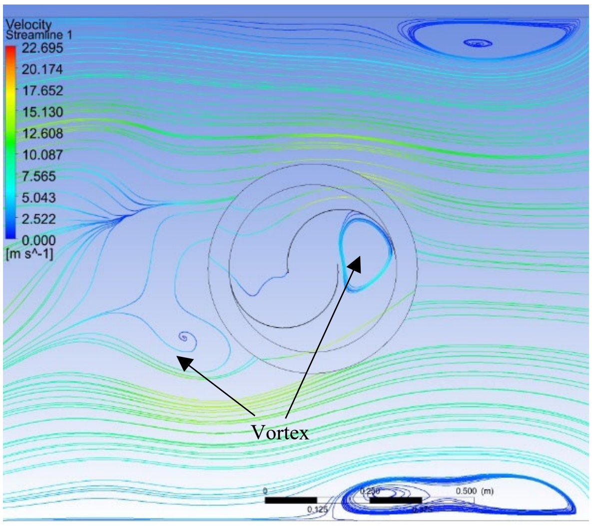

Fig. 12. Streamline at blade angle (θ) of 0º overlap without cylinder at 5 m/s.

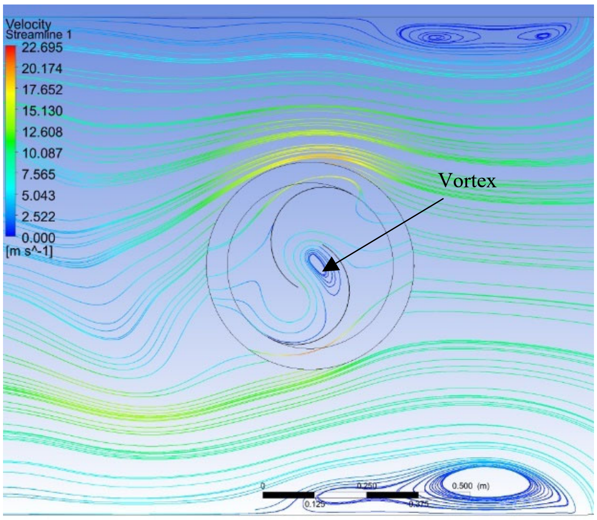

Fig. 13. Streamline at blade angle (θ) of 50º overlap without cylinder at 5 m/s.

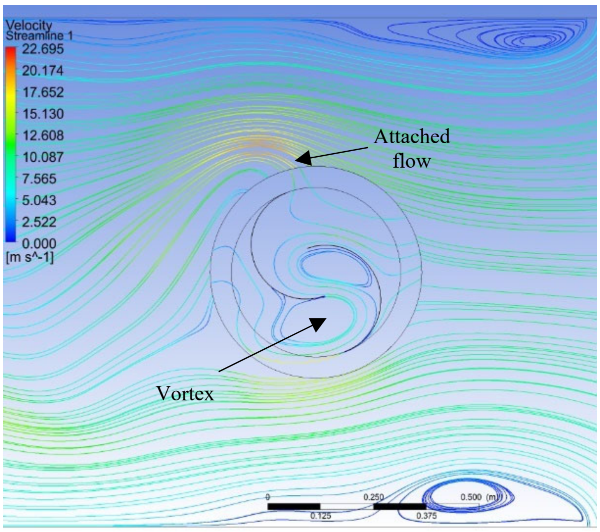

Fig. 14. Streamline at blade angle (θ) of 100º overlap without cylinder at 5 m/s.

The streamline flow velocity that occurs in the Savonius wind turbine overlaps the cylindrical stagger angle of 55° at various turbine blade angle variations. The fluid flows from upstream to downstream. At a blade angle of 0˚ shown in Fig. 12, a vortex is formed on returning concave side. The stagnation point occurs at the tip of the Savonius blade. In Fig. 13, for a blade angle of 50°, a vortex forms around the center of the turbine, causes torque on the advancing side to increase, and causes the Savonius wind turbine to rotate. Meanwhile, in Fig. 14, for a blade angle of 100°, two vortices are formed on the back side of the returning area. The advancing blade tip experiences reattached flow, causing an increase in velocity or a decrease in pressure on the convex side, which will have an impact on reducing the drag value on the advancing side. This causes total drag enhancement on the advancing side, which will cause the Savonius turbine to rotate.

