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An experimental facility for the development of a gravitational water vortex turbine

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Abstract

Gravitational water vortex turbine (GVT) is a run-of-the-river hydroelectric system used for generating electricity in the absence of a large dam and a reservoir; i.e., GVT generates power using the water natural flow rate. Recently, the development of GVT is gaining a growing interest within the scientific community concerning the advantages associated with the technology in the process of electric power production. This work describes the design of an experimental facility for the characterization of a GVT in order to understand in a detailed way the effect of the variation of hydrodynamic and geometric parameters on the performance curve of the turbine. The experimental results demonstrated that a wider vortex is generated at lower channel inflow velocities. Additionally, a maximum efficiency of 0.495 at 140.25 rpm was found for the GVT tested.

Key words. Water vortex power plant, experimental facility, conical basin, turbine efficiency

1. Introduction

In order to improve the performance of a gravitational water vortex turbine (GVT), analytical, numerical and experimental studies can be carried out. However, the experimental studies are still limited, and further research is needed for the development of efficient GVT. These turbines can be easily designed and developed for generating power from a free-surface water vortex generated in a conical or cylindrical cross-section basin [1-3]. They could be operated under a wide range of flow rates, even in at very low hydro heads. A GVT is a renewable and eco-friendly energy technology that is easy to be installed and operated. Additionally, this technology provides clean energy in a noise-free way. The construction requirements are simple and woks under low head. In this regard, GVT can produce electricity in rural communities with hydro-energy potential [1-3].

GVT consists of an inlet channel, a basin structure, the turbine runner and the electric generator. The water flow guided through an inlet channel is tangentially fed into the round basin structure to form powerful water vortex due to the induced circulation at the inlet and the localized low pressure at the orifice (exit) [4]. The kinetic energy of the water vortex is converted into mechanical energy through the turbine runner that is located at the centre of the water vortex [4, 5, 6]. The efficiency of this turbine depends on the geometry of the inlet channel and basin, the volume of water entering the turbine, the quality of the vortex that can be induced in the basin, the position of the runner in the vortex and the runner type and its geometry (blade design, blade number, etc.) [4-7].

Recently, several lab-scale testing facilities have been built by researchers with interest in the development of GVT. Among the experimental studies reported in the literature, Dhakal et al. conducted experiments on different basin structures [8]. They found that the optimized conical basin has a higher efficiency in comparison with the cylindrical basin. A higher inlet flow rate improves the efficiency of the GVT as informed by Rahman et al. [9]. Small penstock feeding width and large deflector length result in a higher power output and efficiency. On the other hand, Dhakal et al. discovered that the turbine blades installed near the basin bottom can extract maximum power [10]. In turn, lighter blade materials with low density, as shown by Sritram et al., can produce a higher rotational speed and are more effective in power production [11]. The output power can be extracted from swirling water by assembling booster runner with a single main runner for all similar inlet conditions as demonstrated Gautam et al. [12]. Power and co-workers showed that the power decreases after reaching a certain limit of blade size and number [13]. The efficiency of GVT is improved by adding curves at the exit of the turbine blades compared to straight blades, according to Kueh et al. [14]. Additionally, Wichian et al. found that adding baffle plates on the propeller enhances the efficiency of the impeller with five blades uniformly positioned around the circumference and with 50% baffle plates area. Efficiency should be the output reference for the study of GVT.

In general, experimental facilities are essential for designing and developing innovative technologies like GVT. These facilities enable engineers and scientists to test and validate the performance and efficiency of these turbines in a controlled environment. Modular experimental facilities provide further advantages by allowing researchers to modify and reconfigure the setup easily. This flexibility makes it possible to test different configurations and parameters quickly and efficiently [3, 4, 5]. Additionally, modular experimental facilities are generally more cost-effective and faster to build than traditional fixed installations, making them an attractive option for academic and industrial research institutions. Overall, experimental facilities that are modular provide an excellent platform for developing and optimizing gravitational vortex turbines, leading to significant advancements in renewable energy technology.

