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Prasetyo, Ari
Mechanical Engineering, Vocational Faculty, Universitas Sebelas Maret

Muhamad Dwi Septiyanto
Mechanical Engineering, Engineering Faculty, Universitas Sebelas Maret

Rovianto, Eki
Mechanical Engineering, Vocational Faculty, Universitas Sebelas Maret

Hadi, Syamsul
Mechanical Engineering, Engineering Faculty, Universitas Sebelas Maret

他

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# Investigation of Blade Modifications to Enhance Savonius Water Turbine Performance Through Vertical Pipe Flow

Ari Prasetyo[1*], Muhamad Dwi Septiyanto[2], Eki Rovianto[1], Syamsul Hadi[2], Eko Prasetya Budiana[2], Dominicus Danardono Dwi Prija Tjahjana[2], Indri Yaningsih[2]

1Mechanical Engineering, Vocational Faculty, Universitas Sebelas Maret, Surakarta, Indonesia

[2]Mechanical Engineering, Engineering Faculty, Universitas Sebelas Maret, Surakarta, Indonesia

*Author to whom correspondence should be addressed:
E-mail: ari_prasetyo@staff.uns.ac.id

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**Abstract**: Savonius is a turbine with a simple construction and good initial torque that has become a promising technology for generating electric power. However, the efficiency of the turbine still needs to be improved. Therefore, the proposed study was conducted to enhance the Savonius turbine's performance with additional s/r (straight profile) and l/r (blade end). Rainwater harvesting was used as an experiment with only gravitational potential energy. The resulting power output, coefficient of power, and rotational speeds were used to evaluate the turbine's performance. The additional s/r was used to direct the water before hitting the concave turbine, and the additional l/r was used to catch the energy stored in the water in a more optimum manner. Based on the results, an additional blade end (l/r) of 0.6 and a straight blade (s/r) of 0.75 produced the best performance with 0.29 *Cp*, 1023 rpm of rotational speeds, and a maximum power generated of 60.8 W.

Keywords: Picohydro; Savonius; Blade modification; Coefficient of power; turbine performance

## 1. Introduction

Energy is the most important part of the world, and its existence is important to human life. Globally, Indonesia is among the countries where fossil energy is still dominant, with a dependence of up to 74% of national energy consumption[1)]. The government creates various programs to shift the dominance of fossil fuels, for example, the green building program[2)]. Commonly, the high-rise building is equipped with a pipeline system designed accumulate flowing wastewater. Flowing wastewater at pico hydropower generation systems is a choice for generating electricity and supporting the accomplishment of Green Building Programs. Besides that, the high precipitation levels in Indonesia's climate create favorable conditions for the utilization of pico hydropower generation systems installed through downpipes of tall buildings. Consequently, wastewater from rain gutters and household usage was readily available throughout the year, and the Savonius turbine was considered an effective way to harness these potentials.

Much research has been conducted to enhance the Savonius turbine performance. The research includes the drag-type water turbine installed on a horizontal pipeline that produces 88.2 W electric power for a 5 m pressure drop and 1.5 m/s fluid velocities[3)]. The Savonius wind turbine application as a water turbine is gaining more attention[4)] due to its simple design and economic development[5)]. This turbine also has low initial torque, so these applications are more effective in several conditions with ultra-low heads[6)]. Hamzah's research focused on shifting wind energy to fluid energy on the Savonius turbine because the momentum is higher than that of wind energy. This is because fluids have significantly higher momentum compared to wind. The turbine with driving fluids produced a better power output than Savonius Wind Turbine, with a generated *Cp* is 0.2[7)]. Rosmin et al. also developed a single-stage Savonius turbine in a vertical pipe with 0.3 W of electric power[8)].

Several modifications were made to comprehend the performance of the Savonious turbine better. Improving fluid direction enhances the performance turbine significantly conducted by Askary et al.[9)]. The directing systems implemented as a flow concentrator also prove the bigger generated torque[10)]. According to literature, the flow direction of working fluids significantly influences the generating performance[11,12,13)]. The directing techniques were also proven through simulation, which showed a 14% increase in efficiency[14)]

Another factor that influences turbine performance is the shape configuration[15)]. The modification of the

Savonious blade angle has become an interesting subject[16]. Mao and Tian modified the angle of the blade to increase the coefficient of power, where the power output increased to approximately 8.37%[17]. The investigation of modification blades, which involved analyzing their curvature angle, was conducted using SolidWorks Flow simulation[18]. Meanwhile, Hadi et al. investigated the modification's effect on capturing maximum energy, and their results proved an increase in torque[19]. A more considerable curvature angle value influences the increasing surface area of contact between the blades and water, allowing for more stored energy extraction.[20,21,22,23].

