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Numerical and experimental evaluation of the performance of a gravitational vortex turbine rotor

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Abstract.

In this study, the evaluation of the rotor performance of a gravitational vortex turbine (TVG) for its application in distributed power generation is presented. A numerical analysis was carried out on a specific configuration of a TVG, characterized by its spiral inlet and conical discharge. The dimensions of the discharge chamber and the inlet channel, such as the inlet channel width (w), length (L), and height (h), the discharge cone height (H) and diameter (d), and the envelope angle (γ) were determined through previous optimization studies documented in the literature. These dimensions are related to the basin diameter (D), which was set at 500 mm for this study. The ratios used, such as L/D, h/D, H/D, γ w/D and d/D were 1.518, 0.565, 1.572, 92.41°, 0.362, and 0.108, respectively.

The rotor has a curvature and a helical pitch angle of 68.8°, has 6 blades, a rotor height of 200 mm and the middle section of the rotor is 314.4 mm (0.4H) from the top of the discharge cone, with an lower and upper diameter of 151.60 mm and 284.44 mm. Using a three-dimensional computational domain and unsteady flow simulations, efficiency curves as a function of angular velocity were obtained. In addition, the TVG was manufactured and experimental tests were carried out on a laboratory-scale test bench to validate its performance. These tests allowed us to compare the experimental results (33.84% at 88 RPM) with the numerical results (32.67% at 106,667 RPM), revealing a difference of 3.37% between the maximum efficiency values. It is essential to continue the turbine optimization process to ensure that the designed TVG plays a role in fostering sustainability and facilitating the shift towards cleaner and sustainable energy alternatives.

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

1. Introduction

The constant growth in energy consumption today poses important challenges in terms of sustainable supply and reduction of polluting emissions [1]. In this context, renewable energies are presented as a key solution to meet the growing energy demand without compromising our environment [2,3,4]. Within this broad spectrum of clean energies, run-of-river turbines emerge as a promising and versatile option. In particular, gravitational vortex turbines stand out for their ability to efficiently take advantage of low-speed water currents, without the need to dam rivers or canals. These technologies not only offer a constant and sustainable source of energy generation, but also reduce the impacts ascribed to the construction of large hydroelectric infrastructure. Thus, gravitational vortex turbines stand as an essential component in the transition towards a cleaner energy supply that is respectful of our environment [5, 6, 7, 8].

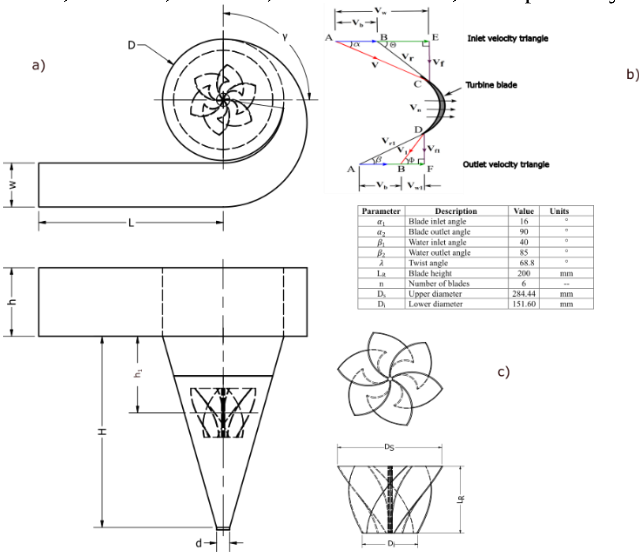
In the literature, there are various studies related to the design and optimization of gravitational vortex turbines, which demonstrates the interest in this emerging technology [5, 6, 7, 8]. However, important challenges remain that require continued numerical and experimental investigation. Improving the efficiency of these turbines and understanding the interaction between the inlet channel, the discharge channel and various rotor geometries remains a key objective, as there is still no clear consensus on the optimal design geometric configuration.
Moreover, it is imperative to emphasize the necessity for these technologies to possess modularity and ease of installation at their designated sites, ensuring both viability and accessibility. Gravitational vortex turbines hold the potential to function as distributed generation systems or complement conventional power generation systems, thereby contributing to a more diversified and sustainable energy matrix [9].

