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Experimental analysis of the hydrodynamic performance in four configurations of gravitational vortex turbines

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Abstract. In this study, an experimental evaluation of four geometric configurations of gravitational vortex turbines was conducted. The configurations result from the combination of two types of inlet channels: a tangential and a spiral, and two types of discharge chambers: a cylindrical and a conical one. The models were fabricated at laboratory scale and tested in a hydraulic test bench under controlled conditions. The configuration combining a spiral inlet channel and a cylindrical discharge chamber exhibited the highest hydraulic efficiency of 60.85%. These tested geometric configurations can be used for distributed generation.

Key words. Gravitational vortex turbines, distributed generation, renewable energy, hydraulic efficiency.

1. Introduction

Global energy consumption has experienced exponential growth in recent decades, driven primarily by industrial development, population growth, and the widespread adoption of new technologies across all aspects of modern life [1]. The heavy reliance on non-renewable energy sources such as coal, oil, and natural gas has led to significant environmental and economic challenges, ranging from the depletion of natural resources to climate change [2]. Despite advancements in renewable energy technologies, conventional sources remain the backbone of the global energy supply. Their continued use is largely sustained by their availability and the extensive infrastructure already in place [3]. However, the intensive reliance on fossil fuels has resulted in adverse effects, including greenhouse gas emissions, environmental pollution, and public health concerns [4].

One of the innovative solutions proposed to mitigate these issues is the use of gravitational vortex turbines (GVT). This technology harnesses the kinetic and potential energy of water by generating a vortex flow, which can be converted into electrical energy [5]. GVT offer several advantages: they are environmentally friendly, do not require large infrastructures, and can be implemented in rivers and small watercourses, making distributed energy generation possible [6].

GVT are currently in the early stages of development, with a focus on optimizing components through numerical and experimental studies. Numerical studies focus on computational simulations and modelling of the turbines' behaviour, allowing for performance and efficiency predictions under various conditions. On the other hand, experimental studies involve physical tests in controlled and real-world environments to validate numerical models and adjust parameters. Combining these approaches is crucial, as numerical studies provide detailed and rapid insights into potential technical improvements, while experimental studies offer essential empirical data to corroborate and refine theories. The need for these studies lies in the pursuit of more efficient energy transformation systems, aiming to reduce losses, increase energy production, and minimize environmental impacts. Only through a rigorous research and development process, incorporating both numerical simulations and experimental tests, can significant advancements in GVT technology be achieved.

The primary goal of this study is to experimentally evaluate the energy conversion efficiency of four different geometric configurations of GVT. To achieve this, tests will be conducted in a hydraulic channel that provides a controlled environment, ensuring precise and reproducible conditions for experimentation. The results will help determine the extent to which these turbines can contribute to the development of more sustainable energy systems, reducing reliance on conventional energy sources.

2. Material and method

The main components of a GVT are the inlet channel, the rotor, and the discharge chamber. The design of these components significantly influences the system's performance. The inlet channel plays a crucial role in regulating the flow into the discharge chamber, and its geometry directly affects the formation and stability of the vortex [7]. A more stable vortex translates to improved rotor momentum, thereby optimizing the system's efficiency. The discharge chamber, on the other hand, defines and maintains the stability of the vortex that drives the rotor, making both elements essential for achieving optimal GVT performance.

In this study, four different geometric configurations of a GVT were evaluated, as shown in Fig. 1. Model 1 comprises a spiral inlet channel and a cylindrical discharge chamber. Model 2 consists of a tangential inlet channel and a cylindrical discharge chamber. Model 3 features a spiral inlet channel and a conical discharge chamber. Model 4 combines a tangential inlet channel with a conical discharge chamber. Each model offers advantages and disadvantages based on flow behavior and vortex stability. Spiral inlet channels tend to induce a more uniform flow towards the center of the chamber, resulting in greater vortex stability. Conversely, tangential channels generate a more turbulent flow, which can enhance efficiency at low flow rates but may lead to potential stability losses under higher flow conditions. Conical discharge chambers, compared to cylindrical ones, allow for greater vortex compression, potentially increasing the tangential velocity of the flow and thereby improving rotor efficiency.

