Research Article

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The effect of multi-stage modification on the performance of Savonius water turbines under the horizontal axis condition

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Abstract: Indonesia has the abundant potential of hydropower but not yet processed optimally, which intensely depends on fossil fuel. Hydropower installed in Indonesia is only 11,272 MW, from the estimated potential approximately 94,476 MW. This data shows that 89% of the hydropower potential in Indonesia has not been processed. One of the present efforts to utilize this resource is addressed to develop the Savonius water turbine. Conventional water Savonius turbines have a comprehensible structure and easy to be applied. However, the turbines produce relatively small power, which requires further assessment to improve its performance. The current study is performed by considering geometric changes on the water Savonius turbine to observe their effect on power characteristics. Considered changes are made on the number of stages, and the angle between stages, specifically a single-stage, two-stage 0°, Two-stage 90°, three-stage 0°, and three Stage 120°. The research was carried out by designing simulation model using ANSYS software with CFX Solver. Water speed is determined to 0.8 m/s, while plates with 110 mm in diameter and 110 mm in height are incorporated as rotor configuration. Based on this study, it can be concluded that the addition of the stage affected improving the performance of the Savonius water turbine, where the multi-stage turbine experienced an increment compared to conventional water turbines. The interesting tendency was found on the two-stage rotors with angle of 0° which produced a smaller $C_{pmax}$ compared to the conventional water Savonius turbines.

Keywords: Multi-Stage, Hydropower, Renewable Energy, Savonius Water Turbine, Coefficient of Power

Specifications

| Symbol | Definition |
|--------|------------|
| $A$    | swept area of the rotor |
| $C_t$  | torque coefficient |
| $C_p$  | power coefficient |
| $C_{pmax}$ | power coefficient maximum |
| $T$    | torque |
| $TSR$  | tip speed ratio |
| $\omega$ | angular velocity |
| $U$    | velocity |
| $\rho$ | water density |
| $x$, $y$, $z$ | Cartesian coordinates |

Geometrical parameters of the prototype

| Symbol | Definition |
|--------|------------|
| $D$    | endplate diameter |
| $d$    | rotor diameter |
| $H$    | rotor height |
| $h$    | height of rotor stage |
| $t$    | rotor thickness |

1 Introduction

An average increase in electrical energy consumption by 4.7% and production by 11.8% in the last three years in Indonesia. Electricity consumption is dominated by the household, business, and industrial sectors. The National Power Plant is supplied by 61% of coal power plants [1]. However, the energy source has decreased every year. An-
other energy source that has great potential in Indonesia is Hydropower. Hydro energy and micro-mini hydro have a potential of 76% compared to other energy sources [2]. The development of a water turbine is one of the efforts to process water energy into electricity. Research on hydro turbines has been carried out such as screw-type at small hydropower plants [3]. In general, turbines are divided into horizontal axis and the vertical axis in this study using a horizontal axis Savonius type turbine. In the 1920s, Savonius published the results of carried out tests on his rotor design. They are operating in both wind and water. In the case of water, the test was carried out in the river flow, tidal waters and sea waves [4].

Research has been conducted on Savonius type turbines, especially on the vertical axis and wind turbines. Research on the effect of the overlap ratio has been carried out on vertical wind turbines. The study was conducted in an overlap ratio of 0 to 0.3. The results of the study show that the overlap ratio of 0 produces the highest $C_{p_{max}}$ [5]. In another study regarding the overlap ratio that has been carried out on horizontal axis water turbines, it shows that $C_{p_{max}}$ is obtained in 0.3 overlaps. The $C_{p_{max}}$ produced in the study was 0.19 at TSR 0.79 [6]. Other research is about performance with the addition deflector variation. From this study it was found that the addition of the deflector increased the coefficient of power ($C_p$) by 50% [7]. The change of shape of blade becomes a helix shape, and the addition of deflector has been tested to the water Savonius turbine on the vertical axis. The study resulted in an increase in $C_{p_{max}}$ from 0.125 to 0.14 [8]. Research on Savonius wind turbines with number of blades 2 and 3 was carried out and resulted that the Savonius wind turbines with two blades produced higher $C_{p_{max}}$ compared to wind turbines with three blades [9]. In general, research on Savonius turbine development is about modifying the number of blades and Shape of blade which is carried out either in simulation or experiment [10]. Collaboration of the mentioned methods is very effective as results of experimental works can be expanded by numerical approach, and vice versa, which this research stage is taken as benchmarking in computational fluid dynamic [11–15] and finite element method [16–20].