The aim of this work is to present the development of an experimental facility that has been specifically designed for the purpose of studying GVT. The facility allows for the testing of several geometric configurations and design parameters, which are essential for optimizing the performance of these turbines. The installation is designed to create a controlled environment in which the behaviour of the turbine can be observed and manipulated under different operating conditions. By studying the interaction between the turbine and the fluid flow, the optimal design resulting in the maximum energy efficiency can be identified. The experimental facility provides a valuable tool for the GVT development advancing, leading to a more sustainable future by generating clean renewable energy.

2. Material and methods

The design of a versatile and low-cost experimental installation for the development of GVT is presented. GVT is a unique type of hydroelectric turbine that generates energy by harnessing the vortex effect in the water flow. The GVT performance is affected by various factors, such as the shape and size of the inlet channel, basin and the blades, the rotational speed, and the water flow rate, and optimizing these factors is crucial to achieving maximum energy output. Therefore, GVT requires a precise design and experimental tests to achieve an optimal performance [3, 4, 5].

The experimental setup of a GVT should ensure a stable and laminar water flow that enters the entry channel and circulates towards the discharge chamber, where the vortex is generated, and the runner is installed. To ensure a laminar flow in an experimental setup for testing gravitational vortex turbines, several measures can be taken. Firstly, the inlet and outlet of the system should be designed to minimize turbulence and promote smooth flow. This can be achieved through the use of carefully designed pipes and fittings, as well as the implementation of flow straighteners or screens to eliminate eddies and vortices. Secondly, the flow rate and pressure of the system should be carefully controlled and monitored to prevent disturbances in the flow. Finally, the experimental setup should be kept clean and free from any obstructions that could cause turbulence. By taking these measures, a laminar flow can be maintained, ensuring accurate and consistent testing results for gravitational vortex turbines. In a hydroelectric power plant, ensuring a smooth laminar flow at the intake of water pipes is crucial for efficient energy production. One way to achieve this is through the use of a forebay or intake structure. This structure is designed to slow down the incoming water and distribute it evenly across the intake area, creating a more uniform and steady flow. Additionally, screens or grates can be installed to prevent debris from entering the intake pipes and disrupting the flow. Regular maintenance and cleaning of these structures are also important to prevent blockages and ensure a consistent flow. By implementing these measures, a hydroelectric power plant can guarantee a stable and reliable water supply for its turbines, resulting in optimal energy production.

A pump and a water tank were used to create a stable water flow towards the turbine. The installation aimed to provide an accurate and controlled testing environment to facilitate the GVT development. On the other hand, it is highlighted that the low-cost design of the installation should allow for a cost-effective testing of various turbine designs and blade configurations. The experimental installation versatility enables an easy adjustment of various turbine parameters, such as the blade curvature and rotational speed, to optimize the turbine energy output. Overall, the experimental installation of the current research is a promising tool for the GVT development.

In this work, the experimental setup conducted consists of a reservoir with a capacity of 2 m^3, a centrifugal pump, an input tank with a capacity of 0.18 m^3, which can be coupled with the GVT, consisting of an inlet channel that is flanged to the input tank, a discharge chamber, and a runner. The reservoir was made of fiberglass reinforced with an outer steel structure and input tank was made of 14-gauge steel sheets. The shaft of the turbine is supported on a structure located at the top of the discharge chamber. At the end of the turbine shaft, a torque sensor is coupled, and a motor is connected to the output of the torque sensor, which is used to apply load on the turbine and depict the efficiency curve of the GVT. Fig 1. shows the experimental facility.

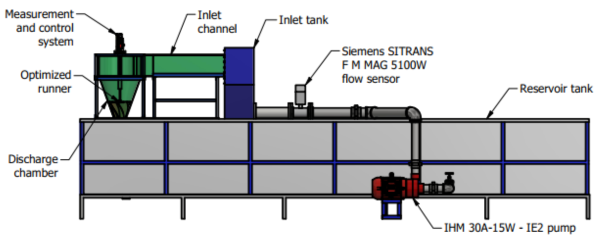
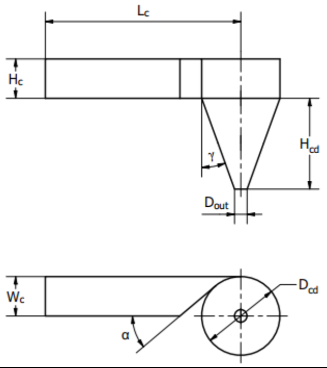


