Study of low head turbine propellers axial flow for use of micro-hydropower plant (MHP) in Aceh, Indonesia

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Abstract. Low head hydropower has the potential to produce green energy with a minimum on the environment and is one of the best choices for decentralized power plants. Aceh is one of many regions in Indonesia with hilly topography and many river streams. Of the 66 rivers in Aceh that have potential energy sources that can be developed 98.5 percent are low head. Generally, the technique for overcoming altitude problems in low river flows is the use of low head turbines. An important aspect of head power generation techniques is the selection of turbines. The study aimed to study low head propeller turbines for the use of micro hydropower plants. By calculating the main dimensions and main components of the turbine, field experiments were carried out to determine turbine rotation and energy, as well as turbine efficiency at a flow rate of 0.06 m³/sec and a 3.5-meter head. The calculation results obtained by a specific turbine speed of 1.53, runner diameter of 0.30 meters, hub diameter of 0.06 meters, shaft diameter 0.03, runner length 1.08, triangular speed of 30 degrees with the number of blades 4 pieces. From the results of field experiments, the maximum turbine rotation speed is 1828 rpm, the turbine power is 2,530 watts with a voltage between 220 to 240 volts while the maximum efficiency is 57 percent. It can be concluded that propeller-type turbines with the low head are suitable for micro power plants, especially in remote areas.

1. Introduction

Low head hydropower has the potential to generate green energy with only a minimal impact on the environment, and it is one of the best options for decentralized power generation. River flow for electrical energy has many advantages compared to the type of wind energy or solar energy. River flow is an energy source that does not pollute the environment [1]. In addition, the energy contained in water flow accounts for around 16.6 percent of all the world's renewable electricity capacity from 24.5% of the total estimated renewal of global electricity production capacity including large hydroelectric power, small hydropower, and marine power, around 1,096 GW [2]. One way to use river flow is to apply hydroelectric power both on a large scale and small scale with a high head and a low head. The construction of small-scale hydroelectric power plants is relatively simple and easy to maintain [3]. However, not all river streams in Indonesia have high heads.

Indonesia is an archipelagic country that has large-scale hydropower potential reaching 75 GW, while for a small scale it is 769.69 MW with an installed capacity of 7,059 MW [4]. Aceh is one of the...
many regions in Indonesia with hilly topography and many rivers [5]. Of the 66 rivers in Aceh that have the potential as a water energy source that can be developed 98.5 percent of which are with low head [6].

The technique for overcoming the problem of the difference in head flow is low is the use of turbines with low altitude differences known as low head turbines. One important aspect of the technique of low head power generation is the selection of turbines. The optimal turbine for relatively small altitude differences in the reaction turbines. The characteristics of a water turbine are the interrelated relationships between variables, namely: discharge, head, rotation, spin speed, power and efficiency [7].

Where the typical characteristic of a reaction turbine is the falling pressure occurs at a fixed angle and a rotating angle [8]. Through a multi-criteria analysis based on quantitative and qualitative analysis of propeller turbines with draft tubes, it has been proven to be the best solution for low head compared to other turbines [9].

Until now there are still very few studies carried out regarding the work of axial turbines or propellers as micro hydropower plant turbines [10]. Based on the description, the axial flow turbine for a low head is the right choice that can later be applied in meeting electricity needs, especially in remote areas that have not been reached by the electricity network and have good prospects to be developed. And studies of axial flow propeller turbines for the low head are needed.

2. Theory and literature review

Turbines change potential and kinetic energy in the flow of water into mechanical energy to drive generators that convert mechanical energy into electrical energy [7]. In terms of the action of water on the turbine runner, it can be either a reaction or a type of impulse turbines. The type of turbine shows the way in which water causes the runner in the turbine to spin. In an impulse turbine where the water pressure changes to kinetic energy before the water reaches the turbine runner. Energy suppresses runners in the form of a high-speed jet. A turbine, where the potential energy from the water directly enters the turbine house to press the turbine blade so that a large pressure change occurs called a reaction turbine [11, [12].

