The effect of basin geometry on gravitational vortex hydropower

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Abstract. This study aims to determine the shape of the conical basin that is suitable to be applied to the gravitational vortex hydropower (GVHP) by observing the shifting location of the core of water vortex. Three types of basin that will be observed are: a basin with cylindrical height of 20 mm (type A); a basin with conical height of 20 mm and cone angle of 60° (type B); and a basin with conical diameter of 50 mm, conical height of 20 mm, and cone angle of 45° (type C). There are two methods which were used, the analytical method was used to determine geometric parameters which affect water vortex formation, and then the numerical method was performed using computational fluid dynamics (CFD) with multiphase, transient-SST, and steady-state condition. Highest velocity was achieved with conical basin type B which will form a strong water vortex formation. If the velocity gets higher, the pressure will also drop. Velocity gets higher gradually until it reaches the outlet, which in turn causing pressure to drop gradually as well. This will create pressure differences which will cause a suction effect and form a strong water vortex. Thus, the conical basin (type B) was concluded to be a basin which creates a good water vortex formation.

Keywords. Pico hydro, Gravitational Vortex Hydropower (GVHP), Computational Fluid Dynamics (CFD)

1. Introduction

Indonesia is an archipelagic country. There are over 17,000 islands scattered along the Pacific and the Indian Ocean [1]. Consequently, many provinces that haven’t been fully electrified by the government. The average of the rural electrification in 2017 is 97.10% with the lowest percentage in Papua (57.03%) [2]. To overcome this, pico hydro is one of the considered solutions in the developing countries to generate electricity in rural areas due to low manufacturing difficulties, lower investment and lower operation cost than other renewable energy technology [3][4]. Moreover, Indonesia has the potential for small hydropower for around 19.4 GW [5].

Pico hydro turbines are a type of power plant which is able to produce electricity with output power up to 5 kW. There are many turbines type that can be used for a pico hydropower plant. Gravitational vortex hydropower (GVHP) is one of the types that can be used for a pico hydropower plant. This type of hydropower plant is effective to be used under low-head and low-flow conditions [6]. The channel and the basin are one of the important factors that will affect GVHP efficiency [7].

There has been a lot of studies about the geometry of the channel and the basin on gravitational vortex hydropower (GVHP). Trismitna and Mulligan [7] did their study on “Water Vortex Hydropower
Technology”. One of these study findings is the design variation of the basin along with the advantages and disadvantages. Dhakal and Trismilna [8] studied several geometric parameters on conical basin design and their effects on the vortex formation and energy. This study concludes that the geometry greatly affects the vortex velocity and the sensitivity of each parameter. Marius-Gheorghe and Tudor [9] studied the speed and the power characteristic of the gravitational vortex of water flow through the conical basin and attempts to perform efficiency modeling. Mizanur Rahman and Tan Jian Hong [10] found that in the model of the power generation system, the maximum hydraulic efficiency was recorded when the turbine rotating speed was half of the vortex tangential velocity. Mulligan and Casserly [11] found that a nondimensional approach flow factor and geometry factor strongly affect the circulation number (\(N\Gamma\)) and field circulation (\(\Gamma\infty\)). Shabara and Yaakob [12] used CFD to investigate the optimum configuration of the water vortex formation. The result of this study showed that by reducing the outlet diameter, the speed increased. Therefore, as the water depth increases, higher velocity can be achieved. Power and McNabola [13] did an experimental study for gravitational vortex hydropower. This study shows that maximum power outputs were found for the largest flow rate tested (0.65 L/s).

All of the previous studies have shown us which type of channel and basin that gives out a good water vortex formation and vortex strength. Many parameters affect the selection of channel and basin such as the approach flow angle, notch length, inlet width, orifice diameter, and many other geometry parameters. This study aims to determine the shape of the basin which forms a strong water vortex formation by using computational fluid dynamics (CFD) method to visualize the distribution of pressure and velocity. Strong water vortex formation can be seen by looking at the velocity and pressure profile. If velocity becomes higher, the pressure will drop. Velocity gets higher gradually until its’ peak when it reaches the outlet. This will make a pressure difference and make a suction effect which forms a strong water vortex formation. The CFD method can show the water vortex formation and velocity distribution which cannot be done with other methods.

