Goose foot water turbine performance with variation of fins quantity and turbine depth using computational fluid dynamics (CFD) approach

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Abstract. Long-term electricity demand in Indonesia for the period 2003 to 2020 increased to 275 TWh. The demand for electricity in Java Island in the same period from 2003 to 2020 reached 200 TWh. Alternative and renewable energy is needed to support the electricity needs of the Indonesian. The potential for water energy is one of the alternative energies that can be maximized to obtain electrical energy, among others, it can be obtained from river water flow without falling heads or free water flow. A turbine innovation that can be used in rivers with free water flow is the goose foot water turbine. This research is focused on calculating the efficiency of the goose foot water turbine based on the variation of the number of fins and the depth of the turbine in order to obtain maximum performance. Performance analysis was conducted using the Computational Fluid Dynamics (CFD) method. The CFD results show that the highest value is obtained at the number of blades is 6, the number is fins 17, and the turbine depth is 0.35 m, namely the highest torque is 1593 Nm, the highest rotational speed is 11,705 rpm, the highest power is 1951.602 W, and the highest efficiency of 86.738%.

Keywords: turbine performance, CFD, goose foot water turbine, blade fin

1. Introduction
Indonesia is a country with the 4th most populous population in the world [1], with a relatively large population, the energy demand in Indonesia is very high. This energy need is mostly found in electrical energy, which is 50% of Indonesia’s national energy consumption, which so far has been sourced from petroleum [2]. Long-term electricity demand in Indonesia for the period 2003 to 2020 has been increased to 275 TWh [3]. The pattern of electricity demand for each sector is different according to the PLN (State Electricity Company) electricity marketing area, in which the more it is to the Eastern Indonesia region, the greater the demand for electricity in the household sector compared to the industrial sector [4]. This is due to the low electrification ratio and the limited number of industries in the area. The demand for electricity in Java Island in the same period from 2003 to 2020 reached 200 TWh. The fact is that there are still many border and
remote villages that have not been obtained by electricity or there are restrictions on the use of electricity.

One solution that can be done to overcome this problem is by optimizing Indonesia’s renewable energy potential, which is 311,232 MW and only 22% is still being utilized. The potential for renewable energy in Indonesia, especially in Java Island, comes from the potential for water energy, especially river flow, where there are 8 main river basins with a total area of half of the area of Java Island. The land status in this main watershed is dominated by cultivated land and urban areas. The characteristic of river discharge throughout the year in Java Island shows high variation. The maximum and minimum discharge ratios vary between 20 and 100 times [5]. The potential for renewable energy that leads to the potential for local resources (local wisdom) can be used to increase the energy ratio in Indonesia, especially to increase the supply of electrical energy by using innovative energy conversion machines.

The energy conversion machine that can extract the potential and kinetic energy of water into mechanical energy is a water turbine. Through a water turbine, mechanical energy is converted into electrical energy with a generator which can then be used to increase the power needs of Indonesian people’s electrical energy [6]. The water turbine innovation designed to adapt the working principle of goose foot when swimming, can be used to extract free water flow energy. The construction of the goose foot water turbine is almost similar with Crossflow Turbine which forms a long horizontal axis. The working principle of the goose foot water turbine is also influenced by the number of blades and the depth factor of the water turbine.

Design analysis needs to be conducted before making a water turbine that has the best efficiency by using the Computational Fluid Dynamics (CFD) method, because the CFD method makes it easier to get analysis results quickly, accurately, and saves experimental costs [7]. In CFD analysis, the physical aspects of fluid flow are governed by three basic principles, namely the law of conservation of mass, Newton’s second law, and the law of conservation of energy [8]. These basic principles can be expressed in mathematical equations in their most general form usually called the Navier-Stokes partial differential equation [9]. CFD predicts flow based on several things, namely mathematical models (partial differential equations) in particular solving the Navier-Stokes equation [10], numerical methods (solution and discretization techniques), and software tools (solvers, tools pre and post processing).

The CFD method as an alternative solution allows scientists and researchers to perform numerical experiments in virtual laboratories because this method can be used to predict fluid flow, heat transfer, and other phenomena using mathematical equations and virtual or computational experiments [11,12].

The water turbine innovation that adapts the motion of opening and closing the goose foot can be used in rivers that do not have a falling head but have the kinetic energy of the water flow [13]. This turbine is very suitable to be used in Indonesian regions because only free water flow can drive the turbine and produce the mechanical energy needed to produce electrical energy [14]. The best performance results based on the variation of blades and the number of fins and the depth of the turbine need to be computationally carried out to obtain faster, more accurate, more efficient analysis results before the actual construction is built.