The Savonius turbine configuration's shape influences fluid direction flow through the blades[24,25]. Therefore, modifying the conventional Savonius turbine in the form of Type L can increase its performance because it is lighter than the conventional form[26]. Based on turbine weight, M. Al-Ghriybah's study investigates the thickness of the turbine base material, which shows that the thickness also increases the turbine weight, so the generated performance increases up to 40%[27]. Further research conducted by Herlambang et al. defined that an additional blade between the two conventional blades proves that the shape configuration influences the turbine's ability to extract energy[28]. The basic principle of this development was to maximize the field of catching the water to improve the turbine performance. Altan's research on modifying Savonius with additional straight blades discovered that it influenced the performance by up to 20%. All related studies prove that the shape and geometry of blades significantly influenced the power coefficient. Therefore, the proposed research has been conducted to develop a modification of the Savonius water blade installed in a pipe to improve the turbine's performance.

## 2. State of the Art

A pico hydro power plant converts the potential energy of flowing water into electrical energy by a generator where the electric power produced is less than 5 kW[29]. This system is suitable for application in hinterland areas that don't have an electric supply network. The Savonius turbine is a type of pico hydro turbine which is a solution for electricity supply, supported by its simple and low-cost construction[26].

Table 1. Classification of hydropower

| No. | Categories | Power output |
|---|---|---|
| 1 | Pico-hydro | <0.005 MW |
| 2 | Micro-hydro | <0.01 MW |
| 3 | Mini-hydro | <1 MW |
| 4 | Small-hydro | <10 MW |
| 5 | Large-hydro | >10 MW |

The modified Savonius turbine with the variations of additional blades between the conventional form was conducted by Herlambang. The schematic design used in this research is shown in Figure 1. The turbine used during studies has 650 mm in diameter and 600 mm in height. Variations in wind speeds are 3 m/s, 5 m/s, 7 m/s, and 9 m/s. The result shows their performance was higher than others, even without any additional forms or shapes. Because the additional blade blocked the number of blades from contacting the water, the generated performance decreased linearly with the increasing proportion of additional blades[28].

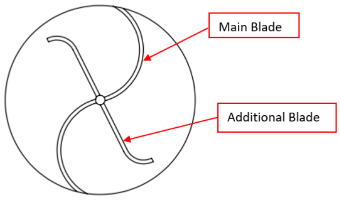



**Fig. 1:** The Schematic turbine with additional blade

The other simulation research proved that the blade configuration shape had influenced the performance of the turbines. The modified Savonius into L-type performs better because it enhances the ability of the turbine to extract more energy. Besides, these configuration turbines are more effective in decreasing negative torque during contacting water[27]. Figure 2 shows the L-type turbines.

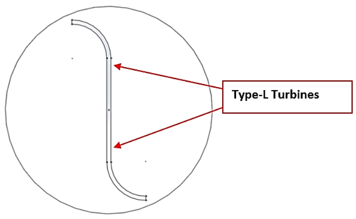



**Fig. 2:** Type-L Savonius Turbine

Sanditya et al. (2018) researched blade curvature on the Savonius rotor, which was applied to a pipe with a 3 inches diameter. The objectives of the research were to investigate the most optimal blade curvature angle. Variations in the angle of curvature of the blades used are 110°, 120°, 130°, and 140°. Based on the research, the blade curvature angle of 120° produces a power output of 39.15 W, a Coefficient of power (*Cp*) of 0.23 and a Tip Speed Ratio (*TSR*) of 1.075. This research has proven that the configuration blade, especially on curvature angle blades, has significantly affected the resulting performance. Figure 3 shows the curvature angle section modified in this research[21].

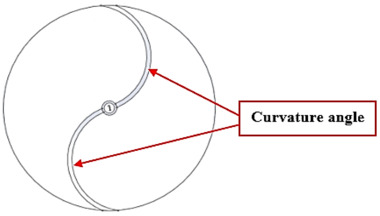



**Fig. 3:** Curvature angle of Savonius turbine

Patel et al. also investigated the modification of blades. The study investigated the performance of the Savonius turbine with an overlap ratio. Three variation overlaps are used, such as 0, 0.1, and 0.2. The overlap was used to direct the fluid hitting the concave turbine blades to increase the positive torque. The variation of the overlap ratio of 0.3 shows a higher torque value because it is more effective in catching energy stored by water[30]. The following figure is the visualization design of the turbine with an overlap ratio.

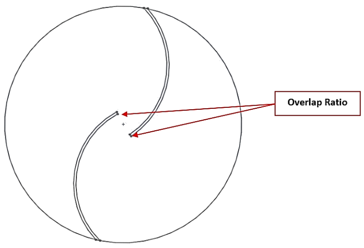



**Fig. 4:** Turbine design with overlap ratio

Modifications to the turbine's shape, including an additional curved blade between the main blade, overlap ratio, modified type L blade, and curvature angle, have been tested in the literature, in order to improve the Savonius turbine performance. The proposed research investigated modifying the blade with an additional s/r (straight profile) and l/r (blade end) on each testing runner.

