Numerical simulation on improvement of a Savonius vertical axis water turbine performance to advancing blade side with a circular cylinder diameter variations

P A Setiawan¹, T Yuwono³, and W A Widodo²

¹Student of Doctoral Program, Mechanical Engineering Department, Sepuluh Nopember Institute of Technology, Surabaya, 60111 Indonesia
²Mechanical Engineering Department, Sepuluh Nopember Institute of Technology, Surabaya, 60111 Indonesia
³Marine Engineering Department, Shipbuilding Institute of Polytechnic Surabaya, Surabaya, 60111 Indonesia
⁴Center of Excellence in Automotive Control & System, Sepuluh Nopember Institute of Technology, Surabaya, 60111 Indonesia

Corresponding author: Email: triyogi@me.its.ac.id

Abstract. The use of fossil fuel will generate particulate gas in the atmosphere and forming the greenhouse effect. One of the ways to reducing greenhouse effect is used renewable energy as hydropower without generating particulate gas impacted in human life. The present study uses hydropower as the renewable energy by using a Savonius turbine. The main objective investigates the performance of Savonius water turbine numerically due to the installation of a circular cylinder beside of the advancing blade with circular cylinder diameter variations. The method used is numerically toward Savonius turbine disturbed a circular cylinder. The numerical simulation using two-dimensional (2D) analysis of Computational Fluid Dynamics (CFD) simulation by using ANSYS 17.0-Fluent and sliding Mesh technique used is to solve the incompressible Unsteady Reynolds Averaged Navier-Stokes (URANS) equations. The turbulence model uses Realizable k-epsilon (RKE) and transport equation uses the finite volume discretization method with the second-order upwind scheme and the SIMPLE algorithm. Firstly, the numerical model has been validated by the published experimental data toward the torque coefficient by using air fluid at Reynolds of 4.32.10⁵. Then the fluid is changed the water fluid at the same Reynolds. The circular cylinder diameter relative to the turbine diameter (ds/D) is varied of 0.1, 0.3, 0.5, 0.7 and 0.9 at X/D of 0.5 and Y/D of 0.7 kept constant with TSR of 0.5, 0.7, 0.9, 1.1 and 1.3. The numerical simulation uses the transient and two dimensional (2D) simulations. The results show that the increase of disturbance diameter (ds/D) will improve the performance of the conventional Savonius turbine and the maximum power coefficient increase about 18.04% at ds/D of 0.7 with TSR of 0.7.

1. Introduction
With REmap, more than half of all renewable energy use in Indonesia in 2030 would be in the form of bioenergy used for process heat in industry or as liquid biofuels in transportation. Solar applications (including Photo Voltaic (PV) and thermal) account for 15% of renewable energy use in all sectors in Indonesia as envisaged by REmap, followed by hydropower (14%) and geothermal power (9%) [1]. By using fossil fuels in combustion can produce carbon dioxide, methane and nitrogen oxides which
contribute to greenhouse gas emissions improving global climate change. This present study uses renewable energy to reduce the fossil fuels and greenhouse gas emissions by improving the performance of the Savonius turbine numerically. Generally two types of a turbine; such as vertical axis turbines (VATs) and horizontal axis turbines (HATs). It based on shaft alignment between their axis of rotation and fluid direction. VATs used to generate small scale power because the turbine performance is not depended on fluid flow direction [2]. Type of VATs generates torque by combining between drag effects and side forces. The energy of hydro from the river, sea current, waves is the best renewable energy sources and very predictable compared to wind energy or the other. Application of vertical axis turbine is generally Savonius turbine, helical turbine and Darrieus turbine [3].

The present study focuses on the hydropower by improving the performance of the Savonius vertical axis turbine and the type of water turbine has the lowest performance compared to others types of the water turbine. That is why various studies have been carried out to improve the performance of the Savonius turbine. Among others, Sheldahl et al. [4] have varied the number of the bucket and the gap spacing between the buckets. Patel et al. [5] conducted a study on the Savonius turbine numerically by varying the overlap ratio of 0, 0.1 and 0.2. They have observed it for varied wind speed the maximum torque has obtained at the overlap ratio of 0.2.