The dimensions of the models were obtained from previous studies reported in the literature, along with the rotor design [5]. The rotor is composed of 6 blades, with upper and lower diameters of 291 mm and 163 mm respectively, a height of 200 mm, and a blade twist angle of 55°. The rotor was fabricated using 3D printing, with polylactic acid (PLA) as the material. The printing conditions included a layer resolution of 0.2 mm, an extrusion temperature of 210°C, and a bed temperature of 60°C. The discharge chamber diameter for all models was 500 mm, ensuring consistency in experimental tests. Both the inlet channel and the discharge chamber were made of acrylic to visualize the flow behavior within the GVT system and its interaction with the rotor.

The hydrodynamic performance of the models was assessed by calculating efficiency (η) using Equation (1). In this context, efficiency is defined as the ratio of the power available from the hydraulic resource to the power generated by the turbine. This ratio quantifies the system's ability to convert flow energy into useful energy, providing a concrete measure of its hydrodynamic performance [8]. Efficiency analysis is fundamental to understanding how different geometric configurations influence the overall performance of the turbine.

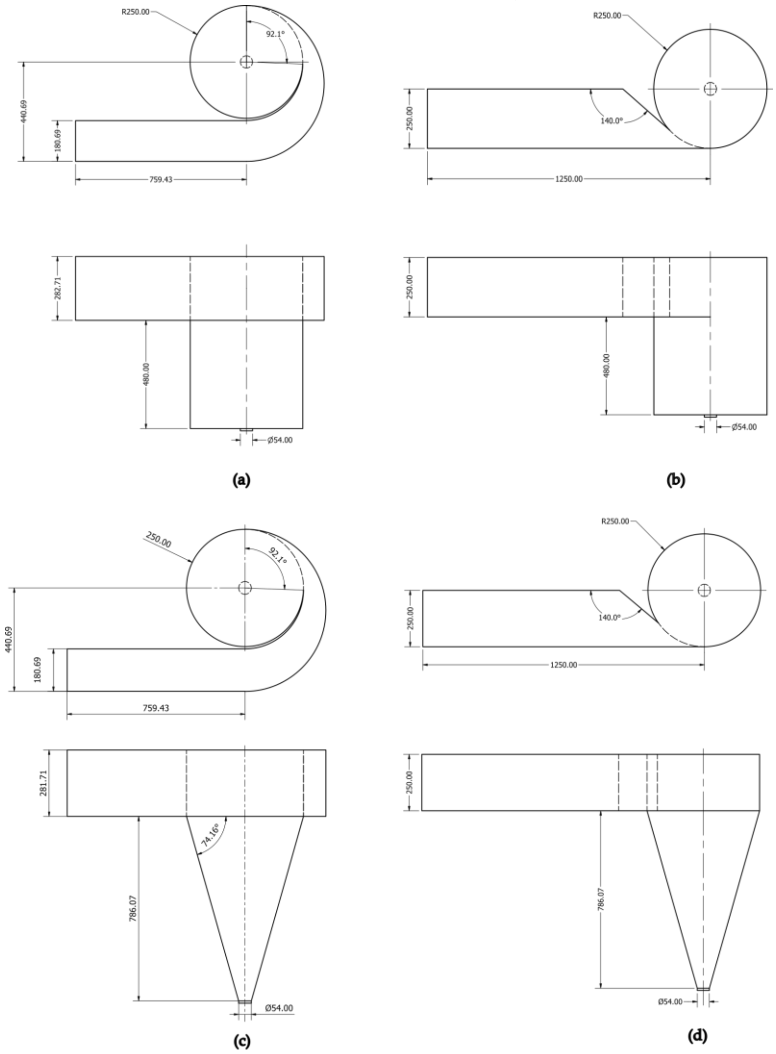


Fig. 1. Gravitational Vortex Turbine. a) Model 1, b) Model 2, c) Model 3, d) Model 4.