Fig. 1. Experimental facility for the development of the gravitational water vortex turbine (GVT)

The geometry of the inlet channel and the discharge chamber was based on a review of relevant studies reported in the literature, primarily Dhakal et al. [15]. The resulting geometry featured a rectangular cross-section inlet channel and a conical discharge chamber, which is designed to optimize the water outlet velocity and the overall efficiency of the system. Fig 2. illustrates the parameters used to define the system geometry and provides specific values for the factors that define the geometries of the inlet channel and the discharge chamber, based on the chosen design. A 5 mm thick acrylic sheet, transparent in nature, was used in the construction of both the inlet channel and the discharge chamber. The entrance channel of the GVT features a rectangular cross-sectional area and a conical discharge chamber, which is designed to be adapted to the runner geometry. Previous studies conducted by other researchers have demonstrated that these geometric configurations enhance the water outlet velocity and are involved in the formation of a strong vortex. These geometric factors are essential for achieving better energy transfer from the water to the runner [3, 8, 10].



Factor	Description	Value
D_{cd}	Upper chamber diameter	500 mm
D_{out}	Outlet diameter	80 mm
H_{cd}	Height of the discharge chamber	577 mm
γ	Cone angle	20°
α	Angle between the inlet channel and the discharge chamber	40°
Hc	Height of the inlet channel	250 mm
W_c	Width of the inlet channel	250 mm
L_c	Length of the inlet channel	1250 mm
D_{out}/D_{cd}	Diameter ratio	0.16

Fig 2. The main factors that define the geometry of the chosen system discharge channel and chamber.

The operation of the experimental bench can be described as follows: 1) the IHM 30A-15W-IE2 pump facilitated the transfer of water from the reservoir tank to the inlet tank of the GVT system. To regulate its performance, a variable frequency drive was connected to a programmable logic controller (PLC), which was responsible for controlling the pump. Additionally, 2) a SITRANS F M MAG 5100 W flow sensor from Siemens was connected to the PLC, which enabled the system to measure the mass flow of water circulating through the GVT system. By using this data, the variable frequency drive could be configured to deliver a water flow that corresponded to the input conditions specified for the experimental tests. Moreover, 3) the inlet tank was filled with water from the bottom, causing the level to rise until it spills over into the inlet channel and then into the discharge chamber, forming a vortex that emptied into the reservoir tank. Finally, 4) the turbine was situated where the vortex made contact, and it was linked to the measurement and control system via a vertical axis. During the stabilization phase, the turbine was allowed to spin freely. The main components used to gauge and regulate the turbine performance are illustrated in Fig. 3. The Pololu 4741 motor was utilized to oppose the runner rotation, acting like a brake or electric generator by energizing itself in the opposite direction of the free surface vortex. An Arduino Nano board controlled this motor via an H-bridge, enabling the power delivered from a DC source to the motor to be adjusted using Pulse Width Modulation (PWM). The Arduino was programmed to increase the pulse width percentage at 12-second intervals, resulting in a corresponding increase in braking power. These values were prolonged enough for the vortex and angular velocity of the runner to achieve a steady state, which was necessary for the measurements to be valid. The step braking process was continued until the turbine came to a halt.

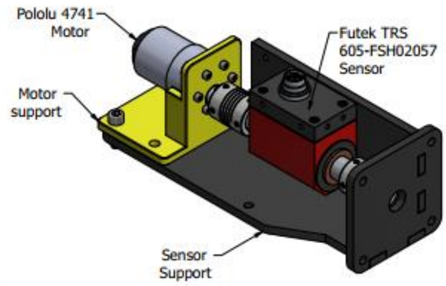


Fig 3. Assemble of measurement and control system

A Futek TRS 605-FSH02057 sensor was placed between the braking motor and the turbine output shaft using two couplings, and it had a resolution of 0.000110 Nm. Its purpose was to collect data on the turbine operating speed, torque and power output. These data were transmitted to a personal computer (PC) via a Futek IHH 500 display, which was linked to the torque sensor and the PC. This arrangement allows for the information provided by the sensor to be recorded and saved.