2. Research method

2.1 Simulation model
Goose foot water turbine has 6 blades and several variations of fins, among others, a number of 9, 11, 13, 15, and 17. The flow rate of river water is 4.5 m$^3$ s$^{-1}$. The depth of the turbine immersed in
water has a variation of 0.2; 0.25; 0.3; 0.35; and 0.4 m. The turbine dimensions can be seen in Figure 1 and Figure 2.

![Figure 1. Dimension of goose foot water turbine](image1)

Goose foot water turbine performance is recognize by performing mathematical calculations [15] [16]. The most common flow equation and involving all flow properties is the Navier Stoke equation as follows (equation 1 to 5).

\[
\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z_2
\]  

(1)

Water flow power

\[ P_a = \rho \times Q \times \frac{V^2}{2} \text{ (Watt)} \]  

(2)

Turbine shaft rotational speed

\[ n = \frac{60 \times u}{\pi D} \text{ (rpm)} \]  

(3)

Turbine power
Turbine efficiency

\[
\eta = \frac{P_t}{P_a} \times 100 \, \% 
\]  \hspace{1cm} (5)

2.2 Simulation process
Computational fluid dynamics (CFD) is used to predict the quantitative and qualitative results of fluid flow in a machine [17]. This computational method can show a detailed and accurate flow pattern whereas if it is conducted with a pure experimental method it will be expensive, time consuming, and only has a single objective, although this CFD method also has disadvantages such as the reliability of the results does not reach 100% because of the data input. Limited, unsuitable mathematical models, and accuracy depending on the computer specifications used [18].

2.3 Computational fluid dynamics (CFD) process
The CFD method is used to determine the value of the torque in the sample used. CFD can calculate both qualitatively and quantitatively of fluid flow using mathematical models (partial differential equations), numerical methods, and computer software (solver, pre-, and postprocessing). The CFD method has three stages, among others.

2.3.1 Preprocessing
The preprocessing stage is the stage before processing or solving, at this stage, a goose foot water turbine design is constructed in the Autodesk Inventor 2018 software and the selection of boundary conditions and fluid properties in the software. Figure 3 show the meshing process of turbine model.

\[
P_t = \frac{2 \times T \times \pi \times n}{60} \, \text{(Watt)} \]  \hspace{1cm} (4)

2.3.2 Solving
The solving stage is the stage where the processing of the design is carried out as shown in the Figure 4. Research assumptions such as no slip wall, smoothness, boundary conditions, and fluid properties are set. The values for several parameters, such as torque and tangential speed can be generated [19].
2.3.3 Post processing

The postprocessing stage is the final stage of the CFD method as shown in the Figure 5. In this stage, setting and reading the results of the streamline and others in the function calculator are performed.

3. Result and discussion

Table 1 and Figure 6 shows the result of relationship between turbine depth and torque value. The highest torque is 1593 Nm is obtained from a 6 blades 17 fins turbine with a depth is 0.35 m. The lowest torque is 757.24 Nm which is obtained from the 6 blades 9 fins turbine with a depth is 0.2 m. The torque value increases to a depth is 0.35 m then decreases at a depth is 0.4 m. The difference in the depth of the turbine causes a difference in the value of torque and tangential speed, the optimal depth of the goose foot water turbine is at a depth is 0.35 m.
Table 1. Goose foot water turbine performance parameters

| Number of Fins | Turbine Depth [m] | Torque [Nm] | Tangential Speed [m/s] | Rotating Speed [rpm] | Turbine Power [W] | Efficiency [%] |
|---------------|------------------|-------------|------------------------|----------------------|-------------------|----------------|
| 9             | 0.2              | 757.24      | 0.448                  | 9.512                | 753.873           | 33.505         |
| 9             | 0.25             | 889.29      | 0.472                  | 10.023               | 932.964           | 41.465         |
| 9             | 0.3              | 1175.73     | 0.494                  | 10.490               | 1290.952          | 57.376         |
| 9             | 0.35             | 1442.28     | 0.521                  | 11.055               | 1668.878          | 74.172         |
| 9             | 0.4              | 1017.22     | 0.415                  | 8.820                | 939.007           | 41.734         |
| 11            | 0.2              | 841.55      | 0.470                  | 9.975                | 878.580           | 39.048         |
| 11            | 0.25             | 991.40      | 0.493                  | 10.463               | 1085.698          | 48.253         |
| 11            | 0.3              | 1302.18     | 0.516                  | 10.951               | 1492.588          | 66.337         |
| 11            | 0.35             | 1548.57     | 0.537                  | 11.399               | 1847.616          | 82.116         |
| 11            | 0.4              | 1103.09     | 0.430                  | 9.127                | 1053.819          | 46.836         |
| 13            | 0.2              | 766.93      | 0.484                  | 10.280               | 825.213           | 36.676         |
| 13            | 0.25             | 937.66      | 0.516                  | 10.949               | 1074.560          | 47.758         |
| 13            | 0.3              | 1217.89     | 0.532                  | 11.293               | 1439.546          | 63.980         |
| 13            | 0.35             | 1452.57     | 0.547                  | 11.607               | 1764.711          | 78.432         |
| 13            | 0.4              | 1058.00     | 0.447                  | 9.499                | 1051.887          | 46.751         |
| 15            | 0.2              | 844.73      | 0.477                  | 10.130               | 895.605           | 39.805         |
| 15            | 0.25             | 1015.04     | 0.496                  | 10.537               | 1119.476          | 49.755         |
| 15            | 0.3              | 1385.39     | 0.526                  | 11.170               | 1619.675          | 71.986         |
| 15            | 0.35             | 1578.14     | 0.536                  | 11.374               | 1878.688          | 83.497         |
| 15            | 0.4              | 1154.15     | 0.440                  | 9.335                | 1127.733          | 50.121         |
| 17            | 0.2              | 817.04      | 0.488                  | 10.365               | 886.393           | 39.395         |
| 17            | 0.25             | 878.87      | 0.496                  | 10.531               | 968.708           | 43.054         |
| 17            | 0.3              | 1322.82     | 0.533                  | 11.323               | 1567.689          | 69.675         |
| 17            | 0.35             | 1593.00     | 0.551                  | 11.705               | 1951.602          | 86.738         |
| 17            | 0.4              | 1114.67     | 0.459                  | 9.752                | 1137.707          | 50.565         |