Based on the runner intrush model, the water turbine can be divided into three types, namely: tangential flow turbines, axial-radial flow turbines, and axial flow turbines [13]. Discussed in more detail below:

1. Tangential flow turbine

In this turbine group, the position of the water entering the runner with the tangential direction or perpendicular to the shaft runner causes the runner to spin, the Pelton turbine is one of the types of turbines [13]. The head height, where the Pelton turbine is used, is between 60 m and more than 1,000 meters. Pelton turbines have high efficiency between 30 percent to 100 percent of the maximum design discharge for one jet turbine of around 10 percent and 100 percent for multi-jet turbines [12].

2. Axial-radial flow turbine

In this turbine, the water enters the runner radially and the runner exits axially parallel to the shaft. Francis Turbine is included in this type [13]. Francis turbines are used for head 25 to 350 meters. This turbine has an efficiency of more than 80 percent with a range between 40 percent up to 100 percent of maximum discharge [12].

3. Axial flow turbine

In this turbine, the water enters the runner and the runner exits parallel to the runner shaft, where the Kaplan turbine and propeller are one example of the axial flow turbine type [13]. Kaplan and propeller turbines are generally used for low heads between 2 meters and 40 meters. Kaplan and propeller turbines have relatively small dimensions at high speeds. The difference between a propeller and a Kaplan turbine is that the Propeller turbine has a fixed blade "single regulative" while the Kaplan turbine has a drive blade that can be adjusted "double regulative" [7]. J. Rabee [12], in the results of his research setting the number of blades for propeller turbines, are as follows:
Table 1 Number of propeller blades

| Specific speed | 1000 | 800  | 600  | 500  | 400  | 300  |
|---------------|------|------|------|------|------|------|
| Number of blade | 3    | 4    | 5    | 6    | 7    | 8    |

Kaplan turbines can work between 15 percent and 100 percent of the maximum design, while propeller turbines can work only between 30 percent and 100 percent with maximum design [11]. However, Propeller turbines for rural areas have optimal efficiency if operated at 1250 rpm to 1500 rpm depending on the condition of the place and the character of the turbine [15].

The power of the water turbine is determined by the amount of water discharge \( Q \) and the head and the efficiency of the water turbine. Turbine power can be calculated by equation 1 [11].

\[
P = QH\eta_h\rho g
\]  

(1)

Where \( Q \) is discharged in \( \text{m}^3/\text{sec} \), \( H \) is gross head in meter, \( \eta_h \) hydraulic efficiency, \( \rho \) is water density in \( \text{kg}/\text{m}^3 \), \( g \) is the acceleration of gravity in \( \text{m}/\text{s}^2 \).

- Basic Selection of Turbines

A turbine is selected and designed according to certain conditions and must operate at high efficiency [15]. Generally, in choosing a hydropower turbine based on the specific speed of the turbine, the non-dimensional parameters include head, output power \( P \), shaft speed output [16]. And guided by the turbine selection chart that has been made by the researchers.

Specific speed

Specific speed \( n_{QE} \) can be calculated by the following equation 2:

\[
n_{QE} = \frac{n \sqrt[3]{E}}{Q^{1/4}} \quad \text{[USSBR]}
\]  

(2)

Where \( E \) is the specific hydraulic energy of the machine in J/kg, \( n \) is the rotational speed of the turbine in rpm.

Table 2 Specific speed ranges for each type of turbine

| Turbine Type            | Specific Speed Ranges |
|-------------------------|-----------------------|
| Pelton one nozzle       | \( 0.005 \leq n_{QE} \leq 0.025 \) |
| Pelton n nozzles        | \( 0.005 \cdot n^{0.5} \leq n_{QE} \leq 0.025 \cdot n^{0.5} \) |
| Francis                 | \( 0.05 \leq n_{QE} \leq 0.33 \) |
| Kaplan, propeller, bulb | \( 0.19 \leq n_{QE} \leq 1.55 \) |

Runner diameter section

The diameter of the runner \( D_e \) can be calculated by the following equation 3:

\[
D_e = 84.5 \cdot \left( 0.79 + 1.602 \cdot n_{QE} \right) \cdot \sqrt[4]{\frac{\eta_h}{n}}
\]  

(3)

