Computational Analysis of Water Wheel for Hydro-Electric Power

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Abstract. The flow of water in the river is one of shallow water flow that has many benefits. One of them is as a power plant that uses a water wheel. Where the water wheel is used utilizing the flow of water in the river. The flow of water in the river in this study has a speed of 1.2 m/s. In the completion of this research, the finite element method in numerical approach is used to analyse the velocity of fluid motion in the river. Where speed inflow can affect electricity production. In the process, this research uses simulation with a software that works based on finite element method that is COMSOL Multiphysics 5.2 in two-dimensional form. The simulations are performed in two-dimensional flow, all the particles are thought to flow in the plane along the flow so that no flow is perpendicular to the plane. The simulation is carried out for 10 seconds and based on three variations of the water wheel height based on the center point of the water wheel is 1 m, 1.25 m and 1.5 m. Of the three variations, the fastest speed is at 1 m with maximum discharge is 34.6 m/s

1. Introduction
Currently, technology and research are growing rapidly to be able to produce energy efficient and cheap electricity [9]. Where the source of electrical energy comes from fossil energy sources (coal, gas oil) and renewable energy sources (geothermal, wind, ocean waves, biogas, and water). In Indonesia alone, the source of electrical energy is still using fossil energy that uses petroleum. As it is known, fossil and petroleum energies are getting smaller and smaller. Therefore, the need for an innovation in generating electrical energy source. One of the new energy sources that are easy to make electrical energy is water. One of the tools used is a water wheel to generate electricity by rotation.

The water wheel is one of the most simple and well-known technologies that can be used as a power producer. The basic shape of a water wheel consists of a large wheel surrounded by a blade. Where if the blades are given a flow of water then the impulse of the water will move the blades and the wheel will rotate on its axis [3]. This study aims to get a calculation in the speed of water wheel round, so the movement to provide maximum power efficiency. In this study the design of the water wheel used is the bottom design. Where the water flow is flat and water flows from left to right. The purpose of this study is not only as a study in the construction of water wheel, but also as a material for further research where water wheels are known as producing electricity. With the help of water flow in the river, electricity generated is low in operational costs, fuel-efficient, and environmentally friendly [8][7].
2. Research methods

In this research, the finite element method is computed using COMSOL Multiphysics 5.2 program. Before conducting any analysis in the program, it is necessary to recognize in the design of the water wheel and how to obtain electrical power based on the speed that will be discussed next. After the simulation, the results obtained are only limited by analyzing the water rate according to three variations of the water wheel form [1][2].

2.1. Water wheel design

In the hydropower field different machine types can be used to convert hydro energy into mechanical energy [10]. One of the mechanical energies applied that kinetic energy can be obtained from the flow of water that moves waterwheel. So, based on the classification of the type of hydroelectric generator engine is hydrostatic pressure converters (HPC). The HPC is like gravity water wheels (undershot, breastshot and overshot) and Archimedes screws.

In this study, the design used is the undershot water wheel design. Undershot water wheel design is the type of water wheel most commonly used by people in ancient times because it is the simplest type of water mill, cheap and easiest for the manufacture. In the design of the water wheel the wheel is placed directly into the stream that flows quickly and is supported from above. The water movement below creates a pushing motion against the submerged paddle at the bottom of the wheel allowing it to rotate in one direction only relative to the direction of the water flow.

This type of water wheel design is usually used in terrain areas that have a natural slope of the ground or where the flow of water moves fast enough. Compared to other water wheel designs, this type of design is very inefficient because of the small amount of potential water energy used to actually turn the wheel. Also, the water energy is only used once to rotate the wheel, after which it flows away with the rest of the water [5].

In addition, the undershot water wheel requires a large amount of water moving at a speed ($V_0$). Therefore, the water wheel under water is usually located on the riverbank because the flow of water in the small river does not have enough potential energy in the moving water.