This research was carried out using a Savonius type turbine on the horizontal axis. Since Savonius has a simple structure that is easy to modify and can operate at low speeds, Savonius has a lower efficiency than other types, so research still needs to be done to improve its performance [21]. This study aims to determine the effect of the number of stage on the performance of Savonius water turbines with considered changes on the number of stages, precisely a single-stage, two-stage $0^\circ$, two-stage $90^\circ$, three-stage $0^\circ$, and three stage $120^\circ$.

2 Data Reduction and Model Geometry

Turbine performance always uses the relationship between the coefficient of power and the Tip Speed Ratio function. So the results of the research that has been carried out through simulation, then processed using equa-

![Figure 1: The geometry of a) Single-stage, b) two-stage 90°, c) three-stage 120°, d) two-stage 0°, and e) three-stage 0°.](image-url)
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Figure 2: Top projection of a) Single-stage, two-stage 0°, and three-stage 0° b) two-stage 90°, and c) three-stage 120°.

Table 1: The dimension of the rotor.

| Parameter | Single Stage | Two-Stage 90° | Rotor Type | Two-Stage 0° | Three Stage 120° | Three Stage 0° |
|-----------|--------------|---------------|------------|--------------|------------------|----------------|
| D (mm)    | 110          | 110           | 110        | 110          | 110              | 110            |
| d (mm)    | 100          | 100           | 100        | 100          | 100              | 100            |
| H (mm)    | 110          | 110           | 110        | 110          | 110              | 110            |
| h (mm)    | -            | 52            | 52         | 34           | 34               | 34             |
| T (mm)    | 2            | 2             | 2          | 2            | 2                | 2              |

$tors to calculate the performance parameters, where $TSR$, $Cp$, and $Ct$ is a non-dimensional number that appropriately used as a design parameter. Mathematical expressions for these terminologies are presented in Equations 1-3.

$TSR$ (Tip Speed Ratio)

$$TSR = \frac{\omega D}{2U}$$  

Coefficient Power ($Cp$)

$$Cp = \frac{T \times \omega}{0.5 \times \rho \times A \times U^3}$$  

Coefficient Torque ($Ct$)

$$Ct = \frac{Cp}{TSR}$$

where $U$ is the free flow velocity, $\rho$ is the water density, $A$ is the Area of the Rotor, $T$ is the torque, $\omega$ is the angular velocity, $Ct$ is Coefficient torque and $Cp$ is the Power coefficient [22].

This study was carried out using the Savonius rotor on the horizontal axis. The research has been done with variation single-stage, two-stage 0°, two-stage 90°, three-stage 90°, and three Stage 120°. The dimensions for each rotor are shown in Table 1. The number of rotors tested is five rotors. Description dimension on the geometry of the rotor shown in Figures 1 and 2. Figure 2 shows the top projection of single-stage rotors, two-stage 0°, and three-stage 0°. Research conducted using the aspect ratio ($D/H$) of 1 and the overlap ratio of 0. Table 1 shows that $D$ is the endplate diameter, $d$ is the rotor diameter, $H$ is the rotor height, $h$ is the stage height of the rotor, and $T$ is the thickness.

3 Methodology

The research was carried out in 3D simulation using Ansys software with cfx solver. The research was conducted with the pre-research and research stages. Performed on pre-study phase is to make 3D design, validate, mesh independence study. The second stage determines boundary conditions, meshing, and running simulations. Validation was carried out on Roy et al. [23]. Validation was carried out at the position of $TSR$ 0.74 where $Cp_{max}$ was reached. $Cp$ at 0.65 $TSR$ obtained from the simulation was 0.252, wherein the mentioned study, it was 0.252. The data shows a 2.35% error rate. Benchmark has shown in Figure 3.

Mesh independence study needs to be done in simulation research. By conducting mesh independence of our research can obtain a number of elements that are effective in the simulation process. Mesh independence study is done by adding cells [24]. Data from the mesh independence study process are shown in Figure 4 which the
4 Numerical Model

Simulations are carried out using mesh with the tetrahedral method and using inflation on the rotor wall. The results of the mesh are shown in Figures 5 and 6. The figure shows the mesh method used and mesh size. Meshing for rotary domains and domain stationaries is done separately. Figure 5 shows the mesh on the rotary domain, and Figure 6 shows the mesh on the stationary domain. In this study, CFX software has been used for computing. Using this software, all rotor designs have been analyzed. Numerical research is possibly done using numerical methods of one dimensional [25] or three-dimensional [26]. Equation of momentum, turbulent kinetic energy has been solved numerically using the software, where the governing equation is shown in Equations 4-7.

