Paper-211-24

21th International Conference on Renewable Energies and Power Quality (ICREPQ'23)
Madrid (Spain), 24th to 26th May 2023
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.21, July 2023

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

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Research problem

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.

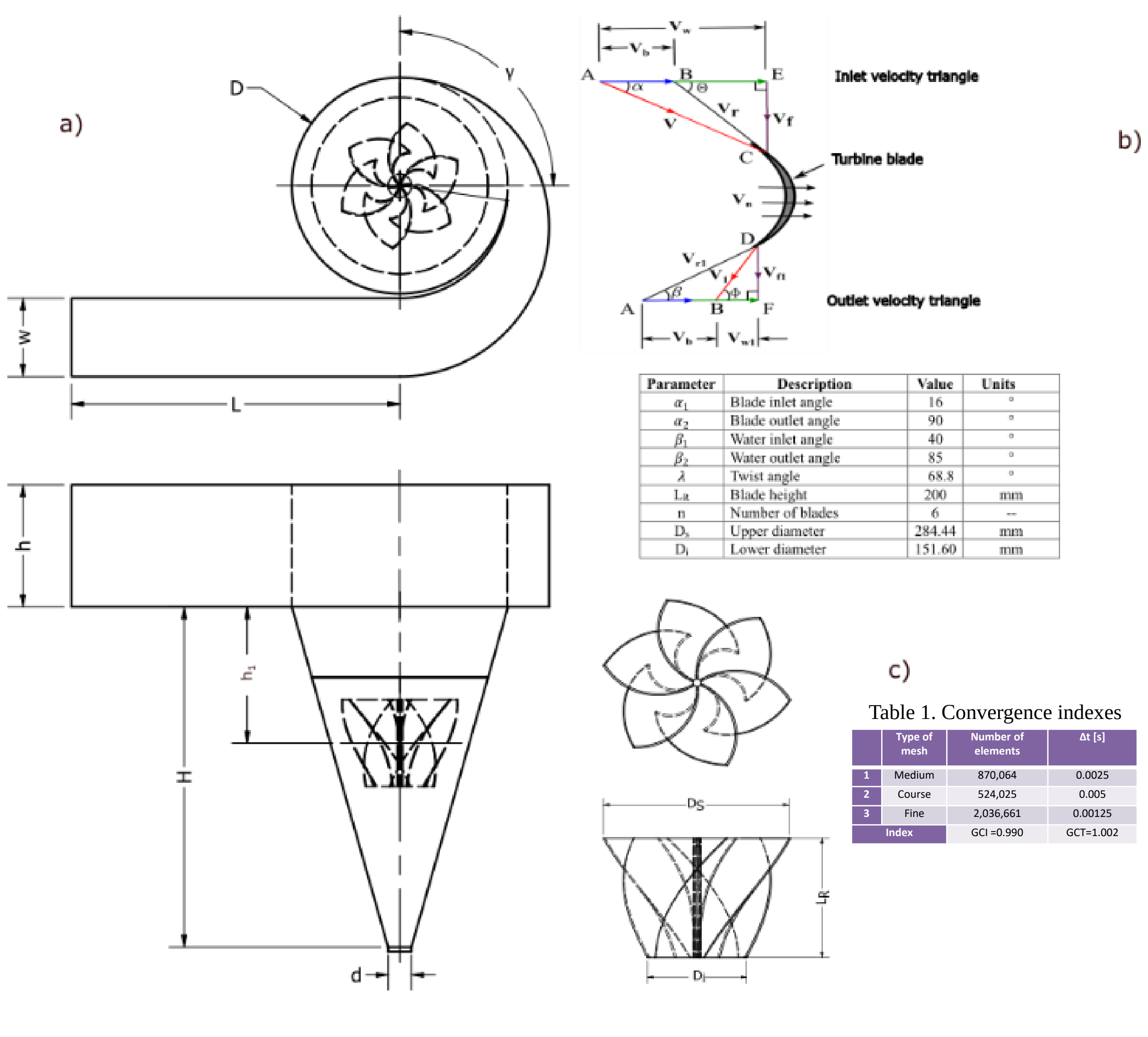
Keywords: Gravitational vortex turbines, distributed generation, renewable energy, hydraulic efficiency.

