Effects of Inlet Flow Rate and Penstock's Geometry on the Performance of Gravitational Water Vortex Power Plant

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Abstract

Gravitational Water Vortex Power Plant (GWVPP) is one of the green technology that utilizes hydropower at low hydraulic head. Different from large-scale hydropower, GWVPP is a micro hydropower plant that harvest energy from water vortex formed in a cylindrical basin. It is advantageous due to its low hydraulic head requirement as well as positive impacts on both environments and social. Experimental approach was taken in this paper to study the effects of inlet flow rate and penstock's geometry of GWVPP on performance of GWVPP. The outlet and basin diameter were fixed at 72mm and 400mm respectively. Inlet flow rates were varied from 5.6m^3/h to 8.8m^3/h while three penstock model A to C have increasing feeding width but same model length while penstock D to F have same feeding width as penstock A but reducing model length. It was discovered that penstock B and C reduced the overall performance of GWVPP while the rest of the penstock have insignificant effects on GWVPP's efficiency. Also, higher inlet flow rate was also discovered to generally increase the efficiency of GWVPP. Future works will involve changing the outlet's diameter as well as elevating the penstock to study its effect on GWVPP's performance.

Keywords
GWVPP, hydropower, vortex

1. Introduction

Hydropower has been one of the most preferred renewable energy resources along with solar and wind energy. This is because at least 71% of earth is covered by water surface. Besides that, it is also one of the cheapest energy source with zero carbon emission. According to Key World Energy Statistics (2017), the world hydro electricity production increased from 1,296 TWh to 3,978 TWh in year 1973 and 2015 respectively. Norway topped the list of domestic hydroelectricity production with 95.9%. (International Energy Agency, 2017)

Hydropower can be divided into a few scales where large scale hydropower involved the construction of huge dam and smaller scale hydropower operates on the hydrostatic or kinetic energy available in the run-of-the-river stream or even wastewater network. Even though large-scale hydropower is able to produce electrical power up to 22,500 megawatts (USGS Water Science School, n.d.), the negative impacts environmentally and socially is significant. Best alternative to avoid the negative impacts would be the development of hydropower at smaller scale. Gravitational Water Vortex Power Plant (GWVPP) fits the criteria as micro hydropower plant.

Franz Zotloterer discovered and invented GWVPP back in year 2006 when he was looking for ways to aerate inactive streams. The discovery of GWVPP made a new milestone in hydrodynamic development because he managed to aerates inactive water so that oxygen saturation in the water increases energy free. Other than that, GWVPP also has very low hydraulic head requirements, causing it to increase attention from researchers. Such requirements actually promote the possibility of implementation at rural areas with water streams or rivers.

A GWVPP consists of a penstock which is connected to a cylindrical basin tangentially. At the central bottom of the basin, a circular outlet is presents. The water from river will be directed into the penstock. Following the penstock, the water will be forced to enter the basin tangentially and exits through the central outlet at the bottom of the basin. The water the exits through the outlet will be directed back into the river through another penstock. Due to the shape of the basin, the water will be forced to travel in circular motion, thus creating water vortex. In order to harvest the energy available in the water vortex, a turbine is placed at the center of the basin. The water vortex in touch with the turbine's blades will force the turbine to rotate in its place, thus driving the generator attached to the turbine. Generator will then convert the obtained energy into electrical energy which will be distributed to houses later. Up to date, the largest GWVPP was developed in Switzerland by GWWK. They claimed to produce annual electrical output between 80,000 kWh and 130,000 kWh. (Christine Power et. al., 2016)

2. Literature Review

Generally, past literatures related solely to GWVPP can be divided into a few categories according to the research interests such as turbine, basin, inlet and outlet developments. Other than that, without the presence of turbine, the research on water vortex formation through similar configurations were carried out as well.