Continuity Equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]  

\((4)\)

X-Momentum:

\[
\frac{\partial p u}{\partial t} + \frac{\partial (p u^2)}{\partial x} + \frac{\partial (p u v)}{\partial y} + \frac{\partial (p u w)}{\partial z} = \frac{\partial p}{\partial x} + \frac{1}{Re} \left( \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} \right)
\]

\((5)\)

Y-Momentum:

\[
\frac{\partial p u}{\partial t} + \frac{\partial (p u v)}{\partial x} + \frac{\partial (p v^2)}{\partial y} + \frac{\partial (p v w)}{\partial z} = \frac{\partial p}{\partial y} + \frac{1}{Re} \left( \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} \right)
\]

\((6)\)

Z-Momentum:

\[
\frac{\partial p u}{\partial t} + \frac{\partial (p u w)}{\partial x} + \frac{\partial (p v w)}{\partial y} + \frac{\partial (p v^2)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re} \left( \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \right)
\]

\((7)\)

where \(\rho\) is the density, \(t\) is the time, \(u\), \(v\), and \(w\) are the velocities in three coordinates of Cartesian, and \(x\), \(y\), and \(z\) are the Cartesian coordinates.

The simulation domain consists of two domains, namely the stationary domain and the rotary domain [27]. A rotary domain is a rotating domain, and this domain consists of parts of the wall rotor, front interface, interface, and rear interface. The rotary domain is shown in Figure 7a. The Stationery domain is non-rotating. This domain consists of six parts. These parts are the front interface, interface, rear interface, inlet, wall, and outlet. The stationary domain is shown in Figure 6b. The rotary domain and stationary domain are connected by the interface section. The overall schematic simulation is shown in Figure 8. An inflation with a 1.2 growth rate and level of 5 was using. The small thickness of the cells in the boundary layer of the blades from the first small layer aim to smooth transition using the \(y \leq 1\) value highly recommended for turbulent models [28].
Figure 5: Mesh on a rotary domain.

Figure 6: Mesh at the stationary domain.

Figure 7: Domain of Simulation.
Simulation is done using water fluid. The incoming inlet flow is subsonic flow using the K-Epsilon turbulence type. The type of analysis used is the transient blade row. The inlet velocity of 0.8 m/s and the simulation is carried out at the TSR interval 0.4–1. The boundary conditions on the wall use the no-slip condition. Water flow in subsonic condition. This research is using Turbulence Model K-epsilon. For other boundary conditions shown in Table 2.

Table 2: Boundary condition of simulations

| No | Parameter type | Value  |
|----|----------------|--------|
| 1. | Fluid type     | Water  |
| 2. | Density (kg/m$^3$) | 1,000  |
| 4. | Water velocity (m/s) | 0.8   |
| 5. | Outlet pressure (atm) | 1    |
| 8. | Gravity (m/s$^2$) | 9.81   |

5 Results and Discussion

The performance of the Savonius hydrokinetic turbine having the variable number of stages on rotor has been investigated numerically in velocity of 0.8 m/s at TSR interval 0.4–1. From the simulation process, the pressure contours and velocity contours of each design are obtained. Also, the torque value is obtained so that $C_p$ can be obtained from each design. Simulation has convergence at residual target $10^{-4}$. Coefficient power ($C_p$) and coefficient torque ($C_t$) generated by the Single Stage Rotor at TSR intervals of 0.3–0.9 are shown on the graph Figure 9. $C_p$ continues to increase at $TSR < 0.6$ and decrease at $TSR > 0.6$. The resulting $C_{p_{max}}$ is 0.1 at $TSR$ 0.7. $C_{t_{max}}$ is obtained at 0.2 at $TSR$ 0.3. Where $C_{p_{max}}$ and $C_{t_{max}}$ are not on the same $TSR$.

Figure 10 shows the $C_p$ and $C_t$ generated by the two-stage Rotor 90° stage at TSR intervals of 0.4-1. $C_p$ increases at $TSR < 0.7$ then decreases at $TSR > 0.7$. The resulting $C_{p_{max}}$ is 0.18 at $TSR$ 0.8. $C_t$ increases at $TSR < 0.5$ $C_t$ values increase, whereas at $TSR > 0.5$ $C_t$ values decrease. $C_{t_{max}}$ is obtained at 0.29 on $TSR$ 0.5. The $C_p$ and $C_t$ produced by the two-stage 0° rotors are shown in Figure 11. The graph shows that the $C_{p_{max}}$ is 0.058 at $TSR$ 0.4. $C_{t_{max}}$ was reached at 0.158 at $TSR$ 0.3. For this rotor, the same as the previous rotor, where $C_{p_{max}}$ and $C_{t_{max}}$ are not on the same $TSR$.