Hub diameter

The hub diameter \( D_h \) can be calculated using the following equation 4:

\[
D_h \left( 0.25 + \frac{0.0951}{n_{QE}} \right)^4 \cdot D_e
\]  

(4)

Shaft diameter:

The shaft diameter \( D_{shaft} \) can be calculated using the following equation 5:

\[
D_{shaft} = \frac{D_{bush}}{4}
\]  

(5)
Length runner:
The length diameter $L_i$ can be calculated using the following equation 6:

$$L_i = \frac{D_{runner} \pi}{2}$$

Turbine selection chart
The selection of the type of turbine can also be done using graphs that have been produced by researchers or manufacturers of turbine units. Figure 1 is a selection chart for various types of turbines:

![Turbine selection chart](image)

**Figure 1.** Turbine selection graph [9], [17], [18] and [19]

The characteristics of a water turbine are the interplay between the main variables of the water turbine, namely discharge, falling water height, specific rotation, power and efficiency [7]. The characteristics of propeller turbines are graphs or curves that show the relationship between the variables of rotation, water flow, power, efficiency, torque, and head. The relationship between power and turbine rotation as shown in figure 2 where the power will drop after the propeller rotation reaches a certain rotation. At a relatively low rotation, the greater the propeller rotation, the power will increase and when the propeller rotation reaches a stall condition, the power will drop slowly [17].

Blade design
Blade design does not only depend on stress analysis [19], several other factors also have a significant role. To determine the optimal design results, leading to the best efficiency point (BEP) of the turbine prototype, it is important to analyze different blade slopes (i.e. angle variations) when designing blade blades. The blade thickness on the blade must also be considered to avoid interference in the flow, which can cause additional losses and can hinder overall efficiency [20].

The velocity triangle
The velocity triangle, which occurs in the blade, plays an important role in determining its distortion. The velocities in the speed triangle are shown in the following Figure 2 [17]:

![Velocity triangle](image)
Where $E$ is tangential speed in m/s, $c$ is the absolute speed in m/s, $w$ is the relative speed in m/s.

The equation used to calculate the angles of velocity and dimensions of the velocity triangle is as follows:

- **Speed angle**

$$u = \pi * n * d$$  \hspace{1cm} \text{(7)}$$

$$c_u = \frac{H_n * g}{u}$$  \hspace{1cm} \text{(8)}$$

$$w_u = c_u * u$$  \hspace{1cm} \text{(9)}$$

$$w_m = \frac{Q}{A}$$  \hspace{1cm} \text{(10)}$$

$$w = \sqrt{w_u^2 + w_m^2}$$  \hspace{1cm} \text{(11)}$$

$$\beta_\infty = \arccos \frac{w_u}{w}$$  \hspace{1cm} \text{(12)}$$

- **Lift coefficient**

The lift coefficient for each radius can be determined by the following equation 13:

$$\zeta_a = \frac{w_2^2 - w_m^2 + 2^*g^*}{K^*w_m^2} \left[ p_{atm} - H_s - P_{min} - \eta_s c_3^2 - c_4^2 \right]$$  \hspace{1cm} \text{(13)}$$

$$c_3 = \frac{Q}{A_3}$$

$$A_3 = \frac{\pi^* D_x^2}{4}$$

Where $w_2$ is relative velocity after the grating in m/s, $w_m$ is the medial relative velocity in m/s, $P_{atm}$ is atmospheric pressure in meter, $H_s$ is suction head in meter, $P_{min}$ is the minimal water pressure in meter, $\eta_s$ is the efficiency of the energy change, $A_3$ is Core cross-section of the thread in m$^2$, $c_3$ is velocity after the runner in m/s, $c_4$ is outlet velocity in m/s, $K$ is profiled characteristic number in m/s.

- **Generator**

In micro-hydro power plants (MHP), two types of generators can be used, namely:

1. The asynchronous generator is a generator that works at a constant speed. To maintain a constant generator, an electronic speed governor is used. This generator can be used directly and does not
require another electricity network system as the initial driver. This type of generator is used for remote areas with an isolation system.