2.1 Turbine Development

As one of the most vital component for GWVPP, turbine development has been the hot topic among researchers in the same field. This is because at the moment, the turbines on the market are not suitable to be used by GWVPP due to the nature and motion of water vortex. Earliest publication that can be tracked is by Marian et. al. (2012) where different sizes Francis turbines at different level of depths were tested through simulation to determine the effects of basin's geometry on GWVPP's performance. It was discovered through simulation and theoretical modelling, that vortex formed was proportional with the rotational speed. The presence of turbine was also found to reduce the vortex height significantly while reducing the efficiency of GWVPP. (Marian et. al., 2012) In next year, Marian et. al. (2013) published two papers in different journals for their contribution towards the development in GWVPP theoretically and experimentally. They found that maximum exergy can be extracted if the turbine was installed near the basin's outlet. The mathematical model that they developed claimed to be able to reach hydraulic efficiency of 90% to 95% with conditions. Subash Dhakal et. al. (2014) found that the performance of GWVPP decreased as the number of blades of specially designed turbine increased from six to twelve while Christine Power et. al. (2016) found otherwise. According to Christine Power et. al. (2016), the performance of GWVPP increased with the increased number of turbine's blades from two to four. Such findings indicated the possibilities of the existence of optimal number of blades for GWVPP's turbine. Its also possible that the findings were different due to difference in turbine's design where Subash Dhakal et. al. (2014) used curved blades while Christine Power et. al. (2016) used flat blades. Besides the opposite finding, Christine Power et. al. (2016) also claimed that highest recorded efficiency of 15.1% was obtained with two of the turbine with large blade's size. According to them, resistance force required to stop the turbine with huge blade was higher, causing the turbine's power output to increase. Sagar Dhakal et. al. (2015) discovered experimentally that the position of turbine should be placed approximately 65% to 75% of total basin's height in order to achieve optimum GWVPP performance. Such findings validated findings by Marian et. al. (2013). They also claimed that conical basin was better than cylindrical basin in terms of overall performance. Aravind Venukumar (2013) designed the turbine to consists of eight inverted cone-shaped blades and provided theoretical calculations for power extraction from his design. Sritram P et. al. (2015) carried out studies to determine the effects of turbine's materials on the performance of GWVPP. They found that aluminum made turbine performed better than steel turbine at increasing electrical loads and flow rates. Wichian and Suntivarakorn conducted experimental study on the effects of baffled turbine's blade on the performance of GWVPP. It was found that 50% baffled turbine performed better compared to unbaffled turbine. They also concluded that torque and efficiency of GWVPP increased with increased inlet flow rates from $0.04m^3/s$ to $0.06m^3/h$.

2.2 Inlet and Outlet Development

The inlet flow rate of GWVPP is in charge of increasing the height of vortex, which affects the potential power available in GWVPP. Different outlet diameter will also affect the performance of GWVPP. Mulligan and Hull (2010) suggested that the optimal vortex strength can be obtained when the ratio of outlet's diameter to basin's diameter is between 0.14 to 0.18. Wanchat et. al. (2013) also carried out similar experiments and obtained efficiency of 30% when the ratio between outlet and basin diameter is 0.2 to 0.35. They are unable to get any results when the ratio is less than 0.2 and more than 0.35, claiming that water vortex cannot overcome the mechanical friction and electrical load of the system at lower ratio while low water level caused the torque to be insufficient at higher ratio. Shabara et. al. (2013) published two papers on the same years where first paper was about simulation study and second paper was regarding experimental study to validate the previous paper. From simulation results, it was discovered that the outlet's discharge speed was inversely proportional to the outlet's diameter. Also, at highest water height, the outlet's discharge velocity was maximum, which was validated by the experimental studies that they carried out and written in second paper of that year. Christine Power et. al. (2016) also discovered that higher inlet flow rate was associated with better GWVPP's performance. Other than that, the optimal water inlet height was found to be one-third of the basin's height. Sreerag S. R. et. al. (2016) discovered through simulations that the tangential velocity maximized when outlet's diameter increased from 100mm to 300mm. They also reproduced Wanchat and Suntivarakorn (2012) CFD model and validated their CFD results with 2% errors. They concluded the optimal outlet diameter to be 30% of basin's diameter.