It is important to note that the runner is the heart of a GVT, since it is responsible for transforming the energy contained in the free vortex into rotational mechanical energy [1-3]. This energy is then converted into electricity when a generator is coupled to the turbine shaft. Because of its critical role, the design of the runner is of utmost importance for the turbine performance [3]. There are various geometries that can be used for runner design, each with unique advantages and disadvantages. The choice of the runner design will depend on the specific application, such as the flow rate and head, as well as other factors, including the efficiency provided and costs incurred. Here, a curved and helical runner with six blades and specific diameter ratios was designed and fabricated using 3D printing technology. This runner geometry was chosen based on previous research and simulation results, which suggested that it would improve the turbine efficiency. In Fig. 4, the runner geometry can be observed, which is characterized by six blades, a twist angle of 55°, an upper runner diameter to upper chamber diameter ratio of 0.5, and a bottom runner diameter to upper chamber diameter ratio of 0.23.

Fig 4. The designed GVT runner

The ability to study different geometries is critical in the development of a GVT. In the experimental installation developed, the entrance channel, the discharge channel, and the runner can be easily interchanged, enabling the study of new geometries in the pursuit of the best configuration for the GVT design.

3. Results and discussion

In a GVT, the formation of the vortex is critical to the operation of the system. This vortex is created by the flow of water through the turbine entrance channel, which causes a rotational movement that produces a low-pressure region at the centre [3, 4]. This low-pressure area creates a vortex that can draw in more water, which further strengthens the rotational flow. The strength of the vortex is dependent on several factors, with circulation being one of the most significant. As the circulation of the water within the system increases, the strength of the vortex also increases. This stronger vortex results in a greater kinetic energy being transferred to the turbine runner, which translates into higher levels of mechanical and electrical power output [3, 4, 5].

Understanding the impact of circulation on the formation of the vortex is crucial for optimizing the GVT design and improving its overall efficiency [4, 5]. Using the experimental facility development in this work was study, the behaviour of the vortex for four different flow velocities (0.04, 0.05, 0.06 and 0.07 m/s) in the inlet channel is shown in Fig. 5. In the figure, the formation of the vortex can be observed. This figure provides visual evidence of how the vortex varies as the flow velocity changes, highlighting the importance of the flow rate in the vortex formation and strength.

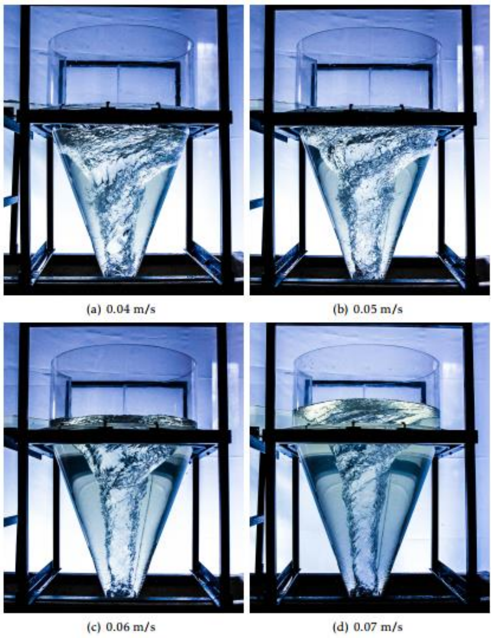


Fig 5. The cross-sections of the vortices formed for different inlet velocities during the experimental tests.

The width of the vortex in the discharge chamber was found to be directly related to the velocity of the fluid flow entering the channel. When the inlet velocity was high, a narrower vortex was generated because the fluid flow had less time to be expanded in the discharge chamber. On the other hand, when the inlet velocity was low, a wider vortex was generated because the fluid flow had more time to be expanded in the discharge chamber. It is important to note that, in addition to the inlet velocity, other factors can also influence the width of the vortex in a GVT, such as the geometry of the discharge chamber, the shape of the runner, and the viscosity of the fluid.