2. Methodology

2.1. Analytical method.

The analytical method is mainly used to determine the geometry of the channel and basin. The rotational strength in water vortex is determined by the circulation parameter \(\Gamma\) given by Eq. (1):

\[
\Gamma = 2\pi r V_\theta
\]  \hspace{1cm} (1)

Approach flow geometry (\(\alpha\)) is a ratio of \(r_{in}/b\) which mostly affect the circulation parameter [14]. Tangential velocity in the equation can be stated with another following Eq. (2):

\[
V_\theta = \frac{Q}{b h_{in}}
\]  \hspace{1cm} (2)

Where \(b\) is the inlet width and \(h_{in}\) is the depth of the water inlet. So, a decrease in the inlet width \(b\), will in return increase the tangential velocity. Therefore, because it is required to reduce the inlet width then there will be a slope from the channel width into the inlet width which called notch length. According to Mulligan [7], notch angle or approach flow has a range from 0\(^\circ\) \(\leq\) \(\alpha\) \(\leq\) 45\(^\circ\). Substituting both of the equation (1) and (2) can achieve the following expressions for the vortex strength or circulation parameter:

\[
\Gamma_v = \frac{2\pi r_{in} Q}{b h_{in}}
\]  \hspace{1cm} (3)

Where \(r_{in}\) is the radius of the water inlet Power and McNabola [13] stated that the optimum ratio for \(h_{in}/l\) is one over three. Mulligan [14] found dimensionless parameters with a simple relationship for the discharge in the system by Eq. (4):

\[
Q = \frac{k_d}{(2\pi r_{in})^{n_d}} \sqrt{g \frac{d^5}{l}}
\]  \hspace{1cm} (4)
Where $k_\alpha$ and $n_\alpha$ are empirical parameters which close the system with this following equation:

\[ n_\alpha = 0.05\alpha^2 - 0.39\alpha - 0.55 \text{ for } 1.3 \leq \alpha \leq 6.22 \]

\[ k_\alpha = -0.12\alpha^3 + 0.79\alpha^2 - 0.62\alpha + 0.36 \text{ for } 1.3 \leq \alpha \leq 6.22 \]

After the outlet diameter was calculated using Eq. (4), then the basin diameter needs to be determined using a ratio from outlet diameter. According to Mulligan [7], there were many ratios that he used for his experimental studies such as:

**Table 1. Ratios basin diameters and nozzle according to outlet diameter**

| $D_{\text{eff}}$ | $B$ |
|------------------|-----|
| 3.0 $d$          | 0.5 $d$  |
| 3.0 $d$          | 1.0 $d$  |
| 3.0 $d$          | 1.5 $d$  |
| 3.0 $d$          | 2.0 $d$  |
| 4.0 $d$          | 0.5 $d$  |
| 4.0 $d$          | 1.0 $d$  |
| 4.0 $d$          | 1.5 $d$  |
| 4.0 $d$          | 2.0 $d$  |
| 5.0 $d$          | 0.5 $d$  |
| 5.0 $d$          | 1.0 $d$  |
| 5.0 $d$          | 1.5 $d$  |
| 5.0 $d$          | 2.0 $d$  |

There hasn’t been an equation to analytically calculate the cone angle of the conical basin. Dhakal and Trismilna [8] stated that the best cone angle for 800 mm diameter basin is 23°. The coefficient of discharge in strong vortex flows that can be used to determining the conical height ($h_d$) [7]:

\[ N_v = (0.686 - C_d)/0.218 \]  
\[ (N_v \cdot \sqrt{h_{in}})/\pi \right)^2 = h_d \]  
\[ C_d = \frac{4Q}{\pi d^2 \sqrt{2gh}} \]
2.2. Numerical method

The simulation of water vortex formation was carried out by using Ansys-FLUENT 18.1. First, the three types of basin geometry were prepared using computer-aided dimension (CAD). All the basin has the same geometry except for the geometry before water discharge. The basin was created with a diameter of 1000 mm with an outlet diameter of 300 mm, as calculated from the analytical results with a given condition flow rate of 160 L/s, total head available (H) of 2.71 m and an assumption of $\alpha$ equals to 2.79287. The first type of basin geometry was a basin with conical water discharge that has an angle of 60° (see Fig. 3). The second was a cylindrical water discharge (see Fig. 4) and the last is similar to the conical but the diameter and the height are smaller than the others (see Fig. 5). To fasten the computational process, the geometry was scaled to 10 times smaller [15].