## 3. Method

### 3.1 Experimental Set-up

An experimental procedure was used to conduct the research, and a simulation process was used to confirm its validity. The apparatus test, which implements the rainwater harvesting operating principle, is the method used in the experiment. The head of this tool has a maximum head height of 2 m. However, it replicates the drainage system used in multi-story buildings. The construction apparatus test refers to the previous research[8]. The following figure is the construction set-up of the Apparatus test shown in Figure 5.

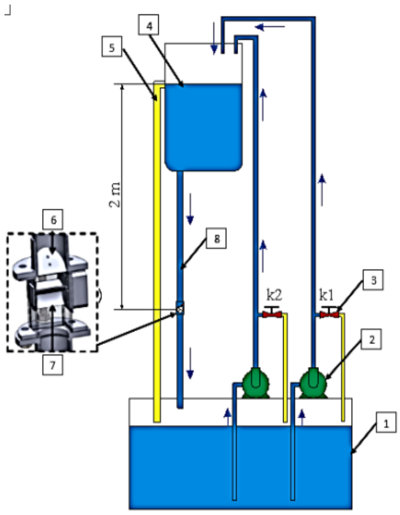



**Fig. 5:** Apparatus Test

**Description :**

1. Water tank
2. Centrifugal pump
3. Valve
4. Reservoir tank
5. Bypass Channel
6. Deflector
7. Savonius turbine
8. Outlet Pipe

### 3.2 Turbine Fabrications

The modifications made to the shape of the turbine consist of adding an end blade (l/r) and an additional straight blade shape (s/r). Ten specimens of the turbine were used during the experiment, which included nine variations of s/r and l/r, along with one conventional shape. The detailed variations of the turbines are shown in Table 2. The schematic of the turbine variations is shown in Figure 6.

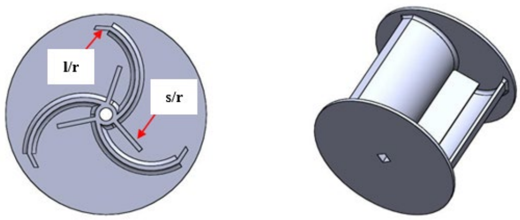



**Fig. 6:** The modification schematic

Table 2. The Turbine Variations

| Variations | | l/r 0.3 | l/r 0.6 | l/r 0.9 |
|---|---|---|---|---|
| s/r | 0.75 | ✓ | ✓ | ✓ |
| s/r | 0.50 | ✓ | ✓ | ✓ |
| s/r | 0.25 | ✓ | ✓ | ✓ |
| Conventional blade | | | | |

**Noted**: ✓ Variations turbine were used on experiment

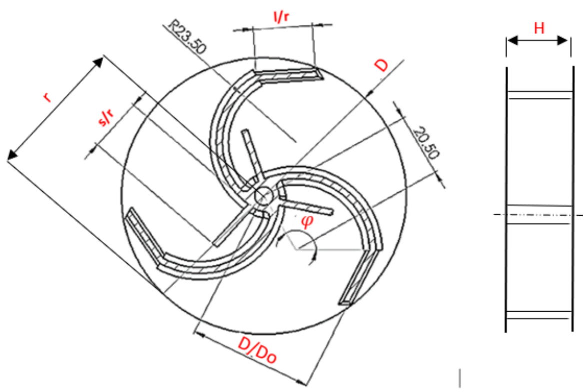



**Fig. 7:** The Dimensions of Turbine

The turbine design and construction are based on the previous study[19]. The turbine has an aspect ratio of H/D = 1 with the values of H = 82 mm and D = 82 mm, and the endplate (D/Do) size is 41 mm[24]. The number of turbine blades is three[7], with turbine curvature at 120°[21] and the deflector angle is 30°[13]. The turbine was made using a 3D printing machine. The Table 3 provides the turbine dimension used during the research.

Table 3. The dimensions of turbines

| Parameter blade | Dimension |
|---|---|
| H | 82 mm |
| D | 82 mm |
| H/D | 1 |
| D/Do | 41 |
| Curvature angle ($\varphi$) | 120º |
| s/r | 0.75, 0.50, and 0,25 |
| l/r | 0.3, 0,6 and 0,9 |

### 3.3 Experimental Framework

Figure 8 shows the research frameworks describing the experimental research process. The research investigates the Savonius turbine's performance with variations in the end blades and the addition of a straight between blades. The performance showed by the power input, rotational speeds, power output, and coefficient of power. When the flow remains stable, the data collection process is performed, and the rpm data is obtained from the tachometer. Additional data includes flow rate, turbine rotation, electric voltage, and current. A multimeter used the measure electric voltage and current.

