Hydrodynamics Performance Analysis of Vertical Axis Water Turbine (VAWT) Gorlov Type Using Computational Fluid Dynamics (CFD) Approach

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Abstract. The Renewable Energy conversion technology has been increasingly developed along with the awareness regarding the negative environmental issues caused by Non-renewable Energy waste. Vertical Axis Water Turbine (VAWT) is an interesting research object because of variety of advantages it offers. The Gorlov type VAWT is famous for its tendency to move regardless the water flow directions and able to rotate twice as fast as the inlet velocity. Things which need to consider important related to the turbine hydrodynamic effects including the quantity of blades, hydrofoil profiles, pitch angle, and turbine’s dimension ratio. In this study, numerous variations were applied to determine the hydrodynamic effects caused especially torque output. Investigations were carried out using Computational Fluid Dynamics (CFD) simulations. The Gorlov type turbine model is simulated in 3D under steady state flow conditions. The software used to run numerical simulations is ANSYS V18.1. The flow model used is laminar according to secondary data analysis. After the numerical simulation results are obtained, validation is performed with an average error rate of less than 10%. Variations chosen in this study is the pitch angle of 40° and 30°, the dimension ratio in the form of 450 mm in diameter, the type of asymmetrical hydrofoil (S1210), and the quantity of blades (2, 3, 4, 5, and 6). Simulation results in the form of torque values showed that the best turbine performance is provided by NACA 0012 symmetrical hydrofoil with 40° pitch angle.

1. Introduction

Water turbines classified into two categories, namely Horizontal Axis Water Turbine (HAWT) and Vertical Axis Water Turbine (VAWT). There are several types of VAWT that are often used for electricity generation, including the types of Darrieus, Savonius, and Gorlov. There is a similarity between the working principle of Darrieus and Gorlov type turbines, where the water turbine utilizes lift / lift to rotate the rotor.
[1]. Gorlov type vertical water turbines have several advantages, including the structure of the turbine that allows the turbine to move regardless of where the current flows and rotates twice faster than the speed of the water that presses it. This turbine only needs a water flow of less than 1 meter per second to start spinning. This turbine can be used in rivers, traditional dams, tidal currents, and ocean currents.

In this study, the authors will compare the hydrodynamic performance of the Gorlov turbine if the geometrical design variations are given in the form of changes in pitch angle, the type of asymmetrical hydrofoils, the quantity of blades and dimension ratio. The analysis was carried out based on the results of numerical simulation (Computational Fluid Dynamics) using ANSYS Fluent software which was previously validated by experimental data. The results of the analysis are presented in the form of torque values and turbine efficiency levels.

The effect of changing the pitch angle by 30° and 40° makes the turbine have a different angle of attack on the hydrofoil. Changes in the dimension ratio of the turbine result in changing the value of the solidity ratio or density ratio (σ). This ratio illustrates the large gaps that occur between blades with one another. By adding blades to the turbine, the turbine's movement is faster because it reduces energy losses in the gap of the blades. Different type of hydrofoils also applied to conduct the impact of asymmetrical hydrofoil in this turbine.

2. Basic Theory

2.1. Computational Fluid Dynamics (CFD)

CFD is a method commonly used to analyze interactions between fluid flow and solid structures. The simulation process is based on physical properties such as speed, pressure, temperature, density and viscosity. Mathematical models and numerical methods of a physical simulations are used in software to analyze fluid flow. Verification of the mathematical model is very important to provide accurate analysis completion. The principle works is the discretization method to solve numerical equations in a smaller volume set. Each volume set is resolved iteratively by solving the governing equation which includes the conservation laws of mass, momentum and energy [2].

CFD analysis process is divided into 3 stages, namely:

1. Pre-processor
   In the CFD program, a mathematical model is necessary to analyze the physical phenomenon of the fluid. This is done through determining the geometry of the model, domain, boundary layer, as well as the discretization of the set volume.