After the geometry preparation has finished, mesh independency test should be performed to make sure that the result doesn’t deviate much anymore. The mesh independency test was performed using the first type of basin. Grid convergence index (GCI) method was used to get the optimum number of mesh to use [16]. Element numbers that were used for this test are 385120, 766597, 1501381, and 3137932 elements. Steady-state, multiphase (VoF), and transition-SST turbulence model were chosen to perform this simulation [7].

Since the multiphase (VoF) was used, there were two fluid phases; water and air. The constant surface tension between these fluids is 0.0728 N/m. The coupled scheme, body forced weighted pressure and second-order upwind were used in this simulation.

Figure 1. Geometry Parameters
3. Results and discussion

3.1. Analytical results.
Table 2 shows the calculation summary from Eq. (4) to (7) with the given experimental condition flow rate of 160 L/s and total head available (H) of 2.71m. The geometry results that were achieved from the analytical calculation needed to be scaled 10 times smaller to fasten the computational process. The model can be seen in Figure 3,4,5 which will be used for the numerical method.

Table 2. Geometry Parameters

| Parameter               | Value   |
|-------------------------|---------|
| Basin Diameter (D<sub>eff</sub>) | 1000 mm |
| Outlet Diameter (d)     | 300 mm  |
| Approach flow angle (α) | 40°     |
| Inlet Height (h<sub>in</sub>) | 333.33 mm |
| Channel Inlet (L)       | 1000 mm |
Figure 4. Basin with Conical Height of 20 mm and Cone Angle of 60° (Type B)

Figure 5. Basin with Conical Diameter of 50 mm, Conical Height of 20 mm, and Cone Angle of 45° (Type C)

3.2. Numerical result.
Mesh independency test was performed using Richardson extrapolation and achieved a result of viscous $x$ which estimated to be around -0.001242742.

| Mesh Number | Grid Spacing | Viscous $x$ | r   | p   | GCI (%) |
|-------------|--------------|------------|-----|-----|---------|
| 385120      | 2.85         | -6.6.E-04  | -   | -   | -       |
| 766597      | 2.02         | -1.2.E-03  | 1.41| -   | 7.467   |
| 1501381     | 1.45         | -1.2.E-03  | 1.40| 6.17| 0.820   |
| 3137932     | 1.00         | -1.2.E-03  | 1.45| 11.01| 0.018   |

A conclusion can be drawn from Table 3 that a grid spacing of 1.41 is accurate enough to be used for CFD simulation since there was an error only around 0.11%. The meshing elements are 1.5 million with a maximum face size of 9.4 x 10^{-4} mm is used.
After mesh independency check was done, the CFD simulation can be run directly for all type of basin, and the results achieved are compared with each other. In this study, velocity and pressure parameters were used to decide which type of basin form a good water vortex formation.

Figure 6 showed that the highest velocity ratio can be achieved using a conical basin (type B). Conical basin (type B) can achieve over 6 times from its average velocity at inlet. Although the cylindrical basin (Type A) also reach a high ratio, the distribution of velocity isn’t spread evenly enough compared to the other two. If the water vortex isn’t spread evenly, there will be eddies from along the vortex formation (can be seen in Figure 9).

![Figure 6. Velocity w Distribution on Outlet](image1)

A velocity w contour will help to visualize what kind of water vortex is formed. Figure 7, 8, and 9 visualized a contour to see the even spread velocity profile. Figure 10 visualized that the center of the vortex is shifting a little bit causing the pressure or velocity isn't spread evenly enough.

![Figure 7. Velocity w Contour of Conical Basin (Type B)](image2)
Figure 8. Velocity w Contour of Conical Basin (Type C)

Figure 9. Velocity w Contour of Cylindrical Basin (Type A)
3.3. Discussion.
From the numerical result, it is concluded that the conical basin (type B) can achieve the highest and the even spread of velocity. Highest velocity is needed because if velocity gets higher, the pressure will drop gradually. Velocity gets higher gradually until its’ peak when it reaches the outlet. This will make a pressure difference and make a suction effect which forms a strong water vortex formation. From Figure 7, type C basin has a very similar velocity profile compared to type B basin. Both of the velocity profile almost spread evenly enough. From Figure 7, 8, 9, and 10, the shifting that happened at the core of the water vortex can be seen clearly. This shifting was estimated at around 5.56 mm from x and z-axis can be seen in Figure 10.