Objective

The primary aim is to conduct a three-dimensional simulation of the gravitational vortex turbine rotor's geometry using Computational Fluid Dynamics (CFD) and the Volume of Fluid (VoF) method. This simulation is intended to provide valuable insights into rotor design and optimization. Subsequently, a physical prototype of the turbine is created using 3D printing technology and installed on a hydraulic bench. Experimental characterization is carried out using a torque sensor with an angular position transducer. The main focus at this stage is to compare the hydraulic efficiency curves based on angular velocity obtained from numerical simulations and experimental results, aiming to validate and refine the gravitational vortex turbine design.

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 was implemented. Typically, cylindrical, or conical circulation chambers are utilized, with conical chambers being preferred due to their ability to generate higher tangential velocity and, consequently, a greater power output in the turbine rotor. 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. 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, 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

Materials and methods



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

Table 1. Convergence indexes

	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

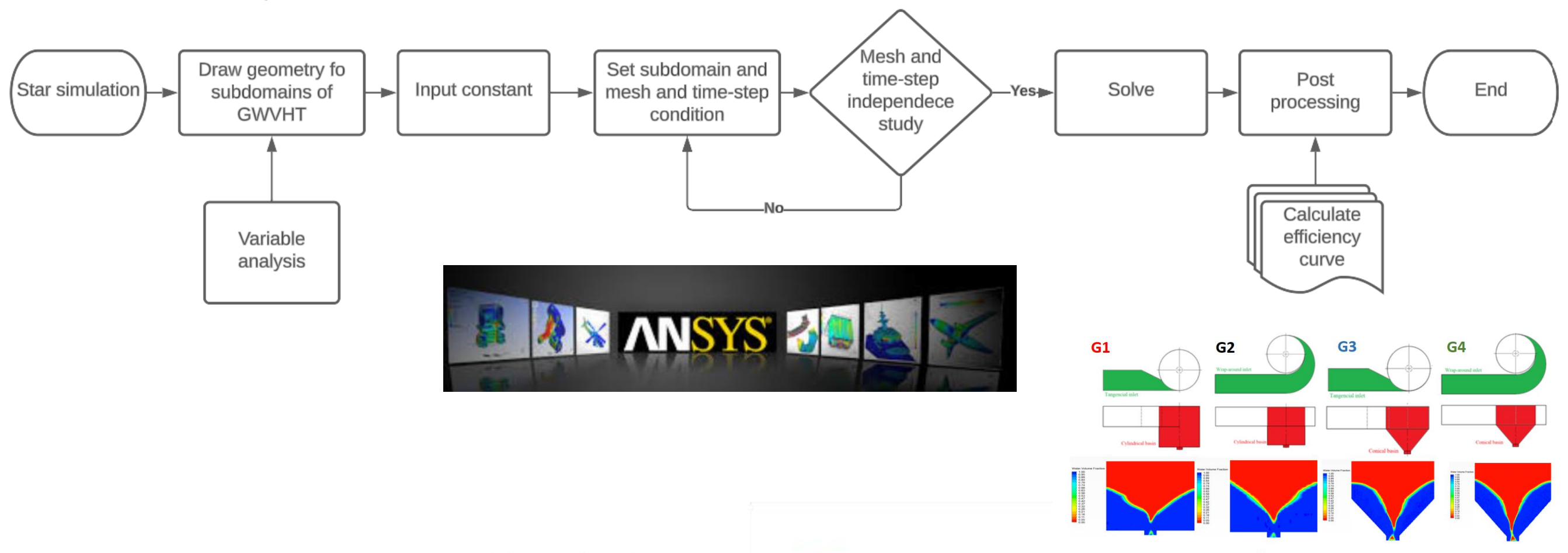
Fig. 1 a) Configuration of the discharge chamber and the inlet channel in the gravitational vortex turbine, b) Geometric parameters, c) Rotor geometry