2. Solver
   The main part of CFD analysis is the solver, which is a numerical calculation using a particular algorithm. This calculation is completed iteratively so that the conditions are convergent and in accordance with predetermined residual criteria.

3. Post-processor
   CFD simulation results are obtained at the post-processor stage. This result is a variable value at a certain point. Data is presented in tabular, graphic or contour form so that it is easy to understand.

3. Research Methods

The steps in this research are as follows:

1. Study of Literature
   The author gathers information from various sources of reference regarding the Gorlov Type Water Turbine theory and references about CFD analysis.

2. Hardware dan Software Preparation
The software used is ANSYS Fluent 16 as a computational software for fluid flow analysis on turbines with the Computational Fluid Dynamics (CFD) method. The geometry design of the turbine model in 3 dimensions carried out on the 2015 SOLIDWORK software. Meshing and CFD post were done with ANSYS Workbench.

3. Dimensional Geometry Making
This stage include making the 3D turbine geometry and entering the hydrofoil coordinates for the twin blade’s turbine. On this case, the hydrofoil used is a 4-digit NACA and formed from mathematical equations with the help of SOLIDWORK 2015.

4. Domain and Mesh Making
Making a domain and mesh in the pre-processing stage of the CFD is important to determine and define the set volume to be numerically calculated. Then the domain is discretized by making mesh using ANSYS Workbench.

5. CFD Simulation Process
The stages of the CFD (solving) simulation process are carried out with the ANSYS Fluent 18 application. At this stage, the completion formula, material properties, physical models, boundary conditions, and the level of correlation and reference values are determined. The simulation process is carried out in 2 stages: steady state and transient state simulations.

6. Interpretation of CFD Simulation Results
This post processing step was done with ANSYS CFD Post and Microsoft Excel to get the graphics and contours of the analysis results.

7. Validation
Validation is important to ensure that the completion of the mathematical model in the CFD simulation has approached the experimental physical model. Validation in this study uses secondary data references in the form of published experimental data.

8. Geometrical Variation
This stage includes rebuilding 3-dimensional geometry by providing variations on the model variables. The variations given are the pitch angle on the 4 digit NACA hydrofoil and the turbine dimension ratio.

9. Analysis of Results and Conclusions
Data analysis is performed and processed in the form of curves and tables that are easy to understand. Conclusions can be drawn based on the problems and objectives of this thesis research.

10. Final Report Compilation
The final stage of this research is the preparation of the Final Assignment report from the results of the Gorlov type VAWT hydrodynamic performance analysis.

4. Analysis of Results and Discussion

4.1. Mesh Accuracy Analysis
Simulation studies are carried out on a validation model with a pitch angle of 0° where the experimental torque results are compared with the results of the steady state and transient state simulations. The number of mesh chosen was initially as many as 700,000 cells and then increased in number by an increase of 3,000,000 cells until the number of mesh reached 3,700,000 cells. The simulation results continue to experience improvements to the mesh number of 4,000,000 cells. But the results of the simulation of 3,700,000 cells with 4,000,000 cells have only a very small difference. In this model in one running steady state simulation takes ± 60 minutes time with standard computer capabilities (CPU core 2 duo) with 24 gigabytes of RAM. While the transient state simulation takes ± 18 hours for 3 turbine rotations.
4.2. Validation

Gorlov turbine structure modelling was carried out using SOLIDWORK software to obtain turbine geometry, ANSYS Fluent to perform CFD simulations to test turbine performance, and Microsoft Excel to process output data from CFD simulation results. Here are the followings of experimental turbine data that will be used:

![Figure 1. Experimental Turbine Torque Value](image)