2. An induction generator is a generator that does not require a voltage and speed regulation system. This generator does not work alone and requires an electrical network system as the initial driver. This type of generator can be used for areas that already have an electricity grid (Gridline) [11]. Synchronous generators are used in most MHP (Micro Hydro Project) because it has the ability to establish its own operating voltage and maintain frequency while it is operating in a remote location [21]

The capacity of a generator can be calculated by the following equation 14:

\[ N_g = N_t \times \eta_g \]  

Where \( N_p \), \( N_t \) is the power design in kW, \( \eta_g \) is turbine efficiency (0.9) in percent

3. Methods

3.1. Calculation method
Calculations are performed by entering parameters into equations used to determine the main dimensions and main components of the Propeller type axial turbines which include: calculation of power, calculation of blade and generator.

3.2. Experimental instruments
This study involved investigating a micro-hydropower plant for axial flow. The turbines installed adjust to the dam conditions in the Solok river flow in Darul Makamur Village, Subulussalam municipality, Sultan Daulat subdistrict, have a 10-inch penstock diameter as shown in Figure 3. Experiment equipment in the form of propeller turbines with specifications of 1500 rpm, 3 kW, specific speed 1.53, runner diameter of 0.30 meters, hub diameter of 0.06 meters with the number of blades 4 pieces.

3.3. Experimental methodology
During the experiment, water has flowed into the generating system at a flow rate of 0.06 m³/sec. At each changing water flow rate, the maximum turbine rotation is measured at no-load conditions. Furthermore, the maximum water turbine rotation parameters are obtained, the load is raised to the prony brake dynamometer and the turbine revolution is reduced by adjusting the spring tension of the prony brake mounted on the turbine shaft. Starting from the highest rotation, the rotation speed is lowered until the shaft stops rotating. The torque produced by revolution reduction can be calculated from the relationships obtained from the measurement of the force of results given to the mechanical dynamometer and the diameter length of the mechanical dynamometer. The turbine rotation speed is measured using a portable tachometer and the water flow rate is measured by an ultrasonic flow meter. The height of the water flowing in the channel is measured, and various parameters are recorded. The parameters are taken to calculate power output from the turbine, hydraulic power to the turbine and turbine efficiency.
Figure 3. The layout of propeller turbines tested

4. Result and discussion
The calculation result of turbine power:

\[ n_{QE} = \frac{2.716}{H_n^{0.5}} \]

\[ H_n = H \times \eta_h \Rightarrow H_n = 3.5 \times 0.9 = 3.15 \text{ m} \]

\[ \Rightarrow n_{QE} = \frac{2.716}{3.15^{0.5}} = 1.53 \]

Calculation results of runner diameter:

\[ D_e = 84.5 \times \left(0.79 + 602 \times n_{QE}\right) \times \frac{\sqrt{H_n}}{n} \]

\[ \Rightarrow D_e = 84.5 \times \left(0.79 + 602 \times 1.53\right) \times \frac{\sqrt{3.15}}{1500} = 0.30 \text{ m} \]

Calculation results of hub diameter:

\[ D_i = \left(0.25 + \frac{0.0951}{n_{QE}}\right) \times D_e \]

\[ \Rightarrow D_i = \left[0.25 + \frac{0.951}{1.53}\right] \times 0.30 = 0.06 \text{ m} \]

The calculation result of shaft diameter:

\[ D_{shaft} = \frac{D_{bush}}{4} \]
\[
D_{\text{shaft}} = \frac{0.06}{4} = 0.03
\]

Calculation of length runner:
\[
L_1 = \frac{D_{\text{runner}} \times \pi}{z}
\]
\[
L_1 = \frac{0.03 \times 14.5}{4} = 1.08
\]