The effect of placing the cylinder in the upstream returning by varying θ of 0°, 50° and 100° at γ of 55° can be observed in Figs. 15–17. The flow starts from the upstream moving towards the downstream. The flow begins to touch the front surface of the cylinder and turns to the returning blade by forming a nozzle effect due to the interaction of the flow occurring on the cylinder and the convex side of the returning blade, thus affecting the flow velocity on the side of the returning blade.

At θ of 0°, the nozzle effect causes the velocity to accelerate and reduces the pressure on the returning convex area. This results in a decrease in pressure, which in turn reduces drag on the leading side, increasing the total drag force. Increasing drag force increases torque and power. A vortex phenomenon is observed on the overlap side at the center of the cylinder.

The analysis becomes more interesting when observations are made at θ of 50° and 100°. A strong nozzle effect has developed, as indicated by the closer contact between the return and the cylinder. Therefore, high velocities occur on the convex surface of the return. This increased velocity will result in a decrease in pressure and a decrease in drag on the return side.

Large vortex formation at the center of the overlap occurs at θ of 0° and the vortex splits into two vortices at α of 50º, while at θ of 100° the vortex enlarges again.

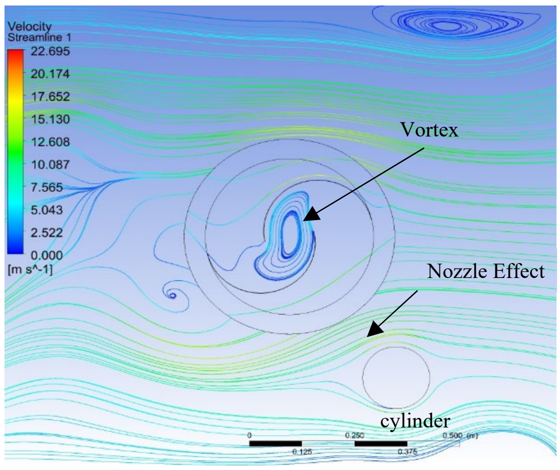

Fig. 15. Streamline for $\theta = 0º$ with $\gamma = 55º$ at 5 m/s.

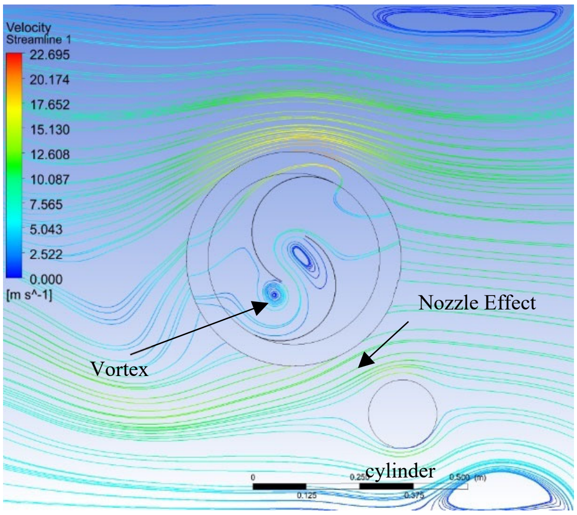

Fig. 16. Streamline for $\theta = 50^{\circ}$ with $\gamma = 55^{\circ}$ at 5 m/s.

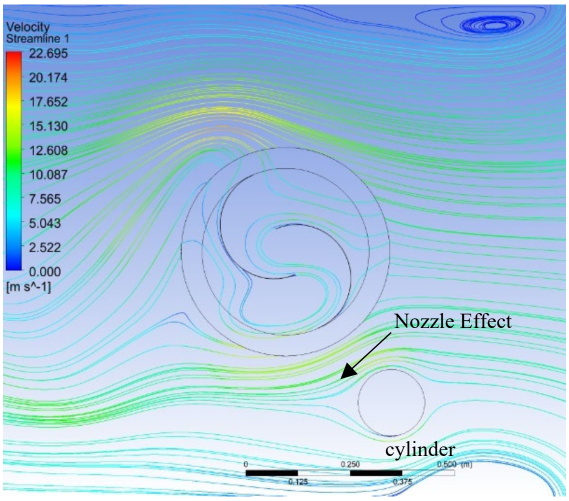

Fig. 17. Streamline for $\theta = 100^{\circ}$ with $\gamma = 55^{\circ}$ at 5 m/s.