While a narrower vortex may be generated at higher inlet velocities, this may not necessarily result in more efficient energy transfer to the runner. In fact, a wider vortex can often lead to a better energy transfer as it provides a larger area of interaction between the fluid and the runner. This is because a wider vortex has a greater volume of fluid that is in contact with the runner, resulting in a higher potential for energy transfer. Additionally, a wider vortex can help reduce energy losses due to fluid turbulence and recirculation. Therefore, it can be argued that a wider vortex is generally better for achieving an optimal energy transfer in a GVT [3, 4, 5].

The integration of the vortex with the runner is a critical aspect of the GVT performance that must be carefully considered in its design and operation. In Fig. 6, this integration can be observed. As the vortex passes over the runner blades, it creates a differential pressure that causes the runner to spin, converting the fluid's kinetic energy into mechanical energy. The shape and position of the runner blades can significantly affect the energy transfer efficiency by controlling the flow of the fluid and enhancing the interaction between the vortex and the runner. Furthermore, the runner design must take into account the size and characteristics of the vortex, ensuring that it can extract as much energy from the fluid flow as possible.

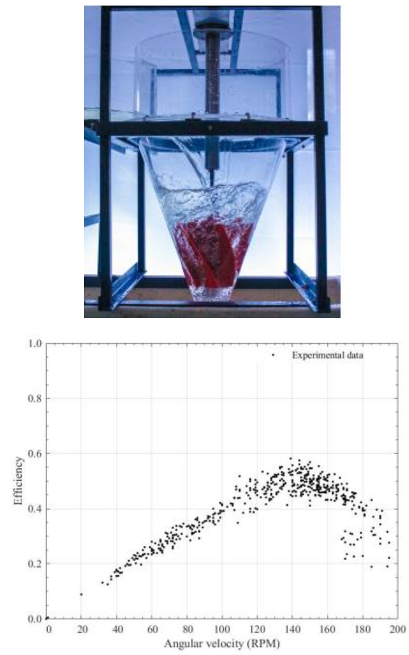


Fig 6. Interaction of the vortex with the runner

Fig. 6 also shows the GVT efficiency curve. This efficiency can be defined as the ratio of the energy output to the energy input. In the current study, it was determined experimentally by measuring the power output and the flow rate of the fluid. By varying the angular velocity of the turbine and measuring the corresponding power output and flow rate, the efficiency curve can be generated. Typically, the GVT efficiency is highest at a specific angular velocity, known as the optimum point. Beyond this point, the turbine efficiency decreases due to increased friction and energy losses. By analysing the efficiency curve of the target GVT, the optimum point allowing an efficiency of 0.495 was identified at 140.25 rpm.

4. Conclusion

The development of experimental facilities is crucial for advancing in the field of GVT. Modular GVT with interchangeable parts can greatly facilitate the testing and development process. A strong vortex in the discharge chamber of a gravitational vortex turbine is crucial for achieving optimal performance. The vortex helps to create a low-pressure zone at the center of the turbine, which results in increased rotational speed and higher energy conversion efficiency. The wider vortex generated at low inlet velocities presents an opportunity for maximizing the energy output of the turbine. During experimental tests on the designed bench, it was observed that a narrower vortex was generated when the inlet velocity was high, as the fluid flow had less time to expand in the discharge chamber. Conversely, a wider vortex was generated when the inlet velocity was low, as the fluid flow had more time to expand in the discharge chamber. It should be noted that factors such as the geometry of the discharge chamber, the shape of the runner, and the viscosity of the fluid, in addition to the inlet velocity, can also influence the width of the vortex in a GVT.

By analysing the efficiency curve of the turbine, the optimal operating point can be identified so that the maximum efficiency is achieved. In the GVT experimental testing, an efficiency of 0.495 was achieved at 140.25 rpm. In this regard, the continued research and development of these turbines have the potential to contribute to the production of clean and sustainable energy.

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