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A Review on the Development of Gravitational Water Vortex Power Plant as Alternative Renewable Energy Resources

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Abstract. Gravitational water vortex power plant is a green technology that generates electricity from alternative or renewable energy source. In the vortex power plant, water is introduced into a circular basin tangentially that creates a free vortex and energy is extracted from the free vortex by using a turbine. The main advantages of this type of power plant is the generation of electricity from ultra-low hydraulic pressure and it is also environmental friendly. Since the hydraulic head requirement is as low as 1m, this type of power plant can be installed at a river or a stream to generate electricity for few houses. It is a new and not well-developed technology to harvest electricity from low pressure water energy sources. There are limited literatures available on the design, fabrication and physical geometry of the vortex turbine and generator. Past researches focus on the optimization of turbine design, inlets, outlets and basin geometry. However, there are still insufficient literatures available for the technology to proceed beyond prototyping stage. The maximum efficiency obtained by the researchers are approximately 30% while the commercial companies claimed about 50% of efficiency with 500W to 20kW of power generated. Hence, the aim of this paper is to determine the gap in the vortex power plant technology development through past works and a set of research recommendations will be developed as efforts to accelerate the development of GWVPP.

1. Introduction

Electricity plays an important role in human community's daily life especially when most of the household appliances are replaced with mechanized robots or machines. British Petroleum (BP) statistical report 2016 shows that the global primary energy consumption increased by 1.0% from year 2014 to year 2015. Globally, about 32.9% consumed energy was from fossil fuels, mainly from oil. The contribution of renewable energy was still very small which was about 213 terawatt-hours only [22]. Many types of renewable energy sources such as wind, hydro, solar and etc. are used all over the world to generate electricity. The generation cost depends on the energy sources and conversion technology. Among all the sources, most economical abounded source is hydro power but the global hydro power output grew by 1% only, which is below the 10-year average of 3% [22]. The most well-known method of generating electricity from hydro power is by creating an artificial lake and develop it into large dam in river pathway. The environmental impacts of this type hydropower plant are significant and therefore reassessment of construction is necessary [26][27][28]. Micro-hydro and mini-hydro power plant can be used to generate electricity at small scale but this type of power plants requires high potential energy head to run the turbine [29]. An alternate option to harvest energy from low head water sources is essential to meet the growing demand of electricity as well as encourage new investor in this field. One of suitable proposal for electricity generation from hydro source is Gravitational Water Vortex Power Plant (GWVPP) [1].

1.1 Gravitational Water Vortex Power Plant
Gravitational Water Vortex Power Plant is a type of green technology that falls in the category of micro hydro power plant. It is currently being categorized as micro hydropower because the maximum reported power generation had not exceeded 100kW [23]. The main advantage of this power plant is the ultra-low hydraulic head requirement [10] as well as environmental friendly [1]. In this plant, the water passes through a large, straight inlet, which then passes tangentially into a round basin. The water will then form a powerful vortex, which exits the outlet at the centre bottom of the shallow basin. Due to its ultra-low hydraulic head requirement, the plant does not work on the pressure difference but on the dynamic force generated by vortex [1][2]. Hence, the development and power generation costs are very low in the GWVPP compared to other hydro power technologies. This type of power plant has found to be advantageous due to the following properties of water vortex:

- Increases the surface area of water [3]
- Maximizes the velocity of flow on the surface area of water [3]
- Disseminates homogenously contaminants in the water. [3]
- Increases the contact surface of the disseminate contaminants for microorganisms and water plants. [3]
- Aerates the water naturally due to the high velocity of flow on the water surface area and the increased water surface area to support the self-purification of water with microorganisms and water plants. [3]
- Increases the head of evaporation so that water can reduce the temperature itself at rising temperatures in the summer. [3]
- Builds up a peripheral zone of ice in the winter to isolate the centre of the vortex. [3]
- Concentrates dense water in the ring-shaped centre to ensure the survival of microorganisms as long as possible. [3]
- Decelerates the flow of water so that is can be used as an active retention pond [3]
- Improves the dissolved oxygen concentration