$$\eta = \frac{P_{out}}{P_{disp}} = \frac{\omega T}{\rho g Q H} \quad (1)$$

Where the power generated by the turbine (P_{Out}) is calculated as the product of torque (T) and angular velocity (ω), while the available hydraulic power (P_{disp}) is obtained by multiplying the density of water (ρ), gravitational acceleration (g), flow rate (Q), and the head difference (H) between the inlet channel and the average position of the rotor [5].

To evaluate the performance of the models, the test bench shown in Fig. 2 was used. This bench was designed to control and direct the inlet flow towards the inlet channel and the discharge chamber of the system. The bench allows for a precise evaluation of different geometric configurations and their effects on turbine performance. The experimental bench consists of a flow entry section and a test section where the turbines are mounted. The entry section ensures a uniform and controlled flow towards the test section, where the turbine is placed, using a centrifugal pump (IHM 30A-15W-IE2) and two water reservoirs. T and ω were measured using a torque sensor with an encoder (Futek TRS 605-FSH02057). This sensor is crucial to obtain accurate data on turbine performance under different operational conditions. To plot the efficiency curve, the turbine was decelerated in a controlled manner using a motor coupled to the output shaft of the torque sensor. The connection was established as follows: the turbine shaft was connected to the input shaft of the torque sensor, and from the output shaft of the torque sensor to the motor shaft. This motor acts as a dynamic brake, allowing the applied load on the turbine to be adjusted gradually. To measure the flow rate of water entering the turbine, a SITRANS F M MAG 5100 W flow sensor from Siemens was used. This experimental setup allows for the precise collection of necessary data to evaluate system efficiency, plotting the relationship between torque, angular velocity, and efficiency, thereby providing a solid basis for optimizing the design and operation of the GVT.