2) *Flow phenomena at pressure contour*

Pressure contour analysis will be used to strengthen the streamline analysis on a Savonius wind turbine by giving overlap ratio of 0.3. Pressure contours will be observed at 0°, 50°, and 100° and a wind celerity of 5 m/s. Pressure contours at $\theta = 0^{\circ}$ with $\gamma = 55^{\circ}$ at a wind celerity of 5 m/s are represented in Figs. 18–20.

The pressure contour of a Savonius wind turbine by giving $\beta = 0.3$, $\theta = 0^{\circ}$, and $\gamma = 55^{\circ}$ at a wind celerity of 5 m/s is shown in Fig. 18. The stagnation point occurs on the front surface of the cylinder and the convex side of the return blade. The static pressure decreases on the lower and upper sides of the cylinder.

The flow characteristics for the pressure contour of a Savonius wind turbine by giving overlap ratio of 0.3, $\theta = 0^{\circ}$, and $\gamma = 55^{\circ}$ at a wind celerity of 5 m/s are shown in Fig. 19. Stagnation points also occur on the front surface of the cylinder and the returning convex area. Static pressure also decreases on the lower and upper sides of the cylinder. The stagnation pressure that occurs at θ of 50° is greater than $\gamma = 0^{\circ}$. This can be seen in Fig. 19 on the front side of the returning convex area.

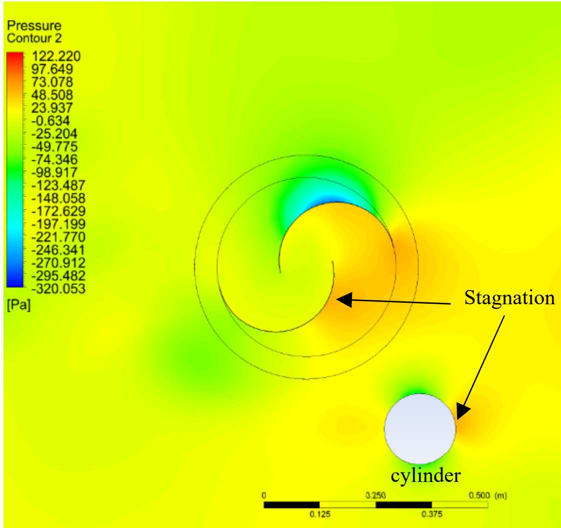

Fig. 18. Pressure contour of overlap Savonius turbine for $\theta = 0^{\circ}$ with $\gamma = 55^{\circ}$ at 5 m/s.

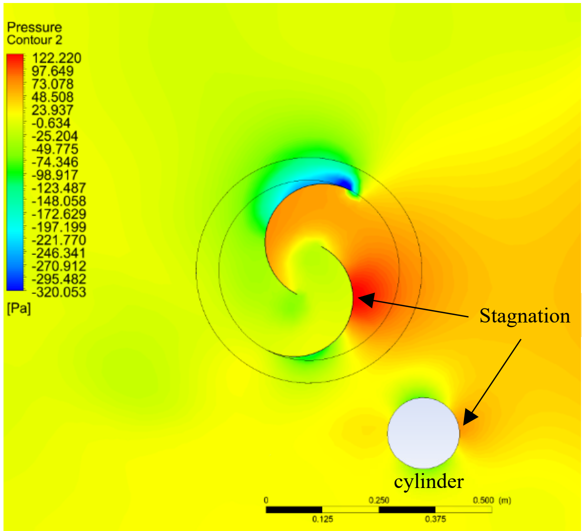

Fig. 19. Pressure contour of overlap Savonius turbine for $\theta = 50^{\circ}$ with $\gamma = 55^{\circ}$ at 5 m/s.