2. Literature Review

2.1 Turbine
Turbine is one of the most vital components for GWVPP. It is positioned at the centre, aligned with the central outlet of the basin. The turbine is forced by the water power that came from the water vortex. Most of the researches focused on optimization of turbines to increase the efficiency of the plant [3][4][5][6][7][8][9]. The earliest publication regarding GWVPP is by Marian et. al. in the year 2012 [3]. The main aim of their research is to determine the effects of basin's shape on turbine's performance. Different sizes Francis turbine at different level of depths is a valid option for GWVPP. From the simulation, it is also found that cavern (vortex) formed was proportional with the rotational speed without the presence of turbines in the system but at presence of turbine, the cavern height changed significantly as well as lowering the efficiency [3]. According to Subash Dhakal et. al., as the number of blades of turbine increased from six to twelve, the efficiency of the GWVPP reduced [6]. However, Christine Power et. al. found that the efficiency increased with the increased number of blades from two to four. The opposite findings by both groups of researchers indicate that there might be an optimal number of blades for turbine [9]. The concept of GWVPP is not well established yet therefore different researchers are using different types of vortex turbine plant for their investigation [1][3]. Sagar Dhakal et. al. only simulated different physical parameters of basin of GWVPP therefore validation the results are still questionable. They found that maximum vortex velocity for both cylindrical and conical basin is highest when the position is nearest to the outlet of the basin. However, the argument was made based on CFD modelling results only. The efficiency of conical

basin of GWVPP is also found to be higher than that of cylindrical basin at the same position of turbine [7]. Another researcher, Subash et. al. [6] in the year 2014 also conducted several tests at Manohara River located at Pepsicola, Kathmandu and found that the vortex strength in conical basin is stronger than that of cylindrical basin. In the year 2013, Marian et. al. conducted experiments on vortex turbine power plant by using three different turbines and installed it at different heights in the conical basin [4][30]. According to them, the maximum exergy can be harvested if the turbine is installed at near the outlet of the basin. The experimental results are validated with the theoretical analysis and claimed to be in good agreement by considering free vortex flow where variables are considered from flow, speed and power characteristics [4][30]. Since the blade profile has not been considered during the analysis of the efficiency of the turbine, it is recommended as future research. In the year 2013, Aravind Venukumar generated electricity by using Artificial Vortex power generator which consists of eight inverted cone design blades. The prototype managed to produce more than 150W of electricity [5]. In order to improve the efficiency of GWVPP, study also shows that researchers should focus on turbine's materials to reduce weight, maximize flow rates by optimize canal and notch angle as well as outlet diameter [6]. Sritram P et. al. also managed to prove that GWVPP with aluminium turbine has higher efficiency at different loads and flow rate when compared to steel turbine. Besides that, the higher the electrical loads, the lower the efficiency [8]. In the year 2016, Christine Power et. al. found that parameters including turbines, inlet height and flow rates have significant effects on the efficiency when vertical axis turbine with different blade sizes are used in vortex power plant. A total of nine configurations of turbines were prepared with different sizes and blade numbers. The overall efficiency of the vortex power plant was varied from 15.1% to 25.36% depends on the geometry of the basin, volumetric flow rate, turbine position and blade geometry and number [9].

2.2 Inlet and Outlet Configurations

For GWVPP, the inlet flow rates are the water that is released into a channel connected to the basin. The channel is responsible to direct the water flow into the basin tangentially. It can be horizontal or slanted at desired angle. The channel width between two ends could be different or the same. One of the study that will be mentioned below also shows that the inlet of GWVPP could be in the form of pipe instead of channel [9][19]. The inlet height has two meaning, first one deals with the height of water while another one indicate the height of channel from the bottom of the basin. The inlet and outlet parameters are shown in Figure 1 and Figure 2.