**Figure 1.** Experimental Turbine Torque Value

| No. | Increment Angle | Steady State Simulation Torque (Nm) | Transient State Simulation Torque (Nm) | Experimental Torque (Nm) |
|-----|-----------------|------------------------------------|----------------------------------------|--------------------------|
| 1.  | 0°              | 1.30                               | 0.99                                   | 1.2                      |
| 2.  | 30°             | 1.00                               | 1.70                                   | 0.8                      |
| 3.  | 60°             | 1.16                               | 1.84                                   | 1.2                      |
| 4.  | 90°             | 1.30                               | 1.45                                   | 1.6                      |

**Table 1.** Geometry data of turbine

| Parameter          | Value   |
|--------------------|---------|
| N (number of blade) | 2       |
| D (turbine diameter)| 300 mm  |
| H (turbine height)  | 450 mm  |
| \( \alpha \) (Inclination Angle) | 43.68 deg |
| Pitch Angle        | 0 deg   |
| Hydrofoil Type     | NACA 0012 |

Below, the authors include the results of running the transient method 6 times, but the comparison is made on the 6th round. This following is the comparison of the value of the calculation of the torque magnitude of the steady state, experimental and transient state simulation results:
| No. | Increment Angle | Steady State Simulation Torque (Nm) | Transient State Simulation Torque (Nm) | Experimental Torque (Nm) |
|-----|-----------------|------------------------------------|----------------------------------------|-------------------------|
| 5.  | 120°            | 0.81                               | 0.94                                   | 0.9                     |
| 6.  | 150°            | 0.76                               | 0.54                                   | 0.6                     |
| 7.  | 180°            | 1.30                               | 0.96                                   | 1.2                     |
| 8.  | 210°            | 1.00                               | 1.70                                   | 0.9                     |
| 9.  | 240°            | 1.16                               | 1.84                                   | 1.2                     |
| 10. | 270°            | 1.30                               | 1.45                                   | 1.6                     |
| 11. | 300°            | 0.81                               | 0.94                                   | 1.2                     |
| 12. | 330°            | 0.76                               | 0.54                                   | 0.6                     |
| 13. | 360°            | 1.30                               | 0.99                                   | 1.2                     |

Figure 2 Experimental Data, Steady State Simulation and Transient State Torque Graph

After the authors manage the data, it is found that the average error of the steady MRF method with mesh 800,000 and 4,000,000 are 8% and 28%, respectively. Whereas in the Transient method with a mesh of 3,000,000, the average error was 23%. A large error in the Transient method is because transient simulations require larger mesh than the steady method. Therefore, to simulate variations in this final project, the author uses the steady MRF method with a mesh of 4,000,000 with a laminar flow pattern.

In the steady state CFD simulation, the results of the output have been able to show the same behavior compared to the experimental results even though there is still an average error difference of 8%. The purpose of this study is not to find out the efficiency of a turbine in detail, but rather as a complementary tool to compare variations with one another. Therefore, despite differences, the 3-dimensional CFD simulation model is valid for use at a later stage.

4.3. Pitch Angle Variation

Variations in pitch angles are hypothetically have a significant effect on turbine performance. That happened because there was a change in angle of attack. Where angle of attack provides an important role in the performance of hydrodynamics. In this simulation the NACA 0012 symmetric hydrofoil model is given with a pitch angle of 30° and 40°.
Table 3. Torque values table of 30° and 40° pitch angle variation

| No. | Increment Angle | Torque 30° (Nm) | Torque 40° (Nm) |
|-----|-----------------|-----------------|-----------------|
| 1.  | 0°              | 1,192           | 1,358           |
| 2.  | 30°             | 2,055           | 2,289           |
| 3.  | 60°             | 1,764           | 2,324           |
| 4.  | 90°             | 0,602           | 2,755           |
| 5.  | 120°            | 1,717           | 1,121           |
| 6.  | 150°            | 0,212           | 0,238           |
| 7.  | 180°            | 1,298           | 1,026           |
| 8.  | 210°            | 2,055           | 2,289           |
| 9.  | 240°            | 1,762           | 2,324           |
| 10. | 270°            | 0,602           | 2,755           |
| 11. | 300°            | 1,717           | 1,121           |
| 12. | 330°            | 0,317           | 0,238           |
| 13. | 360°            | 1,298           | 1,026           |

