Numerical Study of the Stagger Angle Effect of a Circular Cylinder Installed in Front of Returning Blade Toward the Vertical Axis Savonius Water Turbine Performance

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Abstract. This paper investigates numerically the effect of the circular cylinder's stagger angle variation installed in front of the returning blade on the performance of Savonius vertical axis water turbine. The numerical simulation uses Computational Fluid Dynamics using ANSYS 17.0 to solve the incompressible Unsteady Reynolds Averaged Navier-Stokes (URANS). Firstly, numerical model is verified by varying the grid size at TSR 1,078. Then numerical results are validated by existing experimental data, in this case the torque coefficients. The working fluid is verified using air at Reynolds of 4.32 x 10^5 and convert to water fluid. Ratio of circular cylinder diameter to the turbine diameter (ds/D) is 0.5 at gap (S/D) of 0.95 with varying TSR of 0.3, 0.5, 0.7, 0.9, 1.1 and 1.3 and stagger angle (α) of 0, 30, 60 and 90 degree. The results show that the maximum power coefficient increases about 29.84% at a TSR of 0.9 for stagger angle of 60 degree.

1. Introduction
Classification of a turbine becomes two types namely vertical and horizontal axis wind turbines. that is based on rotation axis and the wind direction. The improvement of Savonius turbine has conducted by installing deflector. Kailash et al. [1] conducted the performance study of modified Savonius water turbine with two deflector plates. The experimental conducted in open water channel with Reynolds 1.32 x 10^5 based on diameter of rotor. The results of experiment showed the maximum power coefficient using deflector plates on the side of advancing and returning blade improving 0.35 at a tip speed ratio of 1.08. Setiawan et al [2] also conducted numerical study by installing cylinder on side of advancing blade with varying ds/D of 0.1, 0.3, 0.5, 0.7 and 0.9. The maximum of power coefficient occurred at ds/D about 0.7 and tip speed ratio (TSR) of 0.7. Sheldahl et al. [3] conducted experimental in wind tunnel with varying buckets number 2 and 3 and the best performance at 2 buckets. Savonius was tested in wind tunnel at 7 m/s and 14 m/s with Reynolds of 4.32 x 10^5 and 8.67 x 10^5, respectively. The best performance occurred at overlap ratio 0.1 – 0.15. The study also varied overlap ratio from 0.0 to 2.0 conducted by Patel et al. [4] using the numerical simulation. The results of numerical simulation shows...
that the best performance occurred at overlap ratio 0.2. This paper uses overlap ratio of 0 or conventional Savonius.

Freitas et al. [5] stated that is to avoid uncertainty numerical using the produced ten elements of the policy. In this paper, the effort of improving accuracy of numerical results uses second-order upwind, using the turbulence model of Realizable k-ε (RKE), grid independence or convergence with verification using the changing of grid size, numerical run until convergence, numerical uses transient calculation, and published experimental data is used to validate a solution from Sheldhal et al [3]. The numerical studied Savonius turbine for two-dimensional simulations obtained acceptable results by [2], [6], [7], [8], [9].

Authors [10] studied numerical about time step setting influence on vertical axis tidal current turbine. The results of numerical show that TSS apply in simulation around 5° up to 1° for reducing Cp error and setting NTS is 6 rotation to obtain a simulation result with low Cp error.

The aim of this study is to investigate the performance changes of the vertical axis Savonius water turbine due to the effect of installing a circular cylinder with a staggered angle change by using an unsteady numerical simulation. Firstly, the simulation was verified and validated by experimental data obtained by Sheldhal et al. [3] with variations in grid size, and then the results of the grid size validation is conducted by variations in stagger angles. A circular cylinder was installed in front of advancing blade at stagger angle of 0, 30, 60 and 90 degree. Finally, a unsteady Computational Fluid dynamics (CFD) will obtained the coefficient of torque for different rotors angular positions (degree), peak coefficient of performance (torque and power coefficient).