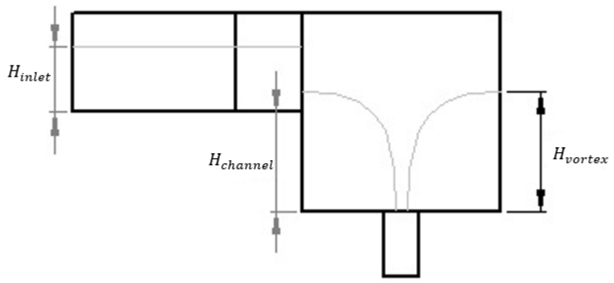

Figure 1. Gravitational Water Vortex Power Plant side view

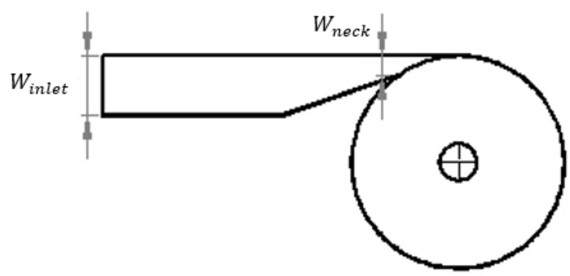

Figure 2. Gravitational Water Vortex Power Plant top view

Figure 2 shows that the outlet was usually at the centre of the basin and its diameter has significant affect on vortex strength as well as efficiency of vortex turbine [10][11][12].
Wanchat et. al. [10] studied the effects of outlet diameter varied from 0.10m to 0.40m on the efficiency of vortex turbine. The inlet velocity was set at 0.1m/s and the inlet channel was converged at the end which was connected to the basin. A five blades vertical axis turbine was used for electricity generation. It is found that the outlet diameter within the range from 0.20m to 0.35m has significant effect on power generation. The overall efficiency was reported as 30%. Shabara et. al. [11][12] conducted simulation and experimental studies. The GWVPP's $H_{channel}$ was zero. The simulation results showed that the outlet speed was inversely proportional to the outlet diameter. For the highest H_{inlet}, the outlet velocity was also maximum, which matched with the experimental results [11][12]. The inlet flow rate has significant effects on efficiency. The efficiency of the vortex turbine is directly proportional to the inlet flow rate and the optimal $H_{channel}$ was one-third of the basin's height [9].

2.3 Basin Configurations
Depending on the design of the basin of GWVPP, the vortex profiles created will be different. Wanchat and Suntivarakorn conducted research through simulations with three proposed designs which were 1) cylindrical basin with central outlet, 2) rectangular basin with pre-rotation and 3) cylindrical basin with inlet guide. It was observed that cylindrical basin with inlet guide was the most suitable basin since it provides better and more uniform velocity compared to others [13]. Dhakal et. al. conducted studies with conical basin instead of conventional cylindrical basin. Vortex velocity was measured for different basin diameter, notch angle, notch inlet width (W_{in}), cone angle and canal height ($H_{channel}$) and it is found that W_{in}, cone angle and $H_{channel}$ have the most significant effects on the vortex velocity. The value of W_{in} was suggested to be as small as possible on the other hand the cone angle and the $H_{channel}$ were suggested to be as high as possible to maximize the performance. Notch length (length of inlet channel) is also recommended to be kept as long as possible to prevent unwanted loses [14].

2.4 Free Surface Vortex
The vortex strength has major effects on the efficiency of the vortex turbine. The strength of the free vortex is weak and creates shallow vortex profile, therefore optimization is required for maximum power generation. The conventional theoretical model can't be used for theoretical analysis since it was developed based on weak air-core vortices above hydraulic intakes [15][16][17].
Sajin and Marian [4] lead the study on free surface vortex by developing theoretical models of the vortex formed in a conical basin. The vortex flow structure can be identified as air cavern (air core of the vortex), forced vortex (area between the surface of the water vortex and free vortex), free vortex (area between forced vortex and boundary layer) and boundary layer (water near the wall of basin). The theoretical model of boundary layer thickness obtained by Sajin and Marian [4] was

$$\delta(R) = \frac{R_0}{\left(\frac{\Gamma}{2\pi \sin(\frac{\alpha}{2})}\right)^{1/2}}\left[4.38\left(1-\frac{R}{R_0}\right)^{1.75} - 9.36\left(1-\frac{R}{R_0}\right)^{1.37} + 5.8\left(1-\frac{R}{R_0}\right)^{0.57} + 1\right] \tag{1}$$

The theoretical model was presented graphically and discussed. Theoretical modelling for forced vortex was described as

$$\frac{p}{\rho} = \frac{\omega^2 r^2}{2} - \frac{\gamma^2}{8} r^2 + \frac{\gamma^2}{2} z^2 - gz - \frac{\sigma}{\rho r} + constant \tag{2}$$

and free surface vortex was modelled as

$$z(r) = \frac{g - [g^2 - 2\gamma^2\left(\frac{\omega^2 r^2}{2} - \frac{\gamma^2}{8}r^2 - \frac{\sigma}{\rho r}\right)]^{1/2}}{\gamma^2} \quad (3)$$