The accessible hydraulic power (P_{dis}) entering the turbine is computed by using Eq. (1).

$$P_{disp} = \rho Q H g = 6.407 W \qquad \text{Eq. (1).}$$

where g and ρ represent the acceleration gravity and the density of water, which were set at 9.81 m/s² and 998.2 kg/m³, respectively. On the other hand, the flow rate is expressed by Q, which has been set to 0.003 m³/s. H is the waterfall height (m).

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 Fig. 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%.


Star simulation
Draw geometry fo subdomains of GWVHT
Input constant
Set subdomain and mesh and time-step condition
Mesh and time-step independece study
Yes
No
Solve
Post processing
End
Variable analysis
Calculate efficiency curve

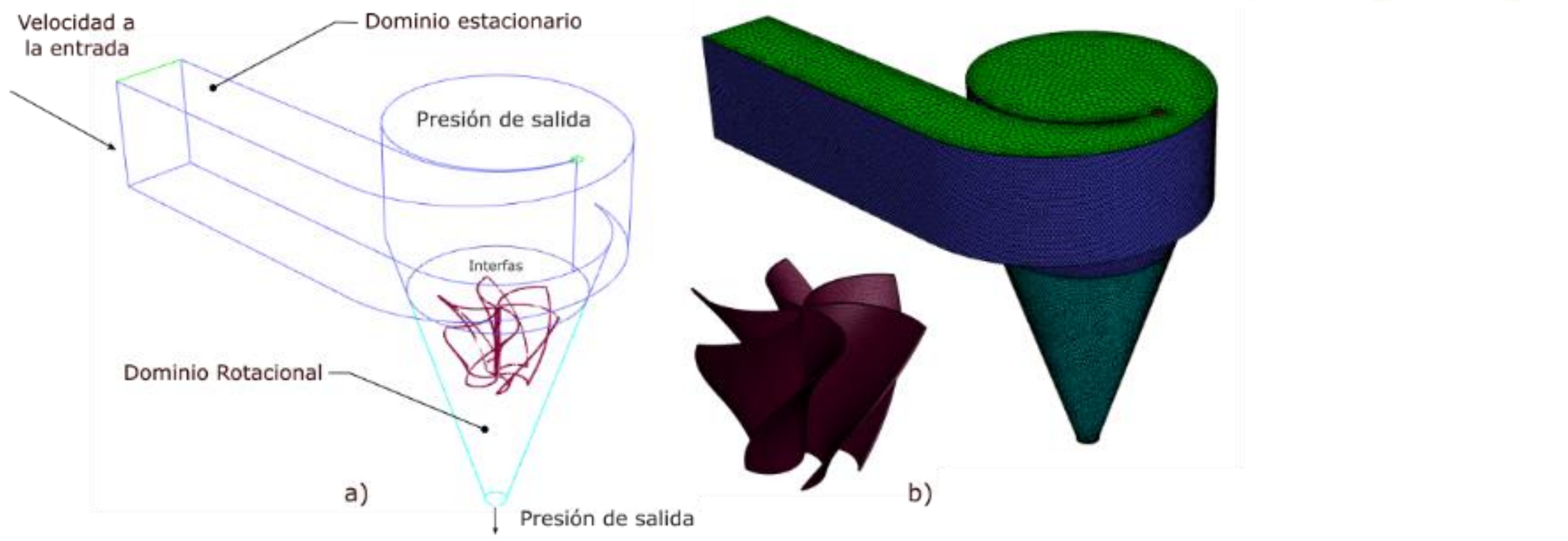