The design process of gravitational vortex turbines demands a multidisciplinary approach that integrates computer simulation and laboratory tests conducted on test benches. Computational simulation offers an efficient avenue to explore a broad spectrum of parameters and design variables, enabling the identification of trends and potential enhancements before transitioning to the experimental phase [8,9]. Conversely, laboratory tests play a vital role in validating numerical results and practically evaluating turbine performance. To yield meaningful outcomes, versatile laboratory facilities are indispensable, capable of replicating pertinent operating conditions and ensuring a controlled environment for precise data collection. This holistic approach, amalgamating the capabilities of computational simulation with experimental validation, stands as a crucial factor for the progression and ongoing optimization of TVG technologies.

In this research, a three-dimensional simulation of the gravitational vortex turbine rotor's geometry was executed through the utilization of CFD (Computational Fluid Dynamics) and the VoF (Volume of Fluid) method. The outcomes derived from this numerical simulation are anticipated to furnish valuable insights and serve as a foundational reference for future enhancements in the rotor design and optimization procedures. Following this, a tangible prototype of the turbine was generated using 3D printing technology. The installation of this prototype on a hydraulic bench ensued, incorporating the utilization of a torque sensor with an angular position transducer to execute its experimental characterization. The principal aim at this stage was to intricately compare the hydraulic efficiency curves concerning angular velocity, as derived from both numerical simulations and experimental outcomes. This comparative analysis facilitated the validation and fine-tuning of the gravitational vortex turbine design.

2. Material and method

The gravitational vortex turbine falls into the category of action turbines, resembling Pelton, Turgo, and crossflow turbines, as it maintains a constant pressure within its rotor (atmospheric pressure). This characteristic denotes the absence of an absorbed pressure head by the rotor [10]. Its operation involves the creation of a vortex in the circulation basin as water passes in its base through a hole. By utilizing a vertical-axis turbine positioned at the centre of the vortex, the turbine captures the kinetic energy of the vortex, converting into electricity the rotor mechanical energy by using a generator. The geometric configuration employed in this investigation, along with its dimensions, is illustrated in Fig. 1. A spiral or envelope inlet channel, akin to those found in cyclonic separators [11], was implemented. Typically, cylindrical, or conical circulation chambers are utilized [12], with conical chambers being preferred due to their ability to generate higher tangential velocity and, consequently, a greater power output in the turbine rotor [5]. The measurements and geometry of the discharge chamber or basin and the inlet channel, including parameters like the height of the discharge cone (H), discharge diameter (d), length of the inlet channel (L), width of the input (w), height of the input channel (h), and envelope angle (γ), were determined based on prior optimization studies identified in the literature [8,9]. These dimensions are correlated with the basin diameter (D), set at 500 mm for this study. The specified ratios, such as L/D, H/D, h/D, d/D, w/D, and γ, are established at 1.518, 1.572, 0.565, 0.108, 0.362, and 92.41°, respectively.



Parameter	Description	Value	Units
α_1	Blade inlet angle	16	°
α_2	Blade outlet angle	90	°
β_1	Water inlet angle	40	°
β_2	Water outlet angle	85	°
λ	Twist angle	68.8	°
L_R	Blade height	200	mm
n	Number of blades	6	--
D_s	Upper diameter	284.44	mm
D_i	Lower diameter	151.60	mm

Fig. 1 a) Configuration of the discharge chamber and the inlet channel in the gravitational vortex turbine, b) Geometric parameters, c) Rotor geometry

The design of the rotor draws inspiration from the operational concept of a crossflow turbine. Water moves from the inlet channel to the basin or discharge chamber and descends from a specific height (h_1). This descent of water from a height triggers the transformation of potential energy into kinetic energy, forming a vortex around an air core with a diminishing radius. The higher the fall distance of the water, the more substantial the kinetic energy produced. The hydraulic power accessible (P_{dis}) entering the turbine is computed using Eq. (1).