2.3 Basin Development

Basin is where the water vortex formation takes place. It is therefore one of the most important component for GWVPP. Wanchat and Suntivarakorn (2012) conducted simulations with three different basin's designs. They concluded that cylindrical basin with inlet guide was the most suitable basin due to its capability to provide uniform velocity. Sagar Dhakal et. al. (2014) also conducted simulations on cone-shaped basin where water vortex's velocity was determined theoretically. They concluded that penstock's feeding width, basin's cone angle and height of penstock from the bottom of the basin have the most significant effects on the vortex's velocity. The penstock's feeding width was suggested to be as small as possible while the cone angle and height of penstock were suggested to be as high as possible to maximize GWVPP's performance. Length of penstock was also recommended to be as long as possible to prevent losses. Kueh et. al. (2014) also discovered that the height of water vortex increased with the increase in height of the inlet. They also conducted simulations to study the formation of vortex surface profile. Sajin and Marian (2013) deduced several theoretical models for GWVPP with cone-shaped basin. They presented theoretically, the flow fields in the boundary layer, velocity distributions in the vortex zone, as well as describing the free surface vortex through equation. Chattha J. A. et. al. (2017) presented numerical analysis on the basin's geometry through CFD simulation. They discovered that tangential velocity increased with the formation of air core in the water vortex. Besides that, the tangential velocity also maximized when water entry in the basin is slightly above the water height and basin's diameter increased up to a certain extent.

2.4 Free Surface Vortex

Vortex strength has major effects on the performance of GWVPP because it is the main factor that decides the potential power that the turbine can harvest. Therefore, the study of water vortex is very important. However, in-depth studies on the topic of water vortex involved a lot of complicated parameters as shown in PhD dissertation of Sean Mulligan (2015). The study of water vortex itself involved high-end equipment to capture the movement of water particles to capture the tangential velocity of water vortex that is directly proportional to the vortex strength as shown in Equation (1). Other than that, different basin's geometry was also found to change the vortex properties. Sean Mulligan published many papers regarding the formation of vortex and he managed to construct many mathematical models that were validated by his own experiments. In order to keep the clarity of this paper, details about Sean Mulligan's findings will not be focused here. Interested readers are suggested to look for his publications at the reference section of this paper.

$$v = \frac{\Gamma}{2\pi r} \tag{1}$$

3. Methodology

In this study, an experimental methodology was used. A laboratory scale GWVPP was designed and fabricated based on past literatures. The fabricated GWVPP is shown in Figure 1.

Figure 1. Laboratory scale GWVPP

3.1 Experimental Setup

The prototype fabricated consists of a cylindrical basin with a ring-shaped outlet at the central bottom of the basin. A penstock is connected tangentially to the basin as shown in Figure 2. At the center of the basin, approximately 0.016m above the bottom of the basin, a vertical axis turbine with three flat blades was placed. Connected to the penstock is a reservoir where water is collected before flowing into the penstock. A tank was situated at the bottom, aligned to the outlet of the basin, to collect the discharged water. The water collected will be pumped up to the reservoir by using a water pump. In order to find out the power output of the system, a prony brake system was used.

The prony brake system used involve a rotating drum, belt, spring balance as well as loads (as shown in Figure 2). The rotating drum with 0.055m radius was connected to the shaft of the turbine while the belt was wrapped around the rotating drum. At one end of the belt, a spring balance was placed, with its one end attached to immovable stainless-steel plate. At another end of the belt, hanging slotted weights were placed. The slotted weights will tighten the belt, causing tension and increasing resistance force on the rotating drum. The resistance force can be found by taking the difference between the spring balance reading and loads.

The water inlet flow rate was measured using a non-digital flow meter and controlled via inlet valve manually as well. The turbine's rotational speed, ω, was measured using a tachometer.

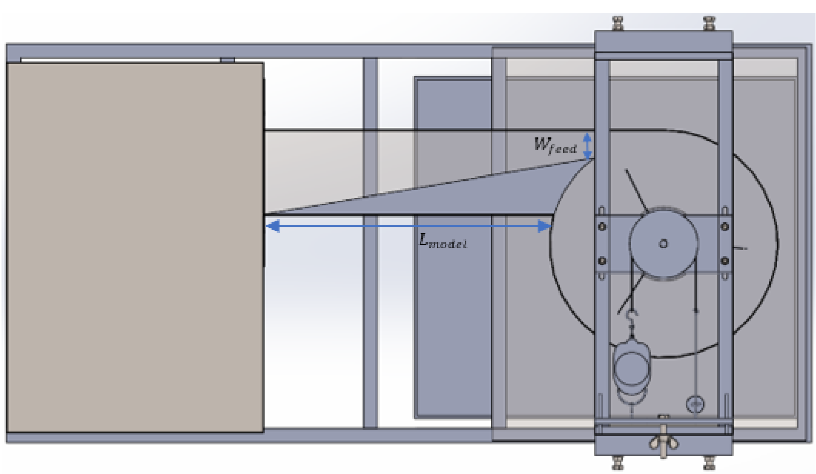

Figure 2. Top view of GWVPP prototype

3.2 Experimental Configuration

In this paper, focuses will be given to the direct effects of varied inlet flow rates and penstock's geometry onto the efficiency of GWVPP. The design of the laboratory scale GWVPP was as follows:

Table 1. Experimental Configuration

Basin	Diameter	0.4m
	Height	0.5m
Outlet	Diameter	0.072m
Turbine	Type	Flat blade vertical axis
	Number of blades	3
	Radius	0.146m
Rotating Drum	Radius	0.055m

The two parameters to be investigated are inlet flow rates and penstock's geometry. In the experiments, the inlet flow rates varied were 5.6m^3/h, 6.4m^3/h, 7.2m^3/h, 8.0m^3/h and 8.8m^3/h. As for the penstock's geometry, there were six different design for the geometry of penstock. Penstock A, B and C will have same L_{model} but different W_{feed} while Penstock D, E and F have same W_{feed} but different L_{model}. The dimensions of the penstock models can be found in Table 2.

Table 2. Penstock models dimension

Penstock	L_{model} (m)	W_{feed} (m)
A	0.513	0.040
B	0.513	0.065
C	0.513	0.090
D	0.385	0.040
E	0.257	0.040
F	0.128	0.040

3.3 Experimental Procedure

According to Christine Power et. al. (2016), prony brake at different loads provide different efficiency. Therefore, it was necessary to carry out tests to find out the maximum achievable efficiency of that particular configuration. The experiment started with the installation of Penstock A and the water inlet flow rate was adjusted to 5.6m^3/h. Once the water height, H, stabilized, the belt was strapped onto the rotating drum and the load of 0.020kg was hanged. The rotational speed of the turbine as well as the height of the water would start to reduce. Once both parameters stopped changing, the rotational speed of the turbine, the height of water, and the spring balance reading were recorded. After that, the load will be increased by 0.020kg and the necessary measurements were taken once the system stabilized. The process of adding loads was repeated until the turbine stopped rotating completely.

After the measurements at different loads for first configurations were taken, the water inlet flow rate was increased to 6.4m^3/h. The mentioned procedures were then repeated until maximum loads were applied so that the turbine stopped rotating. The water inlet flow rates were adjusted until 8.8m^3/h.

Once the measurements for Penstock A under five varied flow rates were recorded, the configurations were then changed to Penstock B and the procedures were repeated from increasing loads at constant flow rates to increasing the flow rates until 8.8m^3/h. These procedures were repeated for every penstock models.

3.4 Calculations

In order to find out the efficiency of the laboratory scale GWVPP, the following formula were used.

$$Efficiency\ of\ GWVPP, \eta = \frac{Power\ output}{Power\ input} \times 100\% \quad (2)$$

$$Power\ output, P_{out} = \tau\omega \quad (3)$$

$$Power\ input, P_{in} = \rho g Q H \quad (4)$$

where
Torque of rotating drum = $\tau = (W_{spring\ balance} - W_{load})gr$
Rotational speed of rotating drum = ω
Density of water = ρ
Inlet flow rate = Q
Height of water = H

4. Results and Discussion

4.1 Inlet Flow Rate

From the experiments, as the inlet flow rates increased from 5.6m^3/h to 8.8m^3/h, it was found that the efficiency of GWVPP increased polynomially. Referring to Figure 3, it was obvious that the performance of GWVPP improved along with increased inlet flow rate even with different penstock models. This is because as the inlet flow rates increased, the height of water increased. In accordance to equation (4), increase in both height of water and inlet flow rates causes the power input to increase. This means higher power is available for extraction, hence improving the performance of GWVPP. This finding validated findings of P. Sritram et. al. (2015), where they found that the performance of GWVPP improved with increasing inlet flow rates. According to the authors, both iron and aluminum made turbine showed improvement in GWVPP performance when inlet flow rates were increased at different electrical loads.

Overall, the performance of GWVPP was found to peaked when the inlet flow rates were between 8.0m^3/h and 8.8m^3/h for all penstock models. The trends, however, showed that the optimal inlet flow rate is more than 8.8m^3/h. Also, Penstock D and E gave positive polynomial trends. It is suspected that such trends were caused by inaccuracy in measurements due to the equipment used such as inlet flow meter and prony brake. Other than that, majority of the penstock showed peak performance between inlet flow rate of 8.8m^3/h and 9.6m^3/h.

