Effect of the number of blades on undershot waterwheel performance for straight blades

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Abstract. Access to electricity in Indonesia is limited due to the remote area of the community. In the modern era, electricity is a primary necessity and indicator of welfare. To overcome this problem, using renewable energy resources in the remote areas of Indonesia is an appropriate alternative. Based on this condition, the pico hydro-type undershot waterwheel is suitable to be used in Indonesia, because undershot waterwheels are appropriate for low head conditions or low river flow. This study will examine the effect of different blade numbers on the performance of undershot waterwheels for straight blades. There are four blade number variations: 8, 12, 16, and 20. The computational fluid dynamic method was used because it can visualise the flow pattern with more detail than other methods. Activating six degrees of freedom is needed to predict the rotational speed of the turbine’s interaction with the water and blade. Based on the results, 20 blades produced higher efficiency than others. However, the 8 blades had a stable performance and produced higher rotational speed than the other. The empirical equation for determining the number of blades of undershot waterwheels adopted by the Pelton turbine is correct.

1. Introduction
In 2018, 2% or 2 million of Indonesians people did not yet have access to electricity. This is due to difficult accessibility to the remote areas of the community. In the modern era, electricity is a primary necessity and indicator of welfare. To overcome this problem, using renewable energy resources in the remote area is an appropriate alternative [1]. Pico hydro (<5 kW) is a possible alternative because the life cycle cost per kW is cheaper than that of a solar PV or wind turbine [2]. Furthermore, Indonesia has 19 GW of water energy sources for small, micro and pico-scale, categorized as low head conditions (< 5m) [3]. Due to this condition, pico hydro-type undershot waterwheel is suitable for use in Indonesia because undershot waterwheels are appropriate for low head conditions or low river flow [4].

Pico hydro type undershot waterwheel is a popular technology in Indonesia called kincir air (water mill) and has been used for a long time (19th century). However, the development of undershot waterwheels continues, especially in the blade characterisation. Sule et al. [5] studied blade shape and the number of undershot waterwheels. The study shows that the performance of 10 blades is higher than 6 and 8 blades [5]. On the other hand, Warjito et al. [4] proposed an empirical equation of the number of blades. The empirical equation is adapted from the Pelton turbine. Based on empirical calculation, the number of blades is 8. Warjito et al. proved the equation by comparing the 8 blades with 6, 7, 9 and 10 blades. This comparison uses the computational fluid dynamics (CFD) method. The results of the study show that the 8 blades have a higher efficiency than other blades [4].
Based on the explanation above, the method to determine the blade number of the undershot waterwheel is still not clear. Using the adopted equation from the Pelton turbine has problems, which for all conditions the calculation will result in 8 blades. Additionally, the results of Warjito et al.’s study showed that there was no significant change in blade efficiency with increasing blade numbers [4]. This is due to the condition of blade number variation being too short. Because of this, we continue the study with more blades. In this study, the variation of blades is 8, 12, 16, and 20 blades. The study was conducted with unsteady CFD simulation.

2. Methodology

2.1. Geometry
In this study, the geometry of the undershot waterwheel turbine has the same main parameter as the previous study [4]. The main parameters are: Blade height (h) = 0.164 m, Inner Diameter (D_i) = 0.820 m, Outer diameter (D_o) = 0.984 m and blade angle (θ) = 45. However, this study uses a different number of blades: 8, 12, 16, and 20. The representation of main parameters and blade number variation are shown in Figure 1 below.

2.2. Simulation setup
This study was conducted with 2-dimensional simulation and was performed with unsteady calculation, which ran in 5 seconds of time step total. On the other hand, the six degrees of freedom (Six-DoF) feature is used. This is due to the recommendation of other researchers that to determine the rotational velocity as a dependent variable, the Six-DoF feature is used to investigate fluid dynamics phenomena by the movement of the domain blades that occur from interactions with fluids [6][7]. According to the Six-DoF feature, it is necessary to perform the simulation with two domains, the rotor domain and the stator domain. Because of this, the interface between the rotor and stator domain is created (see Figure 1b). Additionally, to activate the Six-DoF feature, the blade’s moment of inertia and preload must be defined. In this study, we used 24 N.m of preload and various moments of inertia depending on blade geometry (8 blades: 4.2 kg.m², 12 blades: 6.2 kg.m², 16 blades: 8.3 kg.m², and 20 blades: 10 kg.m²).

