Experimental Study of Multistage Rotor in Gravitational Water Vortex Turbine System with Various Gap Placement Positions and Blade Phase-Shift Angles

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Abstract. Gravitational Water Vortex Turbine (GWVT) has the advantage of harnessing hydro flow energy from the low head. Several research have been conducted to optimize the performance of this turbine type, one of which is by applying multistage rotor. This work is to study the effect of gap placement and phase shift angle between stages that have not been clarified in other works. The result showed that the highest mechanical efficiency belonged to the rotor with gap on the top stage while the implementation of phase shift angle between stages lowers the performance of the rotor.

Keywords: GWVT, multistage, rotor gap, phase-shift angle.

1 Introduction

For decades, renewable energy has become an alternative of fossil energy which is already less and less. Indonesia is one of the countries that great potential of renewable energy source, which is around 443 GW, including geothermal, water, micro-mini hydro, solar, and ocean wave. The second biggest potential of renewable energy source in Indonesia after solar is water and micro-mini hydro which is around 94.4 GW. From this big potential, only 5 GW is already harnessed per 2017 even though water and micro-mini hydro have better possibility of stability to produce electricity than solar [1].

Geographically, one of the water areas in a land that is close to the residential areas, either city or village, is river. Based on the data of Central Bureau of Statistics Republic of Indonesia, rivers in Indonesia have range of debit between 1 and 274 m3/s, with the average debit of 34.69 m3/s per 2015. Furthermore, the potential head of majority of rivers in Indonesia is around 0.12 – 10.21 m, with the average value of 1.63 m[2]. Therefore, hydro turbine systems that can operate in relatively low head and debit are required to give bigger chance of electricity accessibility to the local communities.

Based on the rotational axis, hydro turbine can be classified into Vertical and Horizontal Axis Hydro Turbine. In general, Vertical Axis Hydro Turbines have advantages,

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such as the generator can be put on the water surface and can be directly driven by the shaft. Moreover, due to its vertical axis design, this type of turbine can be combined with other types. For this reason, the tendency to utilize this technology in rural areas that do not have accessibility to the electricity grid in developing countries is quite big.

One of Vertical Axis Turbine types that is still researched and developed is Gravitational Water Vortex Turbine. This type is a system whose electricity is generated by the help of water centrifugal flow which is formed by making a hole in the center of the bottom of a vortex pool. Theoretically, this turbine system combined with a generator can produce electricity on low potential head.

The development of this turbine system type is still conducted through research, some of which are in the topics of shape and material of basin and rotors. Sritram et al investigated the effect of number of rotor blades and addition of rotor endplates to the turbine performance [3]. Nishi et al used blade shape that has straight swept area. Kueh et al, in their research, applied the straight blades whose bottom part is curved to their turbine system [4]. Meanwhile, Dhakal et al conducted research of the three various blade shapes: straight, twisted, and bent [5].

Another approach to harness more energy from this turbine type is by applying rotor with more than one stage. Ullah et al did research about the multistage curved rotor and investigated the performance of each stage independently by using telescopic hub [6] [7]. They found that triple-stage Gravitational Water Vortex Turbine (GWVT) provides more power than single-stage GWVT due to the strengthened vortex in the vicinity of each other. Moreover, they found that there was effect of rotor to basin diameter ratio to the performance of the rotor, and rotor with rotor to basin diameter ratio of 0.6 has the best performance [7]. Meanwhile, the best investigated offset distance between each rotor was 0.11 m [6]. They applied a telescopic shaft to measure the generated mechanical power independently between each stage. This, however, might add weight to the rotor that needs to be rotated by the fluid as well as the complexity to the manufacturing process. Dahal et al investigated the effect of adding booster runner with different blade numbers and inclination angle on the bottom part of shaft thus they only used double stage for rotor configuration [8]. They found that the booster runner with 5 blades or inclination angle of 32° has the best performance among all [8]. One of the disadvantages that may arise is that the water vortex formation in the area of lower stages can be distorted from the impact of water to the upper stages which results in the decrease tendency of power generation [6]. Thus, rotor shape and configuration are some important aspects in the performance of multistage GWVT.