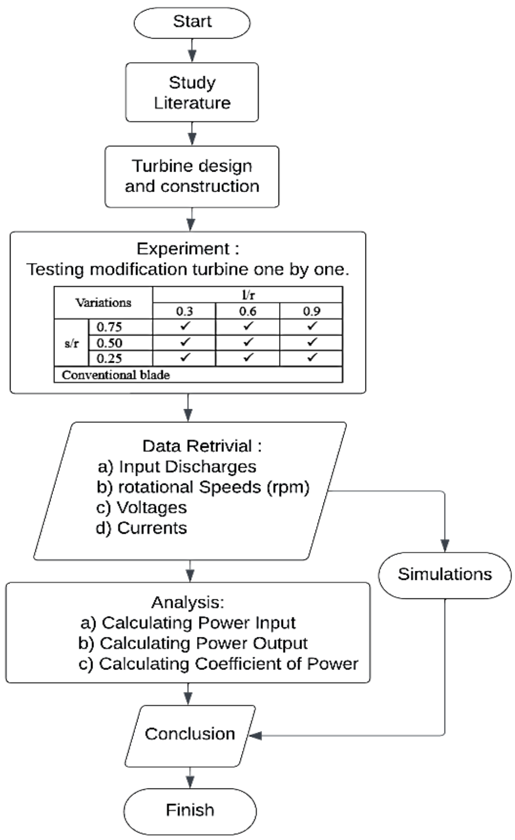



**Fig. 8:** Research frameworks

Simulations analysis was conducted to perform pressure distribution by each variation on different conditions. The simulation was taken on several variations based on the results of experimental data to support the analysis that occurred in the turbine. The effective amount of elements and nodes are needed in the simulation to ensure the number of mesh does not affect the results[23]. The 1,250,000 elements and 250,000 nodes for independent meshing are used in the simulation.

### 3.4 General Equation

The generated performances of the Savonius turbine were calculated using several equations, calculating performances in the form of power input ($P_i$), power output ($P_o$), coefficient of power ($Cp$), and tip speeds ratio ($TSR$). Power input is the energy that flows through the pipe and drives the blades in the water stream that exits from the deflector. The head ($H$) and discharge ($Q$) influence the amount of power input. $\rho$ represent the density of water with 997 kg/m$^3$ and $g$ is the acceleration gravity with 9.81 m/s$^2$.

$$P_i = \rho . g . H . Q \qquad (1)$$

The momentum from the moving fluid causes the rotations of the turbine. The rotating turbine coupled with the generator uses pulley-belt transmission to generate voltage (V) and current (I) electricity. The following equation was used to determine how much electric power the turbine generates:

$$P_o = V.I \qquad (2)$$

The *TSR* is the ratio between blade speed and fluid velocity. Given that $\omega$ performs the angular velocity, *D* performs the diameter of the turbine and the actual velocity by the fluids symbolized by *U*. Tip Speed Ratio produced by the turbines was calculated by the following equation.

$$TSR = (0.5\,.\,\omega\,.\,D)/U \qquad (3)$$

The measuring process using a tachometer produced rotational speeds in the form RPM (*N*), and then the value was converted to the *rad/s* using the following equation.

$$\omega = (2.\pi.N)/60 \qquad (4)$$

The strength of the rotating shaft was performed by *F*, which is the value owned by the load cell on the Prony brake mechanism. The definition of turbine power results from multiplying the angular velocity ($\omega$), force (*F*) and the radius (*r*) of the pully on prony brake.

$$P_t = \omega.F.r \qquad (5)$$

The total energy stored in water was impossible to extract 100% by a turbine. The differences in the value of available energy or power input ($P_i$) and power output $P_t$ was stated as the Coefficient of Power.

$$Cp = P_t/P_i \qquad (6)$$

## 4. Result and Discussion

### 4.1 Power Input

Power input ($Pi$) is the stored energy that hits the turbine and causes turbine rotations. The amounts of generated power inputs were calculated using Eq.1. The fluid that enters pipe channels and then hits the turbine significantly affects the calculation of the power input generated by the turbine. This study used three different discharges as variations during the experiment. The research used the dependence on deflectors to enhance the water velocity before hitting the turbine. As a result, variation 1 produced a flow rate of $10.82\times10^{-3}$ $m^3/s$ and a height difference (h) = 2 m. Variation 2 had a discharge of $8.17\times10^{-3}$ $m^3/s$ and a height difference (h) = 1.8 m, while variation 3 produced a flow rate of $5.66\times10^{-3} m^3/s$ and a height difference (h)=1.6 m. The simplification of analyzing the relationship between the flow rate and head is shown in Figure 9. It was also discovered that the value of the power input increases with a higher flow rate value. Based on the generated head, the calculating power input has been done and shown in Figure 10.