From the simulation results, there is an increase in the value of torque compared to the turbine without variation. The 30° pitch angle turbine torque value ranges from 0.212 N-m to 2.055 N-m with an average torque of 1,276 N-m while the average torque value in the 40° pitch angle turbine is 1,605 N-m with a torque value ranging from 0.238 N-m to 2,755 N-m. This shows that turbines with 40° pitch angle variations are more efficient than turbines with 30° pitch angles.

4.4. Ratio Dimension Variation

This variation results in a change in the value of the solidity ratio (σ). This ratio illustrates how tenuous the gaps that occur between the blades of one another. The diameter of turbine is changed to 450 mm.
Table 4. Table of torque values with variations in dimension ratios

| No. | Increment | Angle | Torque (Nm) |
|-----|-----------|-------|-------------|
| 1.  |           | 0°    | 0.168       |
| 2.  |           | 30°   | 0.272       |
| 3.  |           | 60°   | 1.846       |
| 4.  |           | 90°   | 0.813       |
| 5.  |           | 120°  | 0.141       |
| 6.  |           | 150°  | 0.0605      |
| 7.  |           | 180°  | 0.252       |
| 8.  |           | 210°  | 0.272       |
| 9.  |           | 240°  | 1.846       |
| 10. |           | 270°  | 0.813       |
| 11. |           | 300°  | 0.141       |
| 12. |           | 330°  | 0.061       |
| 13. |           | 360°  | 0.252       |

4.5. Hydrofoil Variation

The hydrofoil variation chosen is S1210 type. In the table and graph below, could be seen that the S1210 hydrofoil has higher torque than NACA 0012. In addition, the S1210's movements are relatively stable at all angles.

Table 5. Hydrofoil Variation Torque Comparison

| No. | Increment | Angle | NACA 0012 Torque (Nm) | S1210 Torque (Nm) |
|-----|-----------|-------|-----------------------|-------------------|
| 1.  |           | 0°    | 1.27                  | 1.60              |
| 2.  |           | 30°   | 0.85                  | 1.23              |
| 3.  |           | 60°   | 1.20                  | 1.21              |
| 4.  |           | 90°   | 1.50                  | 1.20              |
| 5.  |           | 120°  | 0.88                  | 1.10              |
| 6.  |           | 150°  | 0.70                  | 1.20              |
| 7.  |           | 180°  | 1.27                  | 1.60              |
| 8.  |           | 210°  | 0.85                  | 1.23              |
| 9.  |           | 240°  | 1.20                  | 1.21              |
| 10. |           | 270°  | 1.50                  | 1.20              |
| 11. |           | 300°  | 0.88                  | 1.10              |
| 12. |           | 330°  | 0.70                  | 1.20              |
| 13. |           | 360°  | 1.27                  | 1.60              |
4.6. Number of Blades Variation

One of the variations developed is the number of blades. By adding blades to the turbine, the turbine's movement is faster because it reduces energy losses in the gap of the blades. However, the more blades are added, the turbine torque decreases. That is due to the thrust on the blades in the downstream section has decreased dramatically due to the number of blades on the upstream section that hold the water flow.