There is a research conducted by Khan et al which concluded that the crossflow-profile turbine exceeded conical, curved, and twisted model in terms of efficiency [9]. The profile of the crossflow turbine includes the gap on the rotor. Another similar investigated approach in a conventional Savonius turbine is by applying gap to the rotor whose width is measured by means of blade diameter. This gap is called overlap ratio. This has already proven to be effective in increasing the efficiency of the rotor. Meanwhile, in a conventional multistage Savonius rotor, another approach to increase its efficiency is applying phase-shift angle between each stage [10], [11]. The aforementioned factors might be used as the alternative shape and configuration to affect the performance of the multistage rotor of GWVT, but they have not been clarified and studied yet on the multistage rotor of GWVT. Therefore, the aim of this research is to investigate the effect of adding curve, the gap, and varying phase-shift angle of the multistage GWVT rotors to the performance.

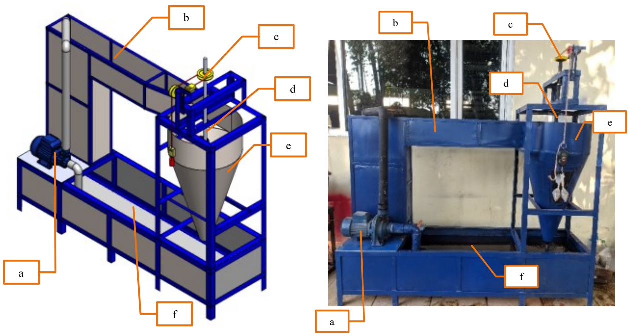
2 Methods

This research refers to the previous studies, in which the optimum ratio of orifice diameter to the basin total diameter is 14-18%, or it is 14.6% in this study. The 3D-designed and manufactured product of the GWVT is shown in Fig. 1 while the parameters of the design are shown in Table I. The material used for basin and rotor is steel with the thickness of 0.8 mm.

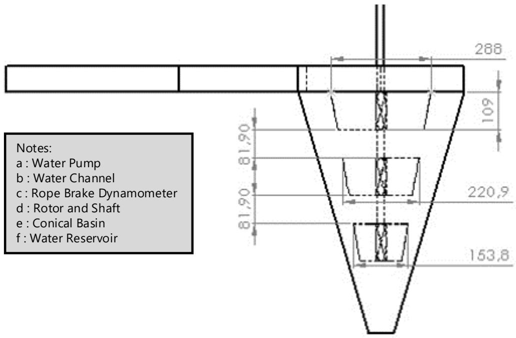
Table 1. Dimension of Gravitational Water Vortex Turbine System of Experiment Setup

Parameter	Dimension
Channel Length	880 mm
Channel Width	200 mm
Channel Height	200 mm
Channel Notch Angle	10°
Basin Total Height	900 mm
Basin Notch Angle	16°
Basin Total Diameter	480 mm
Basin Orifice Diameter	70 mm

The rotor is configured as three stages with the offset between each stage is 81.9 mm or 11% from the total height of the basin. Each stage is connected by a single shaft that has diameter of 25.4 mm and total length of 1200 mm thus each rotor stage was kept rotating in a simultaneous rotation. The ratio of rotor diameter to the basin diameter was 0.6 which was recommended in the study by Ullah et al [7]. The full setup of experiment, including design, manufacture, and dimension illustration are shown in Fig.1, noting that all dimensions shown on the sketch is in mm.



(a) (b)



(c)

Fig. 1. Experiment Setup (a) Design (b) Manufacture Result (c) Dimension Illustration

. The design of the experiment is explained in Table II where n, T, P_{rotor}, and η_m are rotor rotation speed, rotor torque, output rotor mechanical power, and mechanical efficiency respectively. The input flowrate of the water from the channel (Q), radius (R) and height (H) of each rotor and the distance (d) between each stage was kept constant as shown in Fig. 1. The first experiment was conducted to investigate the effect of applying gap to the curved blade. The curved profile of the blade was chosen based on the previous study by Ullah, et al [7]. In this study, they stated that the curved blade had the better performance than the flat blade. Meanwhile, the ratio between gap applied to the blade and the highest diameter of each blade in each stage was 20%. Furthermore, in this scenario, the gap was applied either on the first stage, the second stage, or all stages of the rotor. The gap was not applied to the bottom stage under the assumption that it was not needed to reduce the distortion on the bottom stage as the vortex flow reached the outlet of basin afterwards. The second experiment was carried out to investigate the effect of applying shifted angle between each stage of the rotor, especially on the rotor with the gap on all stages as the reference. The angle shift which was used was $+30^0$ (along the direction of water vortex rotation) and -30^0 (against the direction of water vortex rotation). The design of the various rotor scenario was shown in Fig. 2.