This result was quite similar to many previous studies which stated that conical basin (Figure 4) creates an even spread of velocity which causes strong water vortex formation compared to another basin which can be seen in Figure 7, 8, and 9. Even if the conical angle wasn’t the same as Dhakal et al. [8], a strong water vortex formation can still be achieved.

4. Conclusion
This study concluded that the conical basin (type B) forms the best water vortex formation compared to others. This study also shows that water discharge geometry is an important parameter which greatly affects the water vortex formation on GVHP. The shifting phenomenon indicates that the outlet shouldn’t be in line with the center of the basin to achieve a balance water vortex formation. However, experimental studies are still needed to prove whether that conical basin forms the best water vortex formation.

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References

[1] W. Indonesia, “Ultimate in Diversity,” 2018.
[2] “Statistik Ketenagalistrikan T.A 2017,” 2018.
[3] B. Ho-Yan, “Design of a low head pico hydro turbine for rural electrification in Cameroon.” 2012.
[4] Rahman MM, Tan JH, Fadzlita MT, Muzammil AW. A Review on the development of Gravitational Water Vortex Power Plant as alternative renewable energy resources. InIOP Conference Series: Materials Science and Engineering 2017 Jul (Vol. 217, No. 1, p. 012007). IOP Publishing.
[5] IRENA (2017), Renewable Energy Prospects: Indonesia, a REmap analysis, International Renewable Energy Agency (IRENA), Abu Dhabi, www.irena.org/remap., no. March. 2017.
[6] Nishi Y, Inagaki T. Performance and flow field of a gravitation vortex type water turbine. International Journal of Rotating Machinery. 2017;2017.
[7] Mulligan S. Experimental and numerical analysis of three-dimensional free-surface turbulent vortex flows with strong circulation. Ireland: Institute of Technology Sligo. 2015 Sep.
[8] Dhakal S, Timilsina AB, Dhakal R, Fuyal D, Bajracharya TR, Pandit HP. Effect of dominant parameters for conical basin: Gravitational water vortex power plant. InProceedings of IOE graduate conference 2014 (p. 381).
[9] Marian MG, Sajin T, Azzouz A. Study of Micro Hydropower Plant Operating in Gravitational Vortex Flow Mode. InApplied Mechanics and Materials 2013 (Vol. 371, pp. 601-605). Trans Tech Publications.
[10] Rahman M, Hong TJ, Tang R, Sung LL, Tamiri FB. Experimental Study the Effects of Water Pressure and Turbine Blade Lengths & Numbers on the Model Free Vortex Power Generation System. International Journal of Current Trends in Engineering & Research (IJCTER). 2016;2(9):13-7.
[11] Mulligan S, Casserly J, Sherlock R. Effects of geometry on strong free-surface vortices in subcritical approach flows. Journal of Hydraulic Engineering. 2016 Jul;142(11):04016051.
[12] Shabara HM, Yaakob OB, Ahmed YM, Elbatran AH. CFD simulation of water gravitation vortex pool flow for mini hydropower plants. Jurnal Teknologi. 2015 Mar 25;74(5).
[13] Power C, McNabola A, Coughlan P. A parametric experimental investigation of the operating conditions of gravitational vortex hydropower (GVHP). Journal of Clean Energy Technologies. 2016 Mar;4(2):112-9.
[14] Timilsina AB, Mulligan S, Bajracharya TR. Water vortex hydropower technology: a state-of-the-art review of developmental trends. Clean Technologies and Environmental Policy. 2018 Oct 1;20(8):1737-60.
[15] Heller V. “Model-Prototype Similarity,” 4th Coastlab Teaching School, Wave and Tidal Energy, no. January, pp. 17–20, 2012.
[16] Phillips TS, Roy CJ. Richardson extrapolation-based discretization uncertainty estimation for computational fluid dynamics. Journal of Fluids Engineering. 2014 Dec 1;136(12):121401.