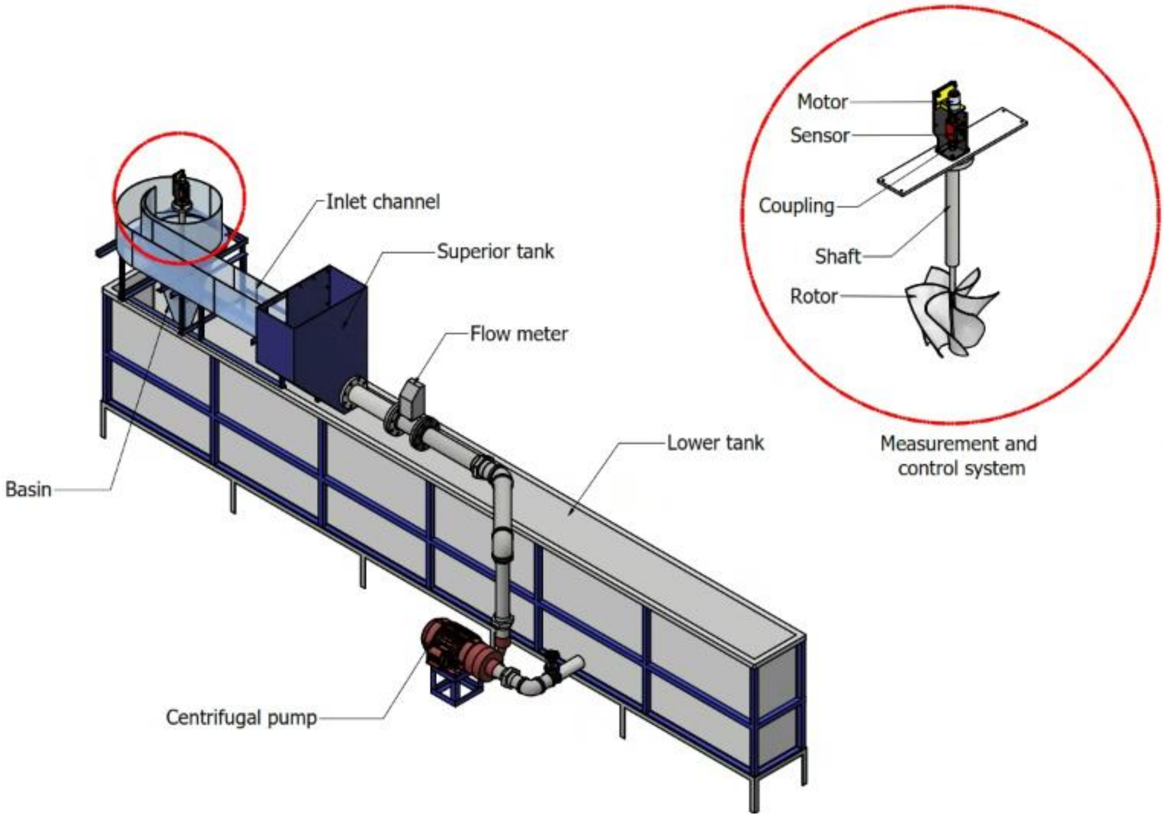


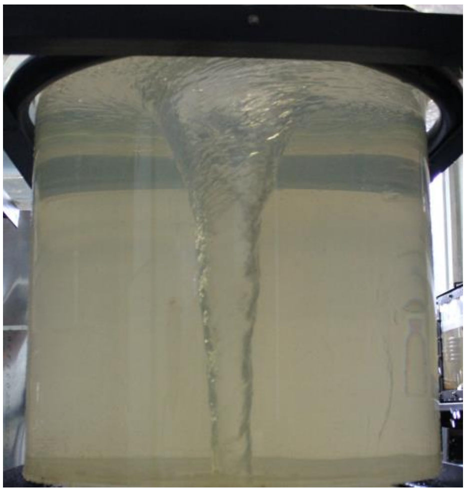
Fig. 2. Experimental Installation of a Gravitational Vortex Turbine (GVT)

The experimental bench provides a controlled environment where critical variables such as flow rate and geometric configurations of GVT can be adjusted. This setup allows for the performance evaluation of GVTs under consistent and reproducible conditions, isolating the effects of different inlet configurations and optimizing the turbine design.

3. Experimental results

Figures 3a and 3b represent two types of vortices generated in Models 1 and 2, respectively. Figure 3a shows the vortex formed in a cylindrical basin with an enveloping inlet. In this case, due to the shape of the inlet channel, the water is distributed around the basin. This tends to generate a smoother and more uniform vortex at the top. It is observed that the base of the vortex is narrower compared to the vortex in Figure 3b, and the water surface in the basin appears to have a more gradual transition towards the vortex. Due to the more homogeneous distribution of the flow, it is likely that the kinetic energy of the vortex is better distributed throughout the basin, leading to a less aggressive but more stable vortex structure.

Figure 3b shows the vortex formed in a cylindrical basin with a tangential inlet. In this configuration, water enters tangentially to the basin wall, inducing a faster and more concentrated vortex in the center. This type of inlet tends to produce a higher angular velocity in the vortex. The vortex is more pronounced and appears to have a stronger twist along its length, with a more noticeable effect on the water column. The vortex is more visible throughout its extent, indicating a higher rotation speed. The fluid energy is concentrated at the center of the basin, which can generate a more vigorous and dynamic vortex. This may result in higher speed at the center, but with greater energy loss due to friction against the basin walls.



a)

b)

Fig. 3. Hydrodynamic behavior of the generated vortex. a) Model 1, b) Model 2.