To increase the rotational efficiency of the power plant waterwheel, it can take advantage of the underwater fluid dynamics that are narrowed to the size of the channel so as to produce more power to rotate the waterwheel. To achieve this, the waterwheel with the undershot model must be narrow and very fit in the channel so that the paddle movement on the water wheel accelerates which results in faster rotation of the waterwheel. And the faster the water wheel turns, the greater the amount of electricity that will be produced [11].

2.2. Water kinetic power

In determining the amount of electric power generated by a water wheel can be seen based on the condition of the water flow and the dimensions of the water wheel. Electric power generated by water wheel comes from water kinetic energy (water flow). If the water flow is directed to a plane, theoretically the plane or wall will accept the force due to the collision of water against the plane. If the walls are mounted on the circumference of the wheels, then the impact forces on the wall will cause torque which will cause the wheel to rotate on its axis. The kinetic energy has been transformed into mechanical energy in the form of rotation. The amount of torque caused by the collision of water is directly related to several things, among others:

1. Flood water flow
2. Size on wall or collision field
3. A diameter of the wheel
4. Water discharge

The equation for the mass of the fluid rate is:

$$\{m\} = \rho A V \tag{1}$$

where the hydraulic power is:
\[ P_h = \rho g h Q \]  

(2)

From the equations (1) and (2) it is known that the flow of water \((Q)\) is the multiplication of the water cross section \((A)\) with the velocity of the water velocity \((V)\)

\[ Q = AV \]  

(3)

Substituting equation (3) into equation (2) is obtained:

\[ P_h = \rho g h AV \]

(4)

From the Bernoulli equation it is known that:

\[ P + \rho g h + \frac{1}{2} \rho V^2 = C \]

(5)

From equation (5) can be show the \(\rho g h\) variable which is an element of the hydraulic power formula and where the variable \(P \approx \rho g h \approx \frac{1}{2} \rho V^2\) so equation (4) becomes:

\[ P_h = P_k = \frac{1}{2} \rho V^2 AV \]

(6)

Substituting equation (1) into equation (6) is obtained:

\[ P_h = P_k = \frac{1}{2} \{\dot{m}\} V^2 \]

(7)

where \(P\) is Fluid pressure [Pa], \(V\) is Water flow rate \([m/s]\), \(h\) is Height [m], \(\rho\) is Density 1000 kg/m\(^3\), \(Q\) is Water flow discharge \([m^3/s]\), \(g\) is Gravity determination \([9.81 m/s^2]\), \{\(\dot{m}\}\} is Water mass rate \([kg/s]\), \(P_h\) is Hydraulic power [Watt], and \(P_k\) is Water kinetic power [Watt].

At the output power generator can be obtained when the voltage and current strength is known, then the formula is obtained that is:

\[ P_L = VI \]

(8)

where \(P_L\) is Electrical power [Watt], \(V\) is Voltage [Volt], and \(I\) is Power current [Ampere].

Determining the efficiency is:

\[ \eta = \frac{P_{out}}{P_{in}} \times 100\% \]

(9)

with \(P_L\) as \(P_{out}\) and \(P_k\) as \(P_{in}\), then the efficiency formula used is:

\[ \eta = \frac{P_L}{P_k} \times 100\% \]

(10)

where \(\eta\) is model efficiency [%], \(P_L\) is Electrical power [Watt], and \(P_k\) is Water kinetic power [Watt].

If the wall has a rotary axis then the torque can be calculated:

\[ T = FR = w A \frac{V^2}{g} \]

(11)

where \(R\) is radius water wheel [m]. Because the wall can rotate on its axis it will cause a peripheral speed at the end of the wall for \(u\). So that will result in the relative speed between water and wall for:

\[ V_r = V - u \]

(12)

where \(u\) is speed around the windmill \((m/s)\). Then the normal style received by the wall will be the following equation:

\[ F = \frac{w aV}{g} (V - u)u \]

(13)

While the circumferential speed \((u)\) theoretically has an approximate relationship with the velocity of water flow \((V)\), where maximum efficiency will occur when the circumferential speed is equal to half the speed of the water flow. It can be downgraded:
\[ E = \frac{m a V}{g} \frac{(V - u)}{p_{wk}} \]  