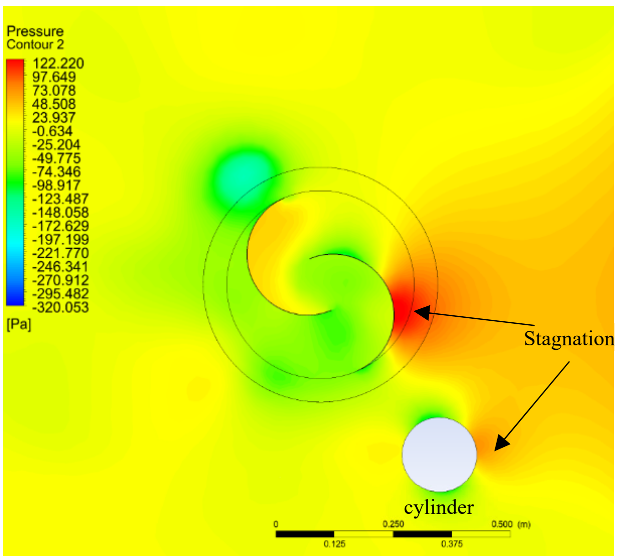

Fig. 20. Pressure contour of overlap Savonius turbine for $\theta = 100^{\circ}$ with $\gamma = 55^{\circ}$ at 5 m/s.

The flow characteristics for the pressure contour of a Savonius wind turbine with β of 0.3, θ = 100°, and γ = 55° at a wind celerity of 5 m/s are shown in Fig. 20. Stagnation points also occur on the front surface of the cylinder and the returning convex blade. Static pressure also decreases on the lower and upper sides of the cylinder. The stagnation pressure that occurs at θ = 100° compared to a θ = 50°. This can be represented in Fig. 20 on the front side of the returning convex.

The flow phenomenon across the Savonius turbine during half a rotation of the Savonius turbine is represented in Fig. 21. From the graph trend, it shows that the presence of a cylinder will increase the torque coefficient from a blade angle (θ) of 0° to 50°. The torque trend will decrease until around a blade angle of 110° and increase again until a blade angle of 180°. Changes in the stagger angle will affect the turbine performance and the best performance is obtained at γ = 55°.

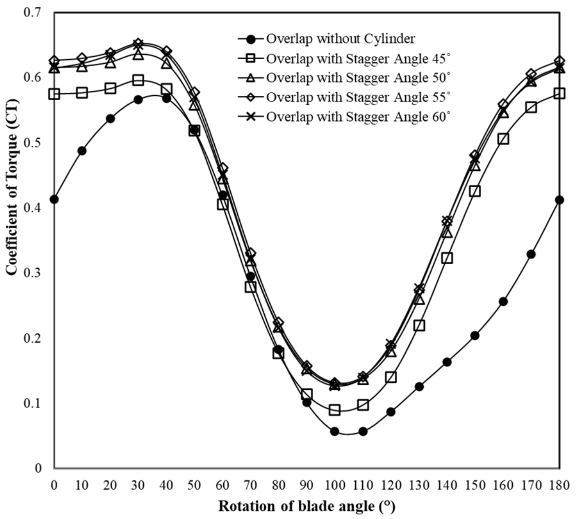

Fig. 21. Coefficient of Torque against Blade angle (°) for without cylinder, stagger angle of 45°, 50°, 55°, and 60°.

V. Conclusion

The result of the effect of adding overlap and variations of γ on the upstream returning position indicates that the highest improvement in the Power Coefficient (Cp) occurs at γ of 55° at a wind celerity of 5 m/s with a Cp = 0.389 at a λ = 0.805 with a performance enhancement of 18.70% from the original Savonius wind turbine. Experimental results have been validated and show an error value of less than 10%. Numerical simulation results indicate the best performance occurs at a stagger angle of 55° both experimentally and numerically. This is demonstrated by the graph of the torque coefficient versus blade angle, which shows that peak performance occurs at a blade angle of 55°.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, Priyo Agus Setiawan, Azli Abd Razak, and Triyogi Yuwono; methodology, Emie Santoso and Projek Priyonggo Sumangun Lukitadi; Experiments, Anda Iviana Juniani, A. Grummy Wailanduw, and Hafiyyan Arif Wicaksono; Numericals and validation, Nopem Ariwiyono and Naffatsa Alza Wiyoga; Writing, Review, and Injection, Priyo Agus Setiawan, Azli Abd Razak, and Triyogi Yuwono. All authors have read and agreed to publish this manuscript.

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