Figure 6. Correlation between turbine depth and torque
Figure 7 shows the relationship between turbine depth and rotational speed. The highest rotational speed is 11,705 rpm is obtained from a 6 blades 17 fins turbine with a depth is 0.35 m. The lowest rotating speed is 8,820 rpm is obtained from a 6 blades 9 fins turbine with a depth is 0.4 m. The rotating speed increases gradually to a depth is 0.35 m then decreases dramatically at a depth is 0.4 m.

Figure 7. Correlation between turbine depth and rotating speed

Figure 8 shows the relationship between turbine depth and power. The highest power of 1951.602 W was obtained from a 6 blades 17 fins turbine with a depth of 0.35 m. The lowest power is 753.873 W which is obtained from the 6 blades 9 fins turbine with a depth is 0.2 m. Power increases to a depth is 0.35 m then decreases to a depth is 0.4 m.

Figure 8. Correlation between turbine depth and turbine power
Figure 9 shows the relationship between turbine depth and efficiency. The highest efficiency of 86.738% is obtained from the 6 blades 17 fins turbine with a depth of 0.35 m. The lowest efficiency of 33.505% is obtained from the 6 blades 9 fins turbine with a depth of 0.2 m. Efficiency increases to a depth of 0.35 m then decreases at a depth of 0.4 m.

![Figure 9. Correlation between turbine depth and efficiency](image)

In contrast to the calculations of Gorban et al. [20], based on the theory of momentum from the principles of basic physical laws, the energy that can be extracted from the fluid flow passing through the cross section of the water turbine is the energy contained in the fluid flow. Furthermore, Gorban found that the optimal power that can be extracted from the fluid flow depends on the ratio between the flow velocity in front of the water turbine and the flow velocity after passing through the converter, with this principle, the Gorban gets a maximum efficiency of 30%. In this study, the working principle of a water turbine that adapts goose-leg movement to its phenomenon can be described as follows: if the water turbine moves forward, the blade fin will close so that it makes the water compressive force blocking the blade becomes smaller, and if the water turbine blade fin moves backward, the blade fin will open so that the compressive force on the blade fin becomes greater so that it can push the water turbine to rotate faster. The rotating impulse which is getting faster and faster is what causes the goose foot water turbine to extract water energy optimally so that the resulting efficiency is quite large, namely 86.738% in a simulation model of 6 blades, 17 fins and a depth of 0.35 m.

4. Conclusion
In this study, the working principle of a water turbine that adapts goose foot movement to the phenomenon of the water turbine moving forward causes the blade fin to close, so that the water compressive force blocking the blade becomes smaller, and if the water turbine blade fin moves backward, the blade fin will open so that the compressive force on the blade fin becomes greater so that it can push the water turbine to rotate faster. The accelerated spinning push is what causes the goose foot water turbine to extract water energy optimally. Based on the simulation results using Computational Fluid Dynamics (CFD), with the number of blades, variations in the number of fins, water velocity and variations in different turbine depths, the values of torque, power and efficiency vary. If the torque value decreases, because it is affected by the increase in rotation due
to the load on the turbine, it will have an impact on the value of the power generated and also affect the efficiency of the turbine. In this study the highest performance value was obtained at the number of fins 17 and the turbine depth level is 0.35 m with the highest torque value is 1,593 Nm, the highest rotational speed is 11,705 rpm, the highest power is 1951.602 W, and the highest efficiency value is 86.738%.

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