In Figure 4a, Model 3, which features an enveloping inlet, demonstrates a more uniform distribution of water flow towards the center of the conical discharge chamber. This results in a smoother and more stable vortex formation, with the conical shape enhancing the tangential velocity of the flow. The smooth flow transition minimizes turbulence, leading to more efficient kinetic energy transfer to the rotor, thus maintaining consistent performance and durability under varying flow conditions. On the other hand, Figure 4b showcases Model 4, which incorporates a tangential inlet, causing water to enter the chamber along a tangential path. This leads to a more concentrated and faster-forming vortex with heightened angular velocity, increasing rotational speed. However, the tangential entry increases turbulence, improving efficiency at lower flow rates but potentially causing stability issues at higher flow conditions. Although the conical chamber shape still compresses the vortex, the combined effect with the tangential entry results in a more vigorous and dynamic vortex, which may lead to greater energy loss due to increased friction against the chamber walls.

a)

b)

Fig. 4. Hydrodynamic behavior of the generated vortex. a) Model 3, b) Model 4.

The experimental tests were performed in triplicate to ensure the reproducibility and reliability of the obtained data. Each turbine configuration was evaluated under controlled conditions, and the tests were repeated three times to measure T and ω using the torque sensor with encoder. The average of the experimental results obtained in each test is presented in Fig. 5 for the four studied models, providing a clear and accurate view of the GVT's performance in the various evaluated geometric configurations.

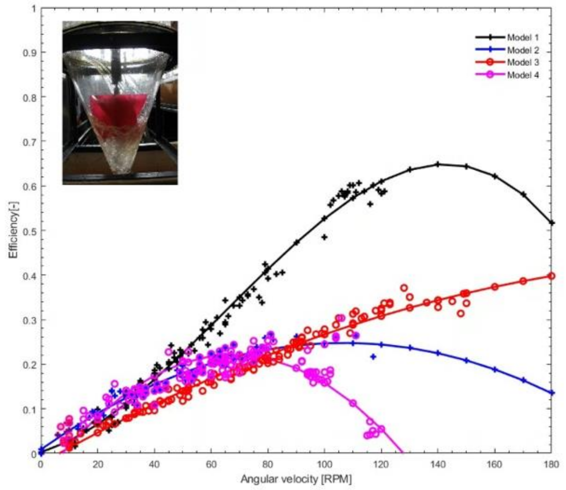


Fig. 5. Efficiency curves of gravitational vortex turbine

In the study, the highest efficiency, 60.85%, was achieved with Model 1, which utilizes a spiral inlet channel, a cylindrical discharge chamber, and a rotor positioned at 50% of the chamber height. This result highlights the importance of optimizing the interaction between the flow and the rotor to maximize captured kinetic energy. The spiral inlet channel allows for more uniform and controlled flow towards the center of the chamber, contributing to the formation of a stable and efficient vortex. The cylindrical chamber, in turn, maintains vortex stability along the chamber's height, minimizing energy losses. The rotor's positioning at 50% of the chamber height facilitates better energy transfer from the vortex to the rotor, taking full advantage of the flow's tangential velocity. Together, these factors contribute to greater system efficiency, emphasizing the need for a geometric design that optimizes the interaction between flow and rotor in GVTs.

4. Conclusion

In this study, a well-equipped experimental setup was used to evaluate four different geometric configurations of Gravitational Vortex Turbines (GVT). The controlled environment allowed for precise adjustment of critical variables such as flow rate and inlet configurations, ensuring consistent and reproducible conditions. The highest efficiency, 60.85%, was achieved with Model 1, which utilized a spiral inlet channel, a cylindrical discharge chamber, and a rotor positioned at 50% of the chamber height. This setup facilitated a uniform flow towards the chamber center, forming a stable and efficient vortex. The cylindrical chamber maintained this stability, minimizing energy losses, while the rotor's position optimized energy transfer from the vortex to the rotor.

The study underscores the importance of a well-equipped experimental installation with reliable sensors to accurately measure and analyze various configurations. Such an approach is crucial for collecting data necessary to enhance the design and operation of GVTs, ultimately contributing to more efficient and sustainable energy systems.

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