| Increment Angle | 2 Blades Torque (Nm) | 3 Blades Torque (Nm) | 4 Blades Torque (Nm) | 5 Blades Torque (Nm) | 6 Blades Torque (Nm) |
|-----------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 0°              | 1.27                 | 1.33                 | 1.60                 | 0.89                 | 0.74                 |
| 30°             | 0.85                 | 1.00                 | 1.40                 | 1.02                 | 0.80                 |
| 60°             | 1.20                 | 0.99                 | 1.30                 | 0.96                 | 0.74                 |
| 90°             | 1.50                 | 1.30                 | 1.60                 | 1.01                 | 0.80                 |
| 120°            | 0.88                 | 1.33                 | 1.40                 | 1.00                 | 0.74                 |
| 150°            | 0.70                 | 1.00                 | 1.30                 | 0.89                 | 0.80                 |
| 180°            | 1.27                 | 0.99                 | 1.60                 | 0.95                 | 0.74                 |
| 210°            | 0.85                 | 1.30                 | 1.40                 | 0.87                 | 0.80                 |
| 240°            | 1.20                 | 1.33                 | 1.30                 | 1.01                 | 0.74                 |
| 270°            | 1.50                 | 1.00                 | 1.60                 | 0.89                 | 0.80                 |
| 300°            | 0.88                 | 0.99                 | 1.40                 | 0.86                 | 0.74                 |
| 330°            | 0.70                 | 1.28                 | 1.30                 | 0.88                 | 0.80                 |
| 360°            | 1.27                 | 1.33                 | 1.60                 | 0.89                 | 0.74                 |
Figure 5 Average Torque Comparison

From the table and graph above, it appears that the torque in the 4 blades turbine is greatest. This is because turbines with a number of blades under 4, have a lot of energy losses because water passes through the turbine. However, the number of blades is more than 4 pieces, making the wake effect greater in the downstream area.

After knowing the simulation results of the overall variation, the turbine efficiency can be determined based on the large torque value using the following formula:

\[
Efficiency (\eta) = \frac{\tau \times \omega}{0.5 \times \rho \times A \times V^3}
\]

Where \(\omega\) is angular velocity (rad/s), \(\tau\) is turbine’s torque, \(\rho\) is fresh water density, \(A\) is the cross-sectional area of water flow, and \(V\) is inlet velocity of the fluid.

From the simulation results, the turbine efficiency value without variation is 19%. In turbines with variations in dimension ratios, the efficiency level is lower at 9%. Turbine with S1210 hydrofoil variation has 22% efficiency. Turbine with 3, 4, 5, and 6 blades have the efficiency respectively 20%, 25%, 16%, and 13%. While turbines with a pitch angle variation of 30° have a higher efficiency that is equal to 22%. The highest efficiency value generated by the turbine with a pitch angle variation of 40° which is 27%.

5. Conclusion

There are several conclusions that can be drawn from this research:

1. Computing with ANSYS Fluent software can be used to validate the results of Computational Fluid Dynamics (CFD) simulations with a 2-dimensional turbine 3-dimensional turbine model.
2. The results of CFD simulations with 2-dimensional 2-blade turbine models are valid enough to know the Gorlov type Vertical Axis Water Turbine behavior even though the simulation results still show an average error of 8%.
3. Analysis with 2 blade models can well answer the phenomenon of large torque values with various variations. From these simulations it is known that:
   a. Provision of pitch angles of 30° and 40° provides the advantage for symmetrical hydrofoil with a significantly higher torque value.
   b. Variation of the dimension ratio causes the value of the torque to fluctuate with a maximum value of the maximum torque compared to the turbine without variation.
   c. Turbines with 4 blades can capture more ocean currents than turbines with 2 blades and 3 blades.
However, if the turbine has more than 4 blades, the turbine torque will decrease due to the wake effect which affects the blades in the turbine downstream area.

d. Turbine with S1210 hydrofoil has greater torque than turbines with NACA 0012 hydrofoil. S1210 hydrofoil has benefits from the presence of a positive camber.

4. Analysis of the results of numerical simulations on turbines shows that giving a variation of pitch angle of 30° can increase the level of efficiency to 22% and pitch angle of 40° to 27%. Turbine with S1210 hydrofoil variation has 22% efficiency. Turbine with 3, 4, 5, and 6 blades have the efficiency respectively 20%, 25%, 16%, and 13%. While the variation of the dimension ratio gives the impact of decreasing the efficiency level to 9%.

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