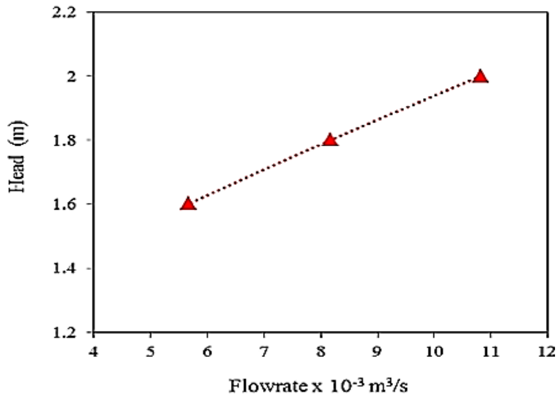



**Fig. 9:** Relations between flowrate and generated discharge

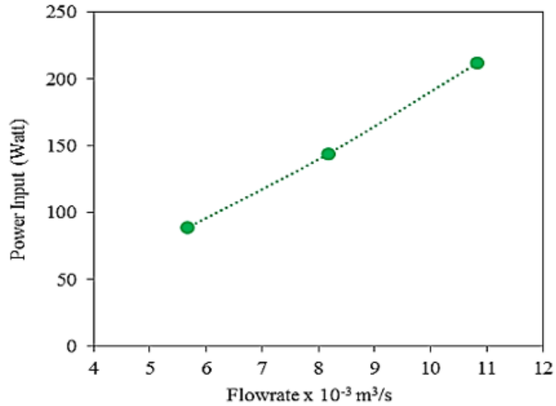
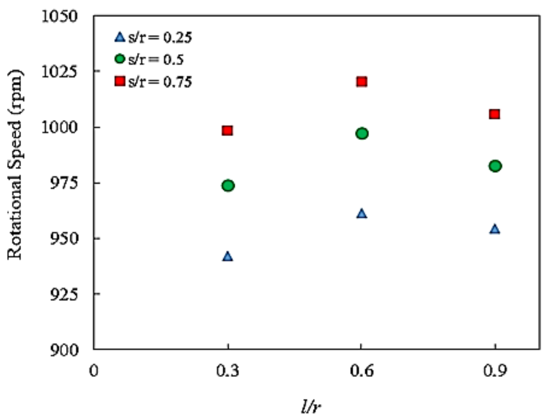
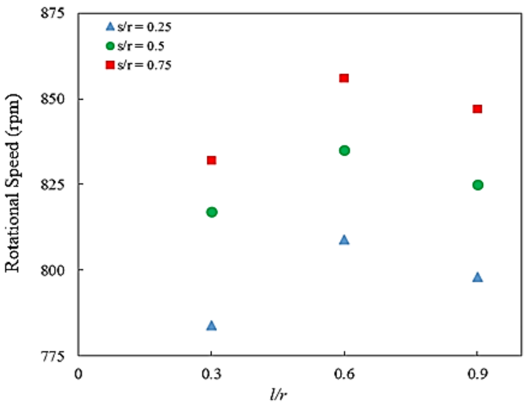



**Fig. 10:** Relations between flowrate and generated power inputs

The generated power input is shown in Figure 10 at different flow rates. A linear relationship exists between the rising power input and the flow rate. Power inputs of 88.58 W, 143.84 W, and 211.67 W were produced by flow rates of $5.66\times10^{-3}$ $m^3/s$, $8.17\times10^{-3}$ $m^3/s$, and $10.82\times10^{-3}$ $m^3/s$, respectively. It is because the highest flow rate stored more potential energy than others and produced the highest head.




(a)

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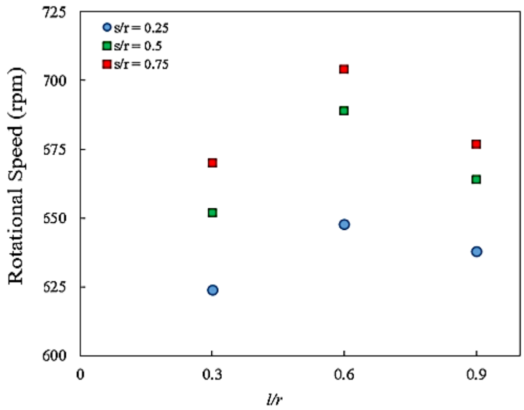
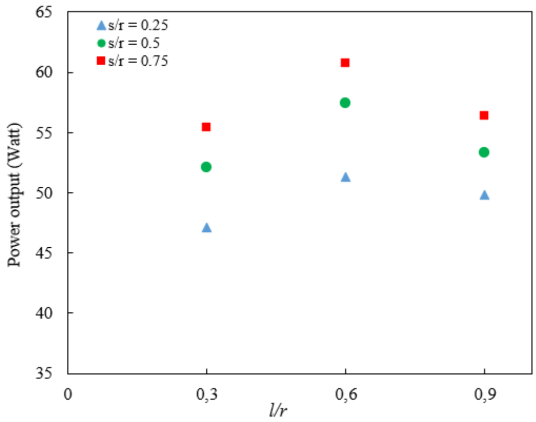



(c)