For

\[ p_{wk} = \frac{1}{2} \frac{w}{v^2} \]  

where, \( E \) is efficiency, \( p_{wk} \) is water kinetic power and \( w = m a V \), so that

\[ E = \frac{m a V}{g} \frac{(V - u)}{m a V^3} = 2 \frac{(V - u)u}{V^2} \]  

So, the maximum Efficiency is:

\[ \frac{d}{du} (V u - u^2) = 0 \]

it is obtained

\[ u = \frac{1}{2} V \]  

The maximum efficiency occurs when the traveling speed is equal to half the speed of the water flow. Then the working force will be as follows:

\[ F = \frac{w a V}{g} (V - \frac{1}{2} V) = \frac{w a V^2}{2g} \]  

Work produced for 1 kg of water / second is the force exerted multiplied by the circumferential velocity, then the work \((W)\) is:

\[ W = F u = \frac{w a V^3}{2g} \]  

When the water flow rate is Volume times density type then

\[ G = (b h V)w \]  

From equations (20) and (21), then the generated power of the wheel can be calculated by the following

\[ P = W G = \frac{w^2 b^2 h^2 V^4}{4g} \]  

3. RESULT AND DISCUSSION

The results of this study were simulated in the COMSOL Multiphysics 5.2 program which will be analyzed based on speeds on three variations of undershot water wheel design. Variations in this study based on the axis of the water wheel axis at 1 meter, 1.25 meters, and 1.5 meters. From each variation will be analysed for 10 seconds. But in the results will only be shown 4 time is 0.4 seconds, 2.08 seconds, 6.66 seconds, and 10 seconds. Where in this simulation used the initial velocity of water on the river is 1.2 m/s and move faster based on time. The simulation will be shown in the picture below.
From the simulation FIGURE 1, result at 1-meter axis ordinate, the maximum speed of water flow based on the simulation result is 34.6 m/s. And the most stable flow is shown at 6.6 seconds.

Based on the simulation FIGURE 2, result at the time of the ordinate of the shaft 1.25 meter, the maximum speed of water flow based on the simulation result is 28.4 m/s. And the most stable flow shown at 6.6 seconds is also the same when the ordinate of the shaft is 1 meter.

Based on the simulation FIGURE 3, result at the time of the ordinate of the shaft 1.5 meter, the maximum speed of water flow based on the simulation result is 26.1 m/s. And the most stable flow shown at 6.6 seconds is also the same at the time of the ordinate of the shaft is 1 meter and 1.25 meters.

From the three variations can be seen, that the flow of fluid in the river, stable or not, based on the travel time of water (probably due to the same water wheel shape) is 6.6 seconds. As for the fluid velocity in the river is more influenced by the axis ordinate. Where as in the discussion section on the design of water wheels, the efficiency of the water wheel is influenced by the location of the water wheel is correct. And proven based on the results of this simulation.

4. Conclusion

Based on the research that has been done that is computationally analysed in the program COMSOL Multiphysics 5.2, obtained variation at the velocity at river flow rate as well as rotation on the water wheel. The change of speed can also be seen based on changes in time and changes in a variation on the model of water wheel. Variations made based on the ordinates on the wheel axle of water wheel that is 1 meter, 1.25 meters, and 1.5 meters. From the time change is obtained the form of change of fluid flow velocity in the most stable river is 6.6 seconds. As for the variation of the water wheel axis, the maximum speed at 1-meter ordinate is 34.6 m/s, in the ordinate 1.25 meters is 28.3 m/s, and at the ordinate 1.5 meters is 26.1 m/s. Although the difference in the pivot height is only 0.25 m, the change in velocity can be seen to change significantly.
From the simulation results, the faster the fluid power flow will be greater. Therefore, the conclusion for the three variations, when the center of the water wheel is at 1 meter, gives optimal results from electric power. Because the resulting speed is faster. For further research it is expected to analyse in different designs in addition to the underwater misting model. And make more variations in design, both in shape and geometry.

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