Table 1. Design of Experiment

No	**Input Parameter**		**Output Parameter**
	Independent Variable	***Controlled Variable***	
1	Gap Placement Position	R, H, Q, d	n, T, P_{rotor}, η_m
2	Phase-Shift Angle between Stages	R, H, Q, d	n, T, P_{rotor}, η_m

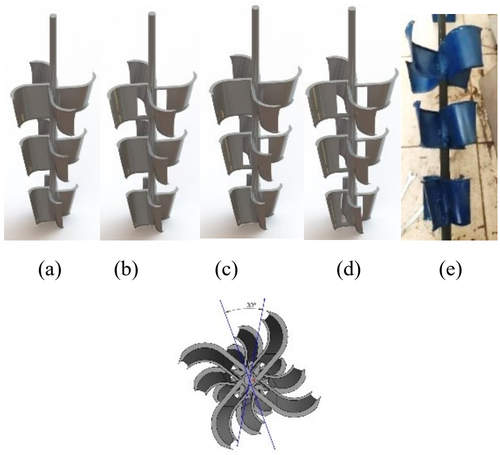


Fig. 2. Various Design of the Utilized Rotor (a) Rotor Without Gap, C1 (b) Rotor With Gap on Top Stage, C2 (c) Rotor With Gap on Middle Stage, C3 (d) With Gap on All Stages, C4 (e) Example of Manufacture Result (f) Rotor With Gap on All Stages and Shifted Angle of +30º, C5, and -30º, C6

The water flowrate measurement on the channel was carried out by using an open channel flowmeter LS300A that was able to measure both flow velocity and flowrate. Its flow velocity range is 0.01 – 4 m/s. In this experiment, the measured input flowrate in the channel was 0.0035 m^3/s. Furthermore, the torque measurement was done by using rope brake dynamometer principle whose schematic is shown in Fig. 3. This principle uses the addition of the various values of load/mass while reading the measured value on the digital scale of m_1 and m_2. The difference of the reading of two scales was then converted to the torque by using (2). Meanwhile, the rotational speed of the rotor was measured by using a digital tachometer.

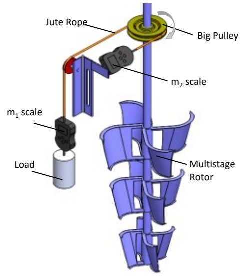


Fig. 3. Schematic of Rope Brake Dynamometer on the Experiment Setup

The collected data were then processed to calculate the input hydro power (P_{hydro}), output rotor mechanical power (P_{rotor}) by using (1) and (2) respectively, where ρ, Q, g, $\mathcal{H}$, ω, n, r_{pulley} are density of water (kg/m^3), water flow rate (m^3/s), gravitation acceleration (m/s^2), water head (m), rotation speed of rotor in the unit of rad/s, rotation speed of rotor in the unit of rpm, and big pulley radius (m) respectively

$$P_{hydro} = \rho Q g \mathcal{H} \quad (1)$$

$$P_{rotor} = \omega T = \left(\frac{2\pi n}{60}\right)\left((m_1 - m_2) g r_{pulley}\right) \qquad (2)$$

Mechanical efficiency (η_m) was defined as the ratio of output mechanical power from the rotor and input hydro power.

$$\eta_m = \frac{P_{rotor}}{P_{hydro}} \times 100\% \qquad (3)$$

3 Result and Discussion

Result and Discussions Chapter involves three categories which are the effect of gap within blades and phase-shift angle of the blades.

3.1 Effect of Gap Placement Position within Blade

The results of the experiment of gap placement position effect to the rotor is shown in Fig. 3. From that figure, the produced torque in each configuration is inversely proportional to the rotational speed of the rotor. This can be explained as follows. In a gravity vortex turbine system, rotor rotation is generated by the whirlpool formed when water exits the outlet basin. In this process, the tangential velocity of the vortex, which is a conversion of the tangential velocity at the basin inlet, strikes the blades, resulting in rotor rotation [6]. Placing the concave part of the rotor towards the basin inlet is applied to direct the flow radially from the outermost part of the blade inward (approaching the shaft) before moving downward axially (parallel to the rotating axis) or through the gap. Furthermore, the force that makes the rotor pushed and produces rotor torque comes from the difference between the tangential velocity of the gravitational vortex in the initial state of the whirlpool colliding with the blade and the speed of the blade itself [6]. As the blade speed decreases because the load of pony brake dynamometer is increased, the speed difference is greater, and the produced torque gets higher.