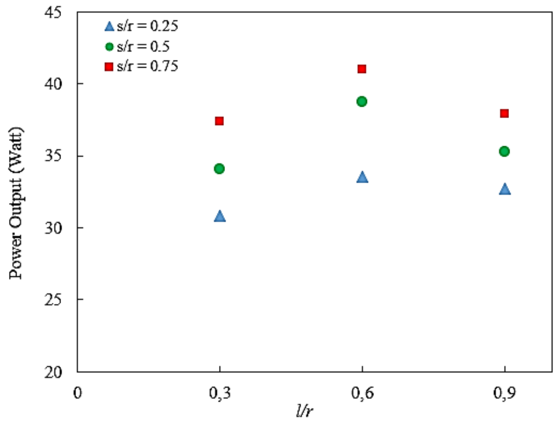
**Fig. 11:** Rotational speeds generated by each variation at (a) $10.8 \times 10^{-3}$ $m^3/s$, (b) $8.17 \times 10^{-3}$ $m^3/s$, (c) $5.66 \times 10^{-3}$ $m^3/s$

### 4.2 Generated Rotational Speeds

Figure 11 shows the rotational speeds at various flow rates. The best performance on rotational speeds was reached by s/r 0.75. On the other hand, the l/r variations generate the highest rotational speeds by l/r 0.6. These affect the electric power value and power output generated at each flow rate. The highest turbine rotation is achieved by s/r 0.75 and l/r 0.6 with a value of 1023 rpm. While the lowest rotation is generated by s/r 0.25 and l/r 0.3 with a value of 624 rpm at a flow rate of $5.66 \times 10^{-3}$ $m^3/s$. It was mentioned that rotational speeds decreased between l/r 0.6 and l/r 0.9 during the tests. These results occur along with varying s/r ratios and increasing discharges.




(a)

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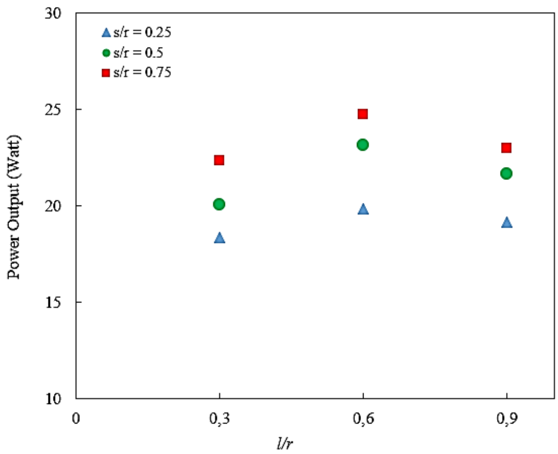


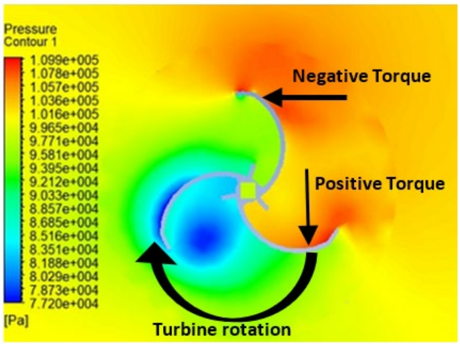

(c)

**Fig. 12:** The power output generated by each variation on (a) $10.8 \times 10^{-3}$ $m^3/s$, (b) $8.17 \times 10^{-3}$ $m^3/s$, (c) $5.66 \times 10^{-3}$ $m^3/s$

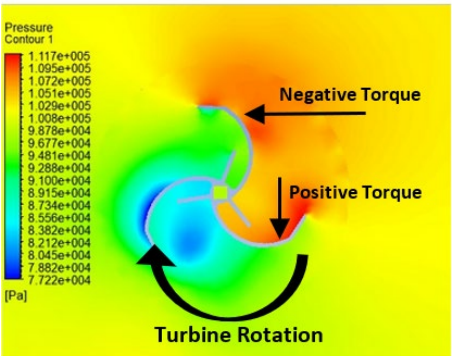
### 4.3 Power Output

A previous study stated that power output describes Savonius turbine performance [23]. Figure 12 presents the results of power output data for each variation of Savonius turbine blade modification at a specific flow rate. The highest power output was generated by s/r 0.75 and l/r 0.6 with a value of 60.8 W calculated using Eq.2. On the other hand, the lowest value was generated by s/r 0.25 and l/r 0.3 with a value of 47.1 W. Figure 12 shows that increasing power output depends on the flow rates used.

The turbine with s/r 0.75 and l/r 0.6 constantly reached the highest value on the power output generated during the experiment by each variation. Its turbine can extract maximum potential energy from the water.