The boundary condition of this study is shown in Figure 1b. The inlet of the boundary condition is velocity inlet, which the magnitude is 1 m/s. The outlet is determined as a pressure outlet with 0 Pa of pressure. The numerical calculation was also conducted with a multiphase simulation. In terms of multiphase simulation, volume of fluid option is selected with surface tension between water and air is 0.0728 N/m. Furthermore, standard k-epsilon is used due to this ability to predict a quite representative
flow characteristic based on previous study [8][2]. The result of the study shows that the k-epsilon turbulent model is the most suitable turbulent model for this kind of turbine.

2.3. Mesh and timestep independency tests
Appropriate mesh and time-step size in unsteady CFD simulation must be determined [8]. Roache explained the grid convergence index (GCI) to calculate the error of mesh number variation [9]. GCI is an extrapolation method to determine the predicted exact value of the dependent variable. In this study, the number of mesh varies at 25,196, 50,969 and 101,117. Figure 2 shows the mesh visualisation with 50,969 elements. Furthermore, to optimize the mesh quality, the mesh size near the wall is refined (Fig. 2).

![2D Domain mesh visualization – 50,969 elements.](image)

3. Results and Discussion

3.1. Independency test results
Figure 3 is a complete calculation of GCI; it determines the torque for each normalisation space. Normalisation of space is the comparison between various numbers of elements. In this study, 101,117 elements were normalized as 1, 50969 as 1.4, and 25196 as 2. The calculations show that the appropriate mesh number in this study is 50,969, with an error of 0.55%.

![Grid convergence index.](image)
On other hand, for timestep, the same method is conducted. Based on previous study, it is found that the appropriate timestep size is 0.001 s [4].

3.2 Runner Performance
Figure 4 is a comparison graph between blade’s tip speed and timestep, showing that the blade’s tip speed was increased at the beginning of the simulation until it reached the maximum speed at timestep 1,200. The blade’s tip speed then decreased and steadied after timestep 4,000. Figure 4 also shows that the more blades on the undershot waterwheel, the more it will produce lower blade’s tip speed. However, anomaly conditions happened with 16 blades, whereas it lowered with 20 blades.

Beside the blade’s tip speed (U), the waterwheel’s torque is also a variable that expresses the undershot waterwheel performance. Figure 5a is the wheel’s torque graph of a various number of blades during the simulation, where they became stable after timestep 2,000. It can be obtained that a higher number of blades produced greater torque. Furthermore, Figure 5b expresses the efficiency of the four testing cases over the simulation process. The highest waterwheel efficiency in this simulation is attained at 46% by 20 blades in the undershot waterwheel with a timestep of about 1,000. Runner-up position is attained by 16 blades, which is about 38% at almost the same timestep. In addition, the undershot waterwheel with 8 blades has the lowest maximum efficiency, which is only about 26%. However, this case has a more stable efficiency graph than others.
It can be summarized from the above discussion that the undershot waterwheels with 20 blades have better efficiency than other cases. However, the 8-blades undershot waterwheel has more stable efficiency and can attain a higher tip speed, which means that it can produce a higher rotational speed. The higher rotational speed is very important when it is easier to attain the generator’s rotational speed requirement. Furthermore, the stable efficiency of the waterwheel is also important due to the fluctuation of input power from the water, which is often faced in micro hydro or pico hydro.

4. Conclusion
Evaluation of the empirical approach of the undershot waterwheel’s blade number is important because the result of the approach is almost always the same. The numerical simulation to verify that the chosen number of blades by the mentioned approach is the best choice has already been done by varying the blade number. The simulation resulted in higher blade numbers producing higher waterwheel efficiency. However, the chosen blade number by the empirical approach has still been recommended due to its stable performance and higher rotational speed. This study must also be proven by a comprehensive experimental study.

5. References
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