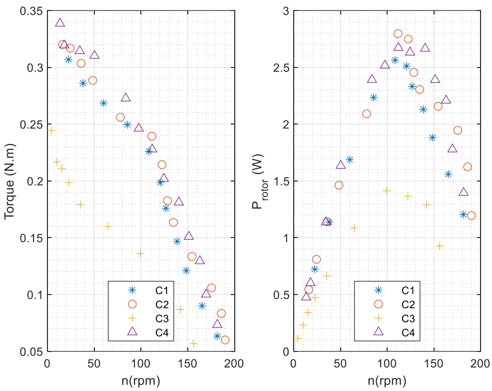


Fig. 4. Experiment Result of Gap Placement Position Effect on the Rotor (a) Rotor Torque vs Rotation Speed (b) Rotor Mechanical Power vs Rotation Speed

Meanwhile, from the graph of Fig. 5, it is noted that the highest mechanical efficiency for all configuration is reached in rotation speed of 100-120 rpm. From both Fig. 4 and Fig. 5, all curves of torque, mechanical power, and mechanical efficiency of C4 are higher than those of C1. Placing multi-stage rotor to the GWVT system can increase the performance when compared to the single-stage rotor but may cause vortex distortion to the next-stage rotor at the same time as reported in [7]. This distortion can be reduced by applying the gap or cross-flow-like shape as reported in [9]. This gap is also used to direct the flow of vortex from one side of the rotor to another part that faces in the opposite direction to support the rotation. Therefore, this results in the ability of the rotor C4 to maintain quite high torque which is around 0.23 Nm at rotation speed of 112 rpm thus produces higher P_{rotor} and higher η_m which are around 2.67 W and 17.74% respectively than those of C1 which are 2.56 W and 17.01%.

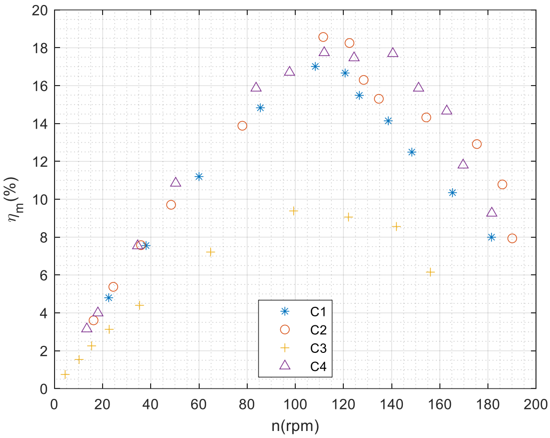


Fig. 5. Mechanical Efficiency vs Rotation Speed of Rotor with Various Gap Placement Positions

The strategy of applying the gap only on the first stage the rotor (C2) makes the mechanical power peak (2.8 W) and mechanical efficiency peak (18.56%) of the rotor slightly higher than those of C4 on about 112 rpm (2.67 W and 17.74%) but overall trend of torque-rotation speed and mechanical efficiency-rotation speed between both variations did not differ much. However, by applying gap on the second stage (C3), overall mechanical efficiency in each rotation speed decreases a lot even when it is compared to the rotor without gap at all. This can be seen as the mechanical power peak and mechanical efficiency peak for this variation are around 1.41 W and 9.38% respectively. This might be explained that, for C3, the distortion of vortex produced by the first stage decreases the water vortex energy to rotate the rotor, and the energy cannot be optimally recovered in the second-stage rotor due to less impact area between the blade and the water.

4 Conclusion

From this work, it can be concluded that placing the gap on the top stage or on all stages was able to make the mechanical power peak and mechanical efficiency peak, which were on around 100-120 rpm, higher than those of the rotor without gap at all. However, placing the rotor with gap on middle stage lowered mechanical power peak as well as mechanical efficiency peak due to the distortion and less impact area between blade and the water on the second stage to recover energy loss.

Furthermore, the implementation of phase shift angle between stages lowers the performance of the multistage rotor without phase shift angle a lot. This proves that this way is not suitable for multistage GWVT whose flow in each stage has dependency each other.

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