(a)

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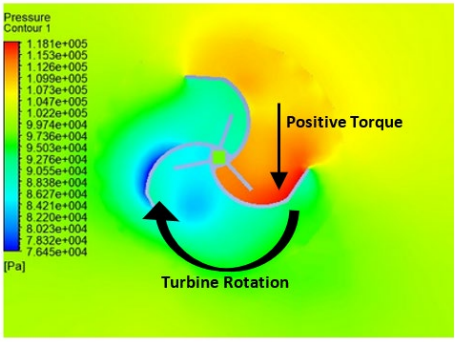
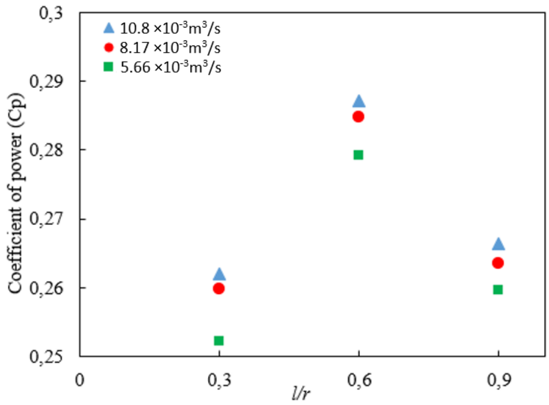


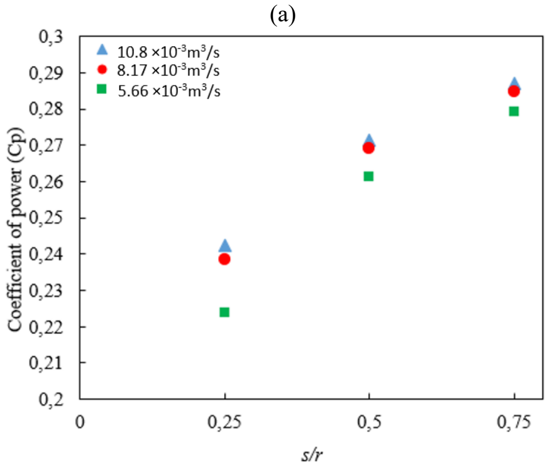

(c)

**Fig. 13:** Pressure contour on the variation of turbine under $10.8 \times 10^{-3} m^3/s$ with (a) l/r 0.3 and s/r 0.25, (b) l/r 0.9 and s/r 0.75 (c) l/r 0.6 and s/r 0.75

Its phenomenon was also investigated using simulation to confirm the experiment result. The s/r 0.75 and l/r 0.6 consistently generate the highest power output compared to the others. As depicted in Figure 13c, the turbines were simulated under $10.8 \times 10^{-3} m^3/s$. A dominant red area along the concave side influences the generating performance. Figure 13a shows the pressure distribution of l/r 0.3 and s/r 0.25, with the red contour dominating the convex side blade and causing highly negative torque. Moreover, the generated performance tends to be lower than other variations. On the other hand, Figure 13b shows that the convex and concave sides have a proportional red contour, leading to a moderate value between the others for l/r 0.9 and l/r 0.7. In conclusion, the simulation results support the experimental analysis that indicates the best turbine variation receives more water momentum than the other variation.




(a)




(b)

**Fig. 14:** The result on *Cp* on (a) Additional end plate and (b) Additional straight blade

## 4.4 The Independent Effect of Additional Straight Blades (s/r) and End Blades (l/r)

In this section, variations of l/r and s/r were tested independently to elaborate on the effect generated by each variation. Firstly, the experiment was conducted with the l/r variations and chosen s/r values under different input discharges. The constant parameter of 0.75 s/r was chosen and considered the best performance during the experiment. Based on figure 14a, the highest *Cp* generated was 0.6, with an l/r ratio of 0.6 and a constant s/r ratio. This result proves that l/r variations influence turbine performance. Furthermore, variations of s/r were investigated with a constant l/r ratio of 0.3.

Figure 14b shows that the increasing *Cp* was linearly proportional to the additional s/r and discharges, with the best performance on *Cp* reached by s/r of 0.75. Regarding Figure 7, the s/r profile is the additional straight blade added between the turbine blade. If the s/r value approaches 1, it's defined that additional s/r totally blocks the concave side from receiving the momentum's water. Because of that, the maximum s/r variation used is 0.75.

Mostly, the additional straight blade extracted energy more optimally, resulting in generated rotational speeds greater than those of the conventional blade. Based on these results, it was concluded that the findings align with previous research[22)].

The water hitting the concave blade of the turbine is captured more optimally at a certain turning angle. Subsequently, the positive torque of the turbine increases with the captured of area. At a certain turning angle, the blade can also reduce positive torque and cause an increase in negative torque. This showed that additional straight blades could also lead to turbulent flow, which creates backflow at the turbine blade.

### 4.5 Comparative Study Between Conventional and Modified Savonius Water Turbine

Figure 15 shows the *Cp* generated by a modified and conventional Savonius water turbine. The modified Savonius (s/r 0.75 and l/r 0.3) performs better than the conventional form, proving that the Cp is higher than the conventional *Cp*. Mostly the generated *Cp* of the modified form produces 0.28, 0.28, and 0.29 sequentially from the discharge used. Besides, the conventional form has 0.19, 0.2, and 0.21 of *Cp*, respectively. Both variations have the same trend of increasing the *Cp* when the discharges increase.