2. Methodology

2.1. Equations and mathematics

Turbine rotation starts from first position rotating and will be back the same position attaining one rotation or 360 degree. Time step size (TSS) and number of the time step (NTS) represents the increment angle for each the rotation of step and represents the total of turbine rotation, respectively. Equation of NTS and TSS can be written as in equation (1) and (2);

\[
NTS = N \frac{360}{\theta} \quad (1)
\]

\[
TSS = \frac{N}{\left(0.15915 \omega \right) \times NTS} \quad (2)
\]

Where rotation number, N, time step rotation degree, \(\theta\), angular speed (rad/s), \(\omega\) and 0.15915 is the conversion results from rad/s to rot/s.

The equation of TSR, Cm, Cp can be written as in equation (3), (4) and (5).

\[
TSR = \frac{\omega \cdot D}{2 \cdot U} \quad (3)
\]

\[
C_m = \frac{1}{\frac{1}{2} \rho A_s D U^2} \quad (4)
\]

\[
C_p = \frac{1}{\frac{1}{2} \rho A_s U^3} \quad (5)
\]

\[
C_p = TSR \times C_m \quad (6)
\]

Where angular speed, \(\omega\), the free stream velocity, U, area of the rotor swept, \(A_s\), \(A_s = D \cdot H\), the Savonius turbine diameter, D, the turbine power, P, power coefficient, Cp and moment coefficient from numerical simulation, Cm. Rotation for Savonius turbine can be seen in Figure 1.
2.2. Numerical method
The first, the numerical results will be verified using experimental data by Sheldahl et al. [3] with respect to torque coefficient at Reynolds number of $4.32 \times 10^5$. The working fluid was air using dimension from Sheldahl et al. [3] with the turbine diameter of 1 m. In this study, the used fluid is water with stagger angle variations. The Savonius turbine diameter and free stream velocity are 0.4 m and 0.22 m/s, respectively. The used circular cylinder diameter is $ds/D$ of 0.5, which was installed at $S/D$ of 0.7 by stagger angle of 0, 30, 60 and 90 of degree in front of returning blade shown in Figure 2.

The boundary consists of three domains as a fixed domain, rotating domain and wake domain as shown in Figure 3. Inlet is inlet velocity 0.22 m/s, upperside and lowerside are simmetry, outlet is pressure outlet. The boundary conditions can be seen in figure 2.

The computation used ANSYS 17.0 with 2D simulation analysis. The quadrilateral shape has high accuracy in numerical solutions as shown in figure 3 (a), (b) and (c). The first layer from surface was set the $y^+$ from the wall surface between 30 and 100, depending on the rotor rotation and element position on the blade as shown in figure 3 (c).
This study uses unsteady simulation and must use the sliding mesh to rotate of turbine area. The structured grid is conducted for all rotor grid system, and the computational domain achieves 10D in the inlet, 10D in the outlet and 6D in the vertical with respect to Savonius turbine. The calculation is made using two-dimensional for unsteady flow assumption.

Firstly, the verification uses the experimental data by Sheldahl et al. [3] with respect to torque coefficient at Reynolds number of $4.32 \times 10^5$. The verification is done by changing the grid size from rough to fine at TSR 1,078. The verification uses size grid 17,006, 61,105 and 120,000 nodes. The time economy was considered in simulation however the simulation will be choosen 61,105 nodes for the simulation for all variations. Numerical uses boundary condition as shown in Figure. 2. The verification and validation could be seen in Figure 4 (a) and 4 (b), respectively.

The numerical result was validated by experimental data from Sheldahl et al. [4]. The acceptable turbulence model used the Realizable $k$–$\varepsilon$ turbulence to predict the performance of Savonius rotor. A range of tip speed ratio was in the numerical from 0.5 to 1.3. The study is in very good agreement with the experimental data by Sheldahl et al. [4] as shown in Figure 4 (b). As a conclusion, the grid characteristics will be operated in the simulation above with considering be valid to simulate the problem.