The calculation result of speed angles:
\[
u = \pi \times n \times d \Rightarrow u = 3.14 \times 0.34 = 16.04 \text{ m/s}
\]
\[
c_{u1} = \frac{H_1 \times g}{u} \Rightarrow c_{u1} = \frac{3.15 \times 9.81}{16.04} = 1.91 \text{ m/s}
\]
\[
c_{u2} = \frac{H_2 \times g}{u} \Rightarrow c_{u2} = \frac{3.18 \times 9.81}{16.04} = 1.95 \text{ m/s}
\]
\[
w_{u1} = c_{u1} = u \Rightarrow w_{u1} = 1.91 - 16.04 = -14.13 \text{ m/s}
\]
\[
w_{u2} = c_{u2} = u \Rightarrow w_{u2} = 1.95 - 16.04 = -14.09 \text{ m/s}
\]
\[
w_{u\infty} = \frac{w_{u1} + w_{u2}}{2} \Rightarrow w_{u\infty} = \frac{-16.04 + (-14.09)}{2} = -14.11 \text{ m/s}
\]
\[
w_m = \frac{Q}{A_\infty}
\]
\[
A_\infty = \frac{\pi^4 (D_\infty^2 - D_i^2)}{4} \Rightarrow A_\infty = \frac{\pi^4 (0.30^2 - 0.06^2)}{4} = 0.07
\]
\[
\Rightarrow w_m = \frac{0.06}{0.07} = 0.86 \text{ m/s}
\]
\[
w_1 = \sqrt{w_{u1}^2 + w_m^2} \Rightarrow w_1 = \sqrt{-14.13^2 + 0.86^2} = 14.15 \text{ m/s}
\]
\[
w_2 = \sqrt{w_{u2}^2 + w_m^2} \Rightarrow w_2 = \sqrt{-14.09^2 + 0.86^2} = 14.11 \text{ m/s}
\]
\[
w_\infty = \sqrt{w_{u\infty}^2 + w_m^2} \Rightarrow w_\infty = \sqrt{-14.11^2 + 0.86^2} = 14.13
\]
\[
\beta_\infty = \arccos \frac{W_{u\infty}}{w_\infty} \Rightarrow \beta_\infty = \arccos \frac{-14.11}{14.13} = 150^\circ
\]
\[
(180^\circ - \beta_\infty) = 180^\circ - 150^\circ = 30^\circ
\]
The calculation result of the lift coefficient:

\[
\zeta_a = \frac{w_2^2 - w_\infty^2 + 2g^* \left[ p_{atm} - H_s - p_{min} - \eta_s c_3^2 c_4^2 \right]}{K W_\infty^2}
\]

\[
c_3 = \frac{Q}{A_3}
\]

\[
A_3 = \frac{\pi D^2_e}{4} \Rightarrow A_3 = \frac{\pi \times 0.324^2}{4} = 0.08 \text{ m}^2
\]

\[
\Rightarrow c_3 = \frac{0.06}{0.082} = 0.73 \text{ m/s}
\]

\[
\Rightarrow \zeta_a = \frac{14.11^2 - 14.13^2 + 2 \times 9.81^* \left[ 10 - 0.02 - 2 - 0.9 \times 0.73^* 0.40^2 \right]}{2.6 \times 14.13^2} = 10.11
\]

4.1. Turbine testing result
Tests were carried out at the Solok river in Darul Makmur village, Subulussalam Sultan Daulat district, which has a 3.5 meters head and 0.06 m³/sec discharge. The turbine testing results are shown in figure 4.

Figure 4. (a). Discharge relationship with rotation, (b). Power relationship with rotation, and (c). Efficiency relationship with the rotation
4.2. Discussion
At the minimum discharge of 0.01 m³/sec was obtained 305.55 rpm, while the power generated at 132.5 watts with 14.36% efficiency, and at the maximum discharge of 0.06 m³/sec was obtained 1828.3 rpm, while the power generated at 2530.17 watts with 57.35% efficiency.

5. Conclusion
Based on the testing of propeller turbines for the axial flow of head 3.5 meters in the Solok river in the village of Darul Makmur, Subulussalam District, Sultan Daulat Regency, Aceh province, inconclusive: From the calculation obtained for the specific turbine speed of 1.53, according to the theory where the speed is specific for Propeller turbines (0.19 ≤ Qe ≤ 1.55) (see table 2) [9]. The turbine efficiency of 57% at 1500 rpm is a fact according to the theory of propeller turbine for the countryside is optimum efficiency when it is operated at rotations between 1250 to 1500 rpm depends on site conditions and the turbine character [15,17]. Stall power the turbine down at 985.42 watts when the turn reaches 1828.3 rpm. If reflected characteristics of a propeller turbine [7]. It can be concluded that axial flow propeller-type turbines can be used for micro-hydropower plants especially with low head.

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