$C_p$ and $C_t$ generated by the Rotor three Stage 120° stage at TSR intervals of 0.4-1.1 are shown in Figure 12. $C_p$ continues to increase at $TSR < 0.9$ and decrease at $TSR > 0.9$. The resulting $C_{p_{max}}$ was 0.197 at $TSR$ 0.9. $C_{t_{max}}$ was obtained at 0.249 at $TSR$ 0.7. Where $C_{p_{max}}$ and $C_{t_{max}}$ are not on the same $TSR$.

Figure 13 shows the $C_p$ and $C_t$ produced by Rotor three-stage 0°. $C_p$ increases at $TSR < 0.4$ then decreases at $TSR > 0.4$. The resulting $C_{p_{max}}$ was 0.048 at $TSR$ 0.4. $C_t$ increases at $TSR < 0.4$ $C_t$ values increase, whereas at $TSR > 0.4$ $C_t$ values decrease. $C_{t_{max}}$ is obtained at 0.12 at $TSR$ 0.4. Where $TSR$ for $C_{p_{max}}$ is the same as $TSR$ for $C_{t_{max}}$.

Besides producing $C_p$ and $C_t$ values, this simulation produces output in the form of pressure contours, velocity contours, and streamlines. The pressure contours for each type of rotor are shown in Figure 14. The velocity contour is shown in Figure 15, and the velocity vector is shown in Figure 16. By studying pressure contours around models with different numbers of stage (Figures 14 and 15), there is a slight difference in pressure distribution in the blade with the same position. Where pressure is seen around the upper blade, more rotors with more stages have greater pressure. This is due to the area of the blade in multi-stage rotors smaller than the single-stage rotors. Figure 16 shows the vector of velocity streamlines at single-stage, two-stage, and three-stage.
Figure 9: Graph of correlation a) $C_p$ with $TSR$ and b) $C_t$ with $TSR$ on Rotor Single-Stage.

Figure 10: Graph of correlation a) $C_p$ with $TSR$ and b) $C_t$ with $TSR$ on Rotor Two-Stage 90°.

Figure 11: Graph of correlation a) $C_p$ with $TSR$ and b) $C_t$ with $TSR$ on Rotor Two-Stage 0°.
Figure 12: Graph of correlation a) $C_p$ with TSR and b) $C_t$ with TSR on Rotor Three Stage 120°.

Figure 13: Graph of correlation a) $C_p$ with TSR and b) $C_t$ with TSR on Rotor Three Stage 0°.

Figure 14: Distribution of pressure on a) Rotor Single Stage, b) Rotor Two-Stage 0°, c) First Stage Rotor Two-Stage 90°, d) Second Stage Rotor Two-Stage 90°, e) Rotor Three Stage 0°, f) First Stage Rotor Three Stage 120°, g) Second Stage Rotor Three Stage 120°, and h) Third Stage Rotor Three Stage 120°.
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Figure 15: Distribution of velocity on a) Rotor Single Stage, b) Rotor Two-Stage 0°, c) First Stage Rotor Two-Stage 90°, d) Second Stage Rotor Two-Stage 90°, e) Rotor Three Stage 0°, f) First Stage Rotor Three Stage 120°, g) Second Stage Rotor Three Stage 120°, and h) Third Stage Rotor Three Stage 120°.

Figure 16: Vector of velocity on a) Rotor Single Stage, b) Rotor Two-Stage 0°, c) First Stage Rotor Two-Stage 90°, d) Second Stage Rotor Two-Stage 90°, e) Rotor Three Stage 0°, f) First Stage Rotor Three Stage 120°, g) Second Stage Rotor Three Stage 120°, and h) Third Stage Rotor Three Stage 120°.
6 Conclusions

The simulation of three different types of Savonius rotors has been carried out by involving single-stage and two-stage. The results of this study conclude that the modification of the Rotor three-stage 120° has the highest coefficient of power maximum ($C_{p_{\text{max}}}$) value compared to another Rotor. The $C_{p_{\text{max}}}$ Rotor three-stage 120° is reached at 0.197, Rotor two-stage 90° is reached at 0.178, and the single-stage $C_{p_{\text{max}}}$ is reached at 0.1. On two-stage and three-stage 0° rotors, $C_{p_{\text{max}}}$ is lower than a single-stage, two-stage 0° is reached at 0.058 and Three-stage 0° at 0.048. Therefore, the three-stage 120° rotor is proved as an alternative design which can improve the performance of water turbine Savonius, especially utilize water resources to produce renewable energy. From this simulation research, we get a picture of the velocity and pressure distribution that can be used as a reference for experimental studies and the development of the next rotor design.

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