$$P_{disp} = \rho Q g h = 6.407W \tag{1}$$

where g and ρ represent the acceleration gravity and the density of water, set at 9.81 m/s² and 998.2 kg/m³ and respectively. On the other hand, the flow rate is expressed by Q, which has been set to 0.003 m³/s. and H is the waterfall height (m). Numerous parameters must be considered during the design process of the rotor to optimize the power generated from the water. This includes dimensions such as the blade number, and their positioning in the basin, the upper and lower diameters of the rotor, the height, and the helical pitch, inlet and outlet angles. The specifications for the rotor, covering dimensions like height and diameter, the count of blades, as well as the entry, exit, and helical pitch angles, were established based on insights gathered from existing literature.

Fig. 1 depicts the characteristic velocity triangles typical of action turbines. In these turbines, the fluid imparts a reactive force on the rotor due to changes in fluid momentum as it moves through the turbine. In such turbines, the fluid velocity at the inlet (V_θ) remains constant [13]. However, in the context of gravitational vortex turbines, alterations in the inlet velocity are correlated with the vortex radius (r), as outlined in Eq. (2).

$$V_\theta = \frac{\Gamma}{2\pi r} \tag{2}$$

In this context, where Γ denotes the circulation, Fig. 1b illustrates various parameters: V signifies the absolute speed, u represents the tangential speed of the rotor, R indicates the relative speed of the fluid in relation to the rotor, v_w denotes the rotational speed, and subscripts 1 and 2 correspond to the inlet and outlet, respectively. Fig. 1c provides a depiction of the rotor design employed in this study.

By examining the geometries of the discharge chamber (or basin), the inlet channel, and the rotor itself, similar characteristics were observed in the rotor behavior. The simulation is designed to calculate the torque (T) generated by the rotor under different configurations and at varying angular speeds (ω). This data is then employed to ascertain the power produced (P_{out}) by the rotor and evaluate the efficiency of the turbine (η). The computations for generated power and efficiency were carried out using Eqs. (3) and (4), respectively [9].

$$P_{out} = T\omega \tag{3}$$

$$\eta = \frac{P_{out}}{P_{dis}} \tag{4}$$

The computational examination was conducted using ANSYS Fluent, involving the consideration of two domains: a rotating domain, where the rotor undergoes rotation, and a stationary domain, where the fluid flows. Both domains are depicted in Figure 2. Meshes were generated using Fluent Meshing, utilizing the poly-hex core mesh type. This innovative poly-hexagonal mesh approach proves advantageous in resolving the flow around intricate geometries with enhanced precision and efficiency, leading to a reduction in calculation time by approximately 40% [14].

To address the unsteady Navier-Stokes equations in the unsteady regime (URANS), a coupled scheme for pressure and velocity was employed, coupled with a second-order upwind discretization. Moreover, VoF method was incorporated in the simulations to account for the presence of multiple fluids, including air and water. The chosen turbulence model was the k-ω SST. An inlet channel velocity of 0.059 m/s was imposed, while 0 Pa of relative pressure was applied in the discharge orifice and on the upper surfaces. In the rotational domain, the angular velocity (ω) was varied within a range from 0 to 17 rad/s.

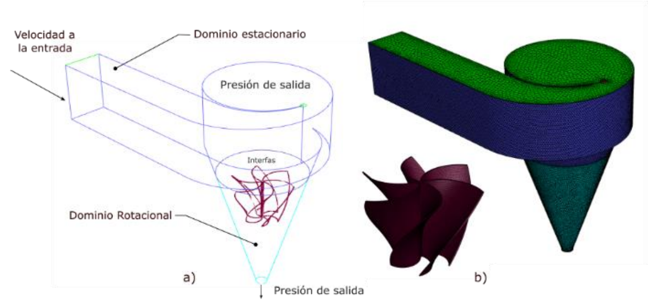


Fig. 2. Computational domain and mesh used in the study.

A research endeavor was undertaken to validate solution convergence by assessing the mesh and time step independence. The specifics of the elements utilized in this investigation are outlined in Table 1. The Grid Convergence Index (GCI) and time step (GCT) method [15] were employed to determine the definitive mesh. When the values of GCI and GCT approach 1.0, it indicates that the solution is situated within the asymptotic range of convergence, signifying that further refinement of the mesh and time step would not substantially alter the numerical solution [16]. In these independence tests, Γ was the variable scrutinized.