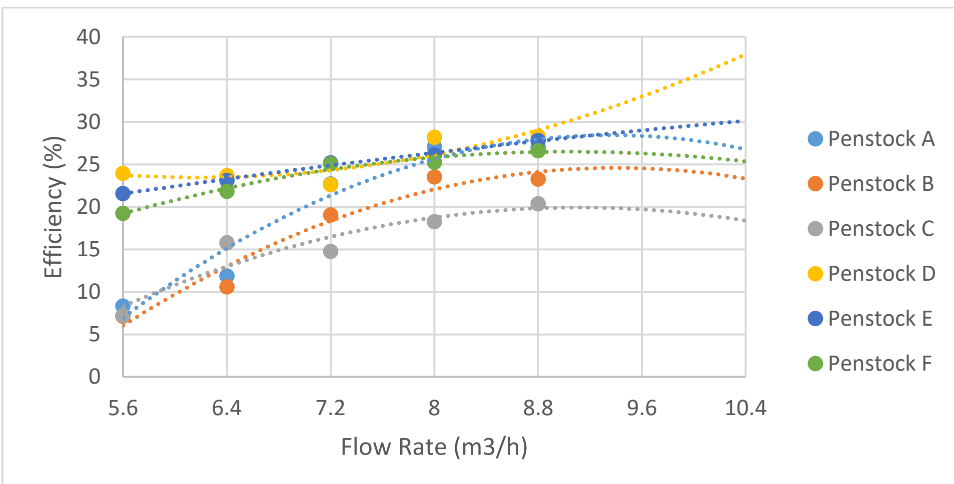

Figure 3. Efficiency of GWVPP with different penstock's geometry

4.2 Penstock Geometry

According to Figure 3, the penstock geometries were found to have significant effects on the performance of GWVPP especially when the W_{feed} increased. Penstock B and C with 0.065m and 0.090m of W_{feed} respectively recorded lowest efficiency across the inlet flow rates. These results are expected because as the W_{feed} increases, the velocity of water should increase. The water exiting the penstock was directed tangentially into the basin. Therefore, the velocity of water exiting the penstock became the tangential velocity of the water vortex. According to equation (1), the strength of vortex, Γ is directly proportional to the tangential velocity, v of the water vortex. Even though at the moment there's still no proper formula to relate the strength of vortex to the power available in the vortex due to uncertainties, the indirect relationship between them is proved in this paper. Reducing the width of penstock feeding width, W_{feed} will increase the tangential velocity, hence increasing the power output and improving the performance of the laboratory scale GWVPP. Sagar et. al. (2014) actually pointed through simulation that increasing W_{feed} will increase the tangential velocity of water vortex.

The performance of turbine when Penstock D, E and F was installed are almost similar. This means that the length of the penstock model, L_{model} have no effects on the performance of turbine. According to Newton's first law of motion, object will remain at rest or in uniform motion in a straight line unless compelled to change its state due to external forces. With that in mind, Penstock A, D, E and F should show significant difference in performance of GWVPP with Penstock A being the most efficient penstock while Penstock F will be the most inefficiency penstock. This is because Penstock A resembles a smooth track for water to travel along the wall with minimal change in motion's path. On the flip side, Penstock D, E and F have shorter L_{model} which resembles obstacle that force the water to change its path when water travelled in straight line. Due to the change in motion's path, energy losses are expected in many forms such as collisions and turbulence. Such losses should then cause the strength of water vortex to reduce.

For the results to not behave as expected, a few speculations have been made. First of all, the equipment used to take measurements need higher accuracy. Besides that, the length of penstock without the model is too short to provide significant energy loss. Or, the energy losses are so insignificant that the energy losses are negligible. Hence, more studies are necessary by using better equipment and larger prototype scale in order to make significant impact on the development of penstock for GWVPP.

5. Conclusion

In a nutshell, the maximum achievable efficiency was found to be 28.29% when Penstock E was installed along with inlet flow rate of $8.8m^3/h$. The power output of the configuration was also highest compared to other configurations. Also, it was found that peak performance of the prototype is between $8.0m^3/h$ to $9.6m^3/h$. However, such finding requires validation because the experiments carried out did not include inlet flow rate of $9.6m^3/h$. Other than that, it was also determined that the smaller the penstock's feeding width, the higher the efficiency of GWVPP.

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