Simulations were carried out to study the water flow in the basin with and without turbine. It was observed that the presence of turbine had huge effect on the vortex flow. Sean Mulligan et. al. [15] found that most of the free-surface vortices were generally in the context of "weak" vortices at hydraulic intakes. Sean et. al. [15] conducted analytical, theoretical and experimental studies on the free-surface vortex. For an ideal vortex model, the flow was classified as irrotational and the tangential velocity profile was described as

$$v_\theta = \frac{\Gamma}{2\pi r} \quad (4)$$

However, for real Newtonian fluid, viscosity must be accounted for. According to Rankines model improved by Vatistas et. al. (1991), Sean et. al. [15] managed to form the expression to describe the radial distribution of the free surface vortex.

$$H_\Delta = \frac{1}{g}\left(\frac{\Gamma}{2\pi}\right)^2 \left(\frac{1}{{r_{in}}^2} - \frac{1}{{r_r}^2}\right) \quad (5)$$

where r_{in} and r_r are radii at the inlet and at an arbitrary radius in the vortex. H_Δ is the height difference between these radii. Sean et. al. [16] [17] continued research on vortex experimentally and develop a surface profile model for open channel flow in the vortex chamber (basin). The theoretical discharge can be calculated from the following equation for a strong free-surface vortex.

$$Q = \frac{\pi}{4} d^2 (1-\lambda)\left(2gE - \frac{4\Gamma^2}{d^2\lambda}\right)^{1/2} \quad (6)$$

Sean [16] also designated dimensionless number, β as the ratio of the inlet radius from the shaft center to the inlet flow cross section. Experiments were carried out for different β value and it was found that for larger β value, discharge head rate was lower but the circulation of the vortex increases as the β increases. Circulation of vortex can be determined from the following equation.

$$\Gamma_n = \frac{4.9972}{{K_1}^{1.002}} \cong \frac{5\beta d}{h} \quad (7)$$

Study showed that higher h/d creates stronger tangential velocity as well as stronger vortex. The flow rate and tangential velocities were predicted the greatest reasonable accuracy [16]. Kueh et. al. [18] took a similar approach in the study of vortex formation in vortex turbine. Simulation using x-flow were conducted and compared with the experimental results. Kueh et. al. also found that as the height of the inlet increases, the vortex height increases. The difference between Kueh et. al. [18] and Sean [16] was the basin geometry. Sean et. al. [16] [17] designed their basins for zero $H_{channel}$ whereas Kueh et. al. [18] conduct experiment for basin $H_{channel} = 0.5\ m$..

2.5 Similarity Modelling

Sean [16] carried out intensive reviews on free-surface vortex. In order to validate the theoretical analyses, it is necessary to construct experimental model. Due to the huge size of actual power plant, scaled down model can be designed according to dimensionless similarity such as Froude number (Fr), Reynolds number (Re) and Weber number (We). According to Sean et. al. [16], the most suitable dimensionless number for free surface vortex is Froude number since the gravitation force is a dominating force for this study. Sean [16] noted that both numbers should be kept above the minimum specified values in the model. Study showed that the outlet Weber number should be maintained as 120 (Jain et. al. [24]) and for Reynolds number the criteria for minimum radial Reynolds number of 10^3 in the model can be implemented [25]. Researchers agreed that the design of GWVPP still has many configurations that have yet to be explored. The lacks of technical information such as appropriate methodology for testing, design configuration, performance calculation, etc. also had undesirable impacts on the development of GWVPP. Table below shows the summary of studies made by highlighting their findings.

Table 1. Summary of GWVPP findings by different authors.