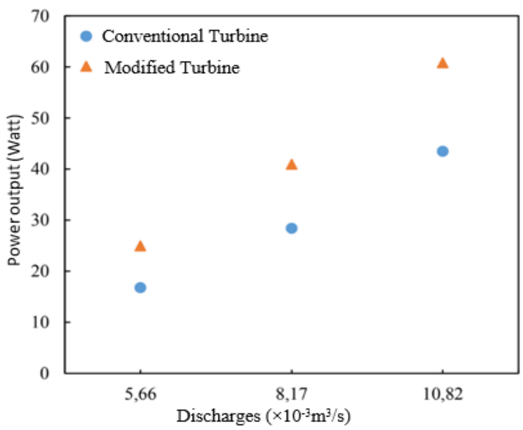
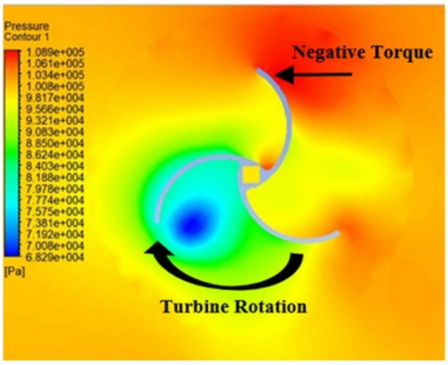
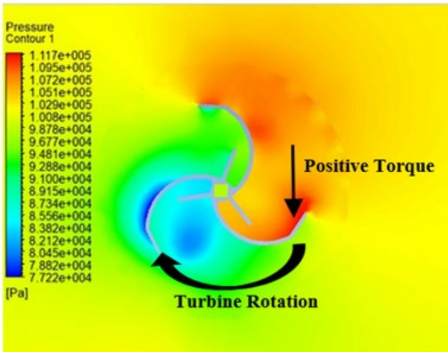



**Fig. 15:** Comparative result on power output between modified and conventional Savonius water turbine

The Savonius modification always produces a higher power output than the conventional Savonius under the same applied discharges. Conventional Savonius produced a power output of 16.8 W, 28.5 W, and 43.4 W, respectively, from the lowest to highest discharges applied. In comparison, the generated power outputs of the modified Savonius are 24.7 W, 40.9 W, and 60.8 W, respectively. Based on each applied discharge, the increasing performances from conventional to the modified Savonius are 48%, 44%, and 40%.




(a)




(b)

**Fig. 16:** Pressure Contour of (a) Conventional an (b) Modified Savonius turbine with 0.75 s/r and 0.3 l/r under $10.8\times10^{-3}m^3/s$

Figure 16 shows the pressure contours on the turbine blade (a) Savonius conventional (b) Savonius modified were simulated under $10.8\times10^{-3}m^3/s$. It was discovered that additional blade ends and straight blades could improve Savonius turbine performance. The result has been proven by the results obtained from the rotational speeds, power output, and coefficient of power. This section describes the function of research variations to improve the generated performance of Savonius turbines through the adjusting flow catching by the turbine. The Savonius additional blade end expands the drag force area to catch water to increase the positive torque acting on the turbine. Meanwhile, the straight blade is used to prevent the flow of water that will hit the gap between the blade and direct the water to the most optimal angle of the convex side. Because of that, the modifying turbine has the most ability to catch more drag force from the water.

## 5. Conclusion

Based on the result, it was concluded that additional blade ends and straight blades significantly affect the generated performance of the Savonius water turbine mounted on a 3-inch pipeline. The best performances are always stored on the highest discharges with the variation of l/r 0.6 and s/r 0.75. These variations generated 60.8 W of power output and 0.29 of *Cp*. The results also show that modified Savonius turbines are more effective in improving their performance during experiments and simulations. The additional s/r and l/r ratios are generally more effective than the conventional Savonius design.

Both modifications have influenced the turbine's interaction with the water. This research contributes to further developing and implementing the Savonius water turbine, particularly in the literature on developing and implementing Pico Hydro turbines, especially in Indonesia. Indonesia has many suitable locations for applying the Pico Hydro Savonius turbine, such as small irrigation channels, rivers, and pipelines in multi-story buildings.

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## Nomenclature

| | |
|---|---|
| *Pi* | Power Input (W) |
| *Cp* | Coefficient of Power |
| $P_o$ | Power Output (W) |
| *TSR* | Tip Speed Ratio |
| *I* | Current (A) |
| *V* | Voltage (V) |
| *g* | Acceleration Gravity (m/s) |
| *H* | Head (m) |
| *Q* | Flow Rate ($m^3/s$) |
| $\omega$ | Angular Velocity (rad/s) |
| *D* | Turbine Diameter (m) |
| *U* | Actual Water Velocity (rad/s) |
| *F* | Force (N) |
| *r* | Turbine Radius (m) |
| $\rho$ | Density of Water ($kg/m^3$) |
| *s/r* | Additional Straight Blades |
| *l/r* | Additional Blade End |

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