Freitas [6] state the numerical study was carried out and developed to improve the performance of the turbine. The study of numerical simulation has been tested to avoid uncertainty numerically. It produces some numerical simulation policy and some policy was essential to improving the results of numerical as discretization second-order upwind and comparison numerical toward experimental data.

The result of the numerical simulation is carried out to compare 2-D and 3-D simulation, where has it shown a good approximating experiment result. The results of 2-D simulation have power coefficient which is more approaching experiment than 3-D simulation [7].

The Spalart-Allmaras (SA) [8] turbulence viscosity model is a one-equation turbulence model where near wall gradients of the transported variable are much smaller than the turbulent kinetic energy based k-ε models and the standard k-ε model [9] is more suitable when flow is fully turbulent and has given better results than SA model for turbine analysis [10]. Previous studies for Savonius turbine has shown that two dimensional simulations give acceptable results [2][11].

This present study is numerically expected to reduce greenhouse gas using Savonius water turbine. Simulation analyzes the unsteady flow around the Savonius turbine by adding circular cylinder placed to advancing blade side with circular cylinder diameter (ds/D) variations.

2. Methodology

2.1. Equations and Mathematics

The Savonius turbine rotates 360 degrees starting from the first position and returns on the same position relative to the center axis for achieving one rotation. The time step size (TSS) represents the increment angle for each the rotation of step and the number of the time step (NTS) represents the total of turbine rotation.

The equation of mathematics of the number of the time step (NTS) and the time step size (TSS) can be written as follows:

\[ \text{NTS} = \frac{360}{\theta} \]  \hfill (1)

\[ \text{TSS} = \frac{N}{0.15915 \times \omega \times \text{Number of time step}} \]  \hfill (2)

Where \( N \) is the number of rotations, \( \theta \) is the increment angle or time step rotation degree, \( \omega \) is the rotation speed of turbine (rad/s) and 0.15915 is a constant (conversion from rad/s to rot/s unit).
The equation of TSR (tip speed ratio), the coefficient of torque, the coefficient of power can be written as follows:

\[
\text{TSR} = \frac{\omega D}{\frac{\pi}{2} U} \\
C_m = \frac{1}{\frac{1}{4} \rho A_s D U^2} \\
C_p = \frac{1}{\frac{1}{2} \rho A_s U^3} \\
C_p = \text{TSR} \ C_m
\]  

Where \(\omega\) is the angular velocity, \(U\) is the free stream velocity, \(A_s\) is the rotor swept area, \(A_s = D H\) and \(D\) is the Savonius turbine diameter, \(P\) is the power of the turbine, \(C_p\) is the coefficient of performance that a non-dimensional parameter used to evaluate the turbine power and \(C_m\) is the coefficient of moment from simulation results.

2.2. Numerical method
Firstly, the numerical model has been validated by the published experimental data Sheldahl et al. [4] toward the torque coefficient by using air fluid at Reynolds of 4.32.10^5. In this present study, the fluid is changed to the water fluid at the same Reynolds with circular cylinder variations. The Savonius turbine diameter is about 0.4 m and a circular cylinder diameter \(d_s/D\) varied 0.1, 0.3, 0.5, 0.7 and 0.9, which installed at the vertical distance relative to keep the turbine diameter constant at \(Y/D\) of 0.7. The horizontal distance relative to the turbine diameter \((X/D)\) is kept constant at 0.5. The boundary condition inlet velocity \(U\) of 0.22 m/s was imposed upstream of the rotor at a distance of 10D from the rotor axis, where \(D\) is the diameter of Savonius turbine. The boundary condition downstream of the rotor is pressure outlet at 10D behind the rotor. The top and bottom of the flow domain were taken at 6D from the rotational axis where the outlet pressure boundary condition is imposed.

![Figure 1. Two-dimensional Computational domain and the Boundary Conditions using a circular cylinder.](image)

This study uses the unsteady incompressible Reynolds-Averaged Navier-Stokes (RANS) equation based on the cell-centered finite volume method and then has implemented the rotation by using the sliding mesh technique to rotate the space of the turbine area. This main study, the structured grid has
been employed for all the grid system of the rotor, and the computational domain reaches to 10D in the inlet direction, 10D in the outlet direction and 6D in the vertical direction towards Savonius turbine. The calculation was made based on the two-dimensional unsteady flow assumption for its relative simplicity. There are three different meshes defined as a fixed domain, wake domain and rotating domain as shown in Figure 2.

The grid of computation was generated using the MESH tool in ANSYS 17.0 with two-dimensional, quadrilateral elements are more desirable and have high accuracy in numerical solutions shown in figure 2 [15]. The surface was made first prism layer with setting the y+ value for the first elements from 30 and 100, depending on the rotation velocity of the rotor and the position of the elements on the blade shown in figure 2(c).

![Figure 2. Grid generation for the fixed domain (a), the wake domain (b), and the rotating domain (c)](image)

Grid independence investigates the change of grid size from coarse to fine 17,006, 61,105 and 120,000 elements. It can be seen that grids with approximately 61,105 and 120,000 elements have around the same results as shown in Figure 3. Considering the time economy in the simulation, the simulation would choose 61,105 elements for the next simulation. The numerical simulation carried out on the conventional Savonius rotor at Re of $4.32 \times 10^5$ with the diameter of Savonius turbine of 1 m, the free stream and angular velocity of 7 m/s and 144.087 rpm respectively. The value of torque coefficient (Cm) reported experimentally by Sheldahl et al. [4] by varying the tip speed ratio of 0.5, 0.7, 0.9, 1.1 and 1.3, where it has the result of simulation approached the value of experimental data reported by Sheldahl et al. [4] as shown in Figure 4.

![Figure 3. Results for grid convergence](image)

![Figure 4. Results for validation](image)
The validation of this numerical simulation was carried out by comparing with the results experimental published by Sheldahl et al. [4]. Comparison of the torque coefficient (Cm) was as the function of the tip speed ratio (TSR) between the results of this numerical simulation to the experimental results of Sheldahl et al. [4] as shown in Figure 4. A range of tip speed ratio of 0.5 to 1.3, Figure 4 shows that the present study is in very good agreement with the experimental results reported by Sheldahl et al. [4]. As a conclusion, so the mesh characteristic, which is operated in the simulation above is considered to be valid and will be used to simulate the real problem proposed in this present study.

3. Results and discussion
In this present study, the air-fluid would be changed to the water fluid after the grid independence is reached. The numerical study was carried out at free stream velocity kept constant in about 0.22 m/s with the rotor diameter of Savonius turbine (D) of 0.4 m. Numerical simulation has achieved grid independence, so the next numerical was carried out by installing a circular cylinder to the advancing blade side. The diameter of the circular cylinder relative to the diameter of the turbine rotor (ds/D) was varied 0.1, 0.3, 0.5, 0.7 and 0.9. The vertical position relative to turbine rotor (Y/D) was kept constant at 0.7 and the horizontal position relative to turbine rotor (X/D) was also kept constant at 0.5 and the simulation was carried out for tip speed ratio (TSR) from 0.5 to 1.3.

![Figure 5](image5.jpg)  ![Figure 6](image6.jpg)

**Figure 5.** The coefficient of torque with respect to TSR with cylinder diameter variations  **Figure 6.** The coefficient of power with respect to TSR with cylinder diameter variations

Graph of torque and power coefficient was shown in figure 5 and 6. It is clear that the numerical simulation by adding a circular cylinder as passive control was installed to advancing blade side influenced the performance of Savonius turbine. The numerical simulation varied circular cylinder diameter relative to Savonius turbine (ds/D) of 0.1, 0.3, 0.5, 0.7 and 0.9. The results showed that the performance of the turbine increased by the change ds/D from 0.1 to 0.9 compared to the Savonius turbine. The maximum power increased at ds/D of 0.7 about 18.04% at TSR of 0.7. Meanwhile at ds/D of 0.9, shown that installation of circular cylinder decreased the performance of the turbine because the formation of streamline on the upper side of circular cylinder caused the flow direction blocking free streamline, however, the performance of the turbine reduces.
Table 1. The maximum coefficient of power for each variation

| Variation     | Peak Cp | Corresponding TSR | Cp Gain (%) relative to conventional Savonius |
|---------------|---------|-------------------|---------------------------------------------|
| Conventional savonius | 0.2295  | 0.9               | 0                                          |
| ds/D = 0.1    | 0.2242  | 0.9               | -2.29                                      |
| ds/D = 0.3    | 0.2498  | 0.9               | 8.83                                       |
| ds/D = 0.5    | 0.2580  | 0.9               | 12.42                                      |
| ds/D = 0.7    | 0.2709  | 0.7               | 18.04                                      |
| ds/D = 0.9    | 0.2372  | 0.7               | 3.36                                       |

The peak power coefficients produced by varying circular cylinder relative to Savonius turbine (ds/D) are compared with the highest performing on conventional Savonius shown in Table 1. Table 1 shows the benefit of the effect of circular diameter variations with a peak power coefficient of 0.2709 obtained at a tip speed ratio of 0.7, which is 18.04% higher than a conventional Savonius turbine.

4. Conclusion
A circular cylinder as passive control contributed great effect to the Savonius turbine performance. From above discussion result, it shows that the increasing of ds/D will increase the torque and power coefficient, which maximum performance occurred at ds/D of 0.7 and power coefficient increase in about 18.04% at a tip speed ratio (TSR) of 0.7. Using renewable energy and increasing the turbine performance will reduce dependence on fossil fuels so that they will reduce the greenhouse gases as a cause of climate change.

References
[1] IRENA 2017 Renewable Energy Prospects: Indonesia, a REMap analysis (Abu Dhabi: International Renewable Energy Agency (IRENA))
[2] Yang B and Lawn C 2015 Fluid dynamic performance of a vertical axis turbine for tidal currents Renewable Energy 36 3355–3366.
[3] Kailash G, Eldho T I and Prabhu S V 2012 Performance Study of Modified Savonius Water Turbine with Two Deflector Plates International Journal of Rotating Machinery 2012 1-12.
[4] Sheldahl R E, Feltz L V and Blackwell B F 1978 Wind Tunnel Performance Data for Two- and Three-Bucket Savonius Rotors Journal of Energy 2 160-4
[5] Patel C R, Patel V K, Prabhu S V and Eldho T I 2013 Investigation of Overlap Ratio for Savonius Type Vertical Axis Hydro Turbine International Journal of Soft Computing and Engineering 3 379 – 83.
[6] Freitas C 1999 The Issue of Numerical Uncertainty The 2nd International Conference on CFD in the Minerals and Process Industries (Melbourne: CSIRO) pp 29-34.
[7] Hyun B S, Choi D H, Han J S and Jin J Y 2012 Performance Analysis and Design of Vertical Axis Tidal Stream Turbine Journal of Shipping and Ocean Engineering 2 191-200
[8] Spalart P R and Allmaras S 1992 A One-Equation Turbulence Model for Aerodynamic Flows 30th Aerospace Sciences Meeting and Exhibit Reno NV U.S.A
[9] Launder B and Spalding D B 1972 Lectures in Mathematical Models of Turbulence (Philadelphia: Academic Press )
[10] Pope K, Rodrigues V, Doyle R, Tsopelas A, Gravelsins R, Naterer G and Tsang E 2010 Effects of stator vanes on power coefficients of a zephyr vertical axis water turbine Renewable Energy 35 1043-51.
[11] Altan B D and Atilgan M 2008 An experimental and numerical study on the improvement of the performance of Savonius wind rotor Energy Convers. Manag 49 3425–32.
Rosario L, Stefano M and Michele M 2014 2D CFD modeling of H-Darrieus Wind turbines using a Transition Turbulence Model Energy Procedia 45 131–40.
McTavish S, Feszty D and Sankar T 2012 Steady and rotating computational fluid dynamics simulations of a novel vertical axis wind turbine for small-scale power generation *Renewable Energy* **41** 171–9

Kacprzak K, Liskiewicz G and Sobczak K 2013 Numerical investigation of conventional and modified Savonius wind turbines *Renewable Energy* **60** 578–85

Wenlong T, Baowei S and Zhaoyang M 2014 Numerical investigation of a Savonius wind turbine with elliptical blades *Proceedings of the CSEE* **34** 796–802