Study	Research Methods	Research Parameters	Findings
		Turbine Configurations	
Marian et. al. [3]	Theoretical	Position of multiple turbines	• Vortex∝rotational speed • Vortex height affect the efficiency of GWVPP
Marian and Sajin [4]	Theoretical and Experimental	Position of multiple turbines	• Turbine extracts more energy near the outlet • Experimental results agree well with theories
Aravind Venukumar [5]	Theoretical	Turbine blades design	• Produced more than 150W of power.
Subash et. al. [6]	Experimental	Position of turbine	• Maximum power was extracted near the outlet
		Number of blades of turbine	• Power reduced as number of blades increased • Maximum efficiency = 25.36%
Sagar et. al. [7]	Experimental	Position of turbine	• Optimal position of turbine is 65% to 75% of GWVPP's height
		Basin's Structure	• Conical basin has higher overall power output • Maximum efficiency = 36.84%
Sitram et. al. [8]	Experimental	Turbine materials	• Aluminum is more efficient than steel • Maximum efficiency = 34.79%
Christine et. al. [9]	Experimental	Number of blades of turbine	• Efficiency∝number of blades
		Size of blades of turbine	• Efficiency∝size of turbine • Maximum efficiency = 15.1%
		Inlet and Outlet Configurations	
Wanchat et. al. [10]	Experimental	Outlet diameter varied	• Maximum efficiency = 30% • Outlet diameter between range of

			0.20m and 0.35m
Shabara et. al. [11] [12]	CFD and Experimental	Outlet diameter varied	• Outlet velocity $\frac{1}{\propto}$ outlet diameter • Maximum outlet velocity at highest H_{inlet} • Maximum efficiency = 40%
Christine et. al. [9]	Experimental	Inlet flow rate $H_{channel}$	• Highest efficiency at maximum inlet flow rate • Optimal $H_{channel}$ at one-third of basin's height
		Basin Configurations	
Wanchat and Suntivarakorn [13]	Simulation	Basin's structure	• Cylindrical basin with inlet guide has the best flow field
Sagar et. al. [14]	Simulation	Basin's dominant parameter	• W_{in} should be as small as possible • Cone angle should be as big • $H_{channel}$ should be high • Shouldn't exceed optimum value

3. Research Recommendations

GWVPP is a low hydraulic head hydropower plant. In order to achieve maximum efficiency, a suitable turbine with optimized shape and blade profile should be designed [4][7]. Sitram et. al. [8] proved that in the GWVPP, the efficiency of the Aluminium turbine is higher compared to Steel turbine. Subash et. al. [6] also suggested that lighter and stronger materials can be used to reduce the weight of the turbines to acquire best performance from GWVPP. Cavitation, cracking and corrosion have significant effects on turbine blades but it is not considered in previous study of GWVPP turbine therefore, these parameters should be considered during the design of efficient turbine.

In addition, Christine et. al. [9] found that efficiency of the power plant increased when numbers of turbine blades increased from two to four. Subash et. al. [6] found that efficiency reduced when turbine blades numbers increased, which is the opposite of Christine et. al.'s [9] findings. It is also found that the size of the blade has significant effect on GWVPP's efficiency. Both studies with opposite findings suggest that the optimal number of turbine blades and ratio between blade sizes and basin diameter might exist. Therefore, optimization of the blade numbers and profile of the turbine blade can also be considered for future studies.

The design of channel is also an important parameter for effective vortex generation. The tangential velocity of water in the vortex basin depends on the inlet width (W_{inlet}) and neck width (W_{neck}). The ratio of these parameters can be optimized by doing extensive research on it to enhance the water flow in the vortex basin. The channel height ($H_{channel}$) may has significant effects on flow that may alter the performance of the GWVPP, since its performance depends on volume of water. So, effects of the height of channel can be examined in future studies. Since free surface vortex is the source of power for GWVPP, it has several notable research topics that would form the core of an excellent future hydraulics research study in this field.

4. Conclusion

GWVPP is capable of generating power from low water head. Therefore, this type of power plant is suitable for the areas with rivers. Since the fossil fuels reserves are declining, GWVPP can be an alternative energy source which is environmentally friendly as well as cost effective. In this paper, the past literatures related to GWVPP have been presented to support the present research. The optimal turbine position is 0.65 to 0.75 of the basin's height. The maximum efficiency varied from 30% to 50% depends on the numbers and size of the blade. Study also showed that conical shape basin has better performance than cylindrical shape basin. In addition, the inlet flow rate has significant effects on the efficiency. It increased with increase of flow rate and vice versa. In a nutshell, studies showed that there are significant research gaps in the development of GWVPP. The research recommendations in this paper are efforts to accelerate the development of GWVPP.

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