In this study, the change of working fluid will be conducted from air to water after the grid is choosen. When the numerical simulation has attained validation step, then the next simulation step is conducted by placing a circular cylinder in front of returning blade with varied the stagger angle. The circular cylinder diameter ($d_s/D$) is 0.5 by stagger angle varied ($\alpha$) of 0, 30, 60 and 90 degree and the simulation is conducted for tip speed ratio from 0.5 to 1.3.

### 3. Results and Discussion

#### 3.1. Comparison of the different stagger angle

Figure 5(a) represents comparison the coefficient of torque (Cm) with respect to tip speed ratio (TSR). The coefficient of torque decreases with increasing the value of tip speed ratio (TSR) for all variations. Figure 5(b) represents comparison the coefficient of power (Cp) for four stagger angle and conventional Savonius in this study. Different stagger angle decreases Cp at 0 degree with the Cp value under conventional Savonius at all TSRs and maximum Cp occur at TSR of 0.8 like conventional Savonius. At low TSR for stagger angle 30 degree, Cp value is still under conventional Savonius at TSR more than 0.9 and Cp value increase at TSR less than 0.9. The stagger angle 60 degree improve Cp value at all TSR and maximum Cp value occur at TSR of 0.9. All variations attain maximum Cp at TSR of 0.7 except at stagger angle 60 degree. The stagger angle 60 degree shows that the best characteristics to other stagger angle and on the other hand, means bigger the coefficient of torque. At the stagger angle 90 degree, the performance of turbine reduces by compared the stagger angle 60 degree and the
A statement can be confirmed the best performance of stagger angle 60 degree not only for TSR 0.9, but also until TSR of 1.3 as shown in Figure 5(b).

![Figure 5. The performance of the Savonius turbine for the coefficient of torque ($C_\text{t}$) (a) and the coefficient of power ($C_p$) (b) with respect to stagger angle variations.](image)

The power coefficient with respect to TSR for stagger angle variations could be seen in Figure 5(b). Stagger angle 0 degree generated the power coefficient curves less than other. In this matter, fluid flow was blocked by circular cylinder or blockage however the circular cylinder reduced flow momentum and the performance of Savonius turbine reduce. The peak power coefficient occurred at TSR of 0.7. In addition, stagger angle 30 degree increased the coefficient of power at TSR less than 0.9 and decreased at TSR more than 0.9. When stagger angle increased until 60 degree, so the coefficient of power increased and peak performance at TSR of 0.9 with the $C_p$ of 0.276. The coefficient of power decreased by increasing stagger angle at 90 degree and the influence of stagger angle decreased to back the characteristic of conventional Savonius turbine.

| Variation       | Peak $C_p$ | Corresponding TSR | $C_p$ Gain (%) relative to conventional Savonius |
|-----------------|------------|-------------------|-----------------------------------------------|
| Savonius        | 0.213      | 0.9               | 0                                             |
| conventional    | 0 degree   | 0.138             | -35.21                                        |
| 30 degree       | 0.227      | 0.7               | 6.40                                          |
| 60 degree       | 0.276      | 0.9               | 29.84                                         |
| 90 degree       | 0.237      | 0.7               | 11.52                                         |

The peak power coefficients varying stagger angle ($\alpha$) are compared with the performance of conventional Savonius as shown in Table 1. The peak power coefficient is 0.276 obtained for the stagger angle of 60 degree at TSR of 0.9 increasing in about 29.84\% compared conventional Savonius. At stagger angle ($\alpha$) 0 degree, The $C_p$ gain (%) relative to conventional was -35.21\%. This shows that the power coefficient under predicted compared by Conventional Savonius turbine.
4. Conclusion
From the results of the discussion above, it can be concluded that the circular cylinder as passive control with varying position in the stagger angle gave a great effect to the Savonius turbine performance. The results show that changes in the stagger angle can increase the power coefficient, where the maximum performance occurs at a stagger angle of 60 degrees, which is increased in the coefficient of power about 29.84% at a tip speed ratio (TSR) of 0.9 compared to the conventional one.

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