Table 1. Convergence indexs

	Type of mesh	Number of elements	Δt [s]
1	Medium	870,064	0.0025
2	Course	524,025	0.005
3	Fine	2,036,661	0.00125
Index		GCI =0.990	GCT=1.002

Following the analysis, a decision was made to employ a time step of 0.0025 s and a moderately sized mesh. This selection aims to diminish the computational time required for simulations. The computational meshes utilized in the domains are depicted in Fig. 2b.

3. Experimental validation

In this investigation, a practical configuration was employed, incorporating a reservoir with a 2 m^3 capacity reservoir, a centrifugal pump, and an inlet tank with a volume of 0.18 m^3 intended for connection to the gravitational vortex turbine. This turbine encompasses an inlet channel interlinked with the inlet tank, a discharge chamber, and a rotor. The tank is crafted using fiberglass reinforced with an external steel framework, while the inlet tank is fashioned from 14-gauge steel sheets. The support for the turbine shaft is provided by a structure situated atop the discharge chamber. To gauge the efficiency curve of the gravitational vortex turbine, a motor and a torque sensor are affixed to the extremity of the turbine shaft to apply a load. The configuration of the experimental setup is illustrated in Fig. 3 [17].

The operational sequence of the experimental setup is outlined as follows: Initially, the IHM 30A-15W-IE2 pump is initiated for the water transportation to the inlet tank from the storage tank within the TVG system. A programmable logic controller (PLC), which allows the pump operation, is linked to a frequency converter to regulate its performance. Additionally, a Siemens SITRANS F M MAG 5100 W flow sensor is integrated with the PLC, simplifying the measurement of the mass flow of the circulating water. Employing the collected data, the variable frequency drive is adjusted to maintain a water flow rate in accordance with the predetermined inlet conditions for the experimental tests. Afterwards, water goes into the inlet tank from below, resulting in a rise in the water level until it spills over into the inlet channel and, subsequently, into the discharge chamber. Inside the discharge chamber, a vortex is induced and directed towards the storage tank [17].

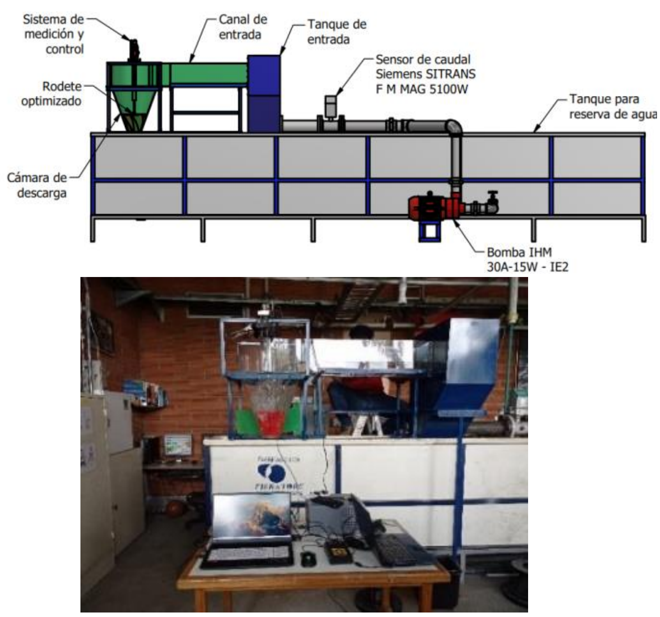


Fig. 3. Experimental installation.

Following this, the turbine is situated at the point of interaction with the vortex and connected to the control and measurement system through a vertical axis. Throughout the stabilization phase, the turbine is permitted to rotate freely. To counter the rotation of the rotor, the Pololu 4741 motor functions as a brake or electrical generator, operating in opposition to the vortex at the free surface. For the motor control, an Arduino Nano board through an H-bridge is used, allowing for the adjustment of the power supplied from a direct current source to the motor using PWM (pulse width modulation) [17]. This system enables to gradually increase the pulse width percentage at 12-second intervals, leading to a breaking power proportional rise. These values are upheld for the duration required for the vortex and the rotor's angular velocity to achieve a stabilized state, an essential prerequisite for obtaining dependable measurements. The gradual braking process is meticulously overseen to ensure a systematic and controlled approach to the experiment. The progressive braking persisted until the turbine came to a complete halt [17].

Results and discussion

Figure 4 illustrates the efficiency curves of the TVG, derived from the numerical data acquired and the conducted experimental tests. In this context, efficiency is defined as the energy produced to the energy supplied ratio. For this study, efficiency assessment was conducted through both numerical simulations and experimental procedures, involving the measurement of the power generated by the rotor in relation to the available power. The construction of these efficiency curves involved the TVG angular speed variation, and the measurement of the generated power alongside the corresponding flow. Typically, the gravitational vortex turbine attains its maximum efficiency at a specific angular velocity, often referred to as the sweet spot.. There is a decline in turbine performance attributed to heightened friction and energy dissipation. Through a scrutiny of the practical efficiency graph for the engineered turbine, we pinpointed the optimum juncture, achieving an efficiency of 33.84% at 88 revolutions per minute (rpm), in contrast to the 32.67% efficiency at 106,667 rpm derived from the curve produced via computational simulations. Upon a comparison of the peak efficiencies, a noticeable percentage disparity of 3.37% is evident.

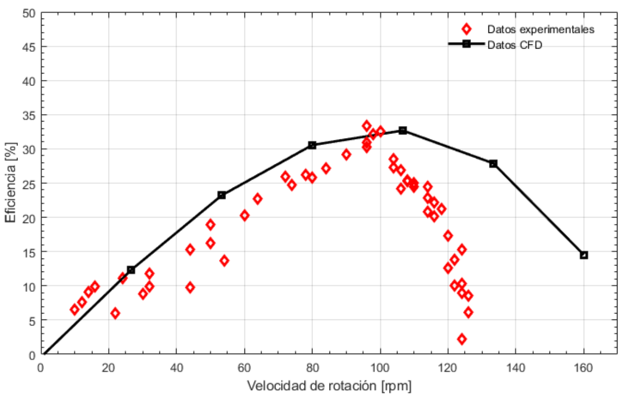


Fig. 4. Comparison between numerical results and experimental findings.

The numerical results demonstrate a pattern akin to the experimental findings, constituting a pertinent discovery in our investigation. It is essential, however, to underscore that the experimental outcomes indicate a slightly diminished efficiency. This variance can be ascribed to the omission, in the numerical simulation, of potential mechanical losses that might arise in the support systems of the turbine shaft. Moreover, it is crucial to acknowledge that the precision of the blade surface finish can impact the forces generating torque on the turbine shaft. The distinction in surface roughness between the experimental and numerical results may further elucidate the efficiency differential noted in the study.

4. Conclusion

This research comprised an evaluation of the rotor in a gravitational vortex turbine through both numerical simulation and experimental analysis. The numerical aspect involved scrutinizing the behaviour of the discharge chamber and the inlet channel in the TVG, with the objective of operating a rotor within the discharge chamber. Concurrently, an experimental setup on a laboratory scale was developed to characterize and validate the prototype.

The peak efficiency observed in the experimental setting for the specified rotor was 33.84% at 88 RPM, contrasting with a 32.67% efficiency obtained in the CFD simulation at 106.667 RPM. The test bench is an adaptable and flexible system, which allows its use in future research that contemplates modifications in the geometric attributes of the channel and the discharge chamber as well as the geometric configuration of the rotor. This approach opens the door to exploring how these parameters influence the performance of vortex turbines and the configuration and behaviour of gravitational vortices.

It is crucial to underline that gravitational vortex turbines offer notable advantages in terms of distributed generation and diversification of available energy sources. Its ability to operate efficiently at low heights and with reduced flow rates results in less environmental impact. However, the need to carry out an optimization process of the rotor of these turbines is highlighted to achieve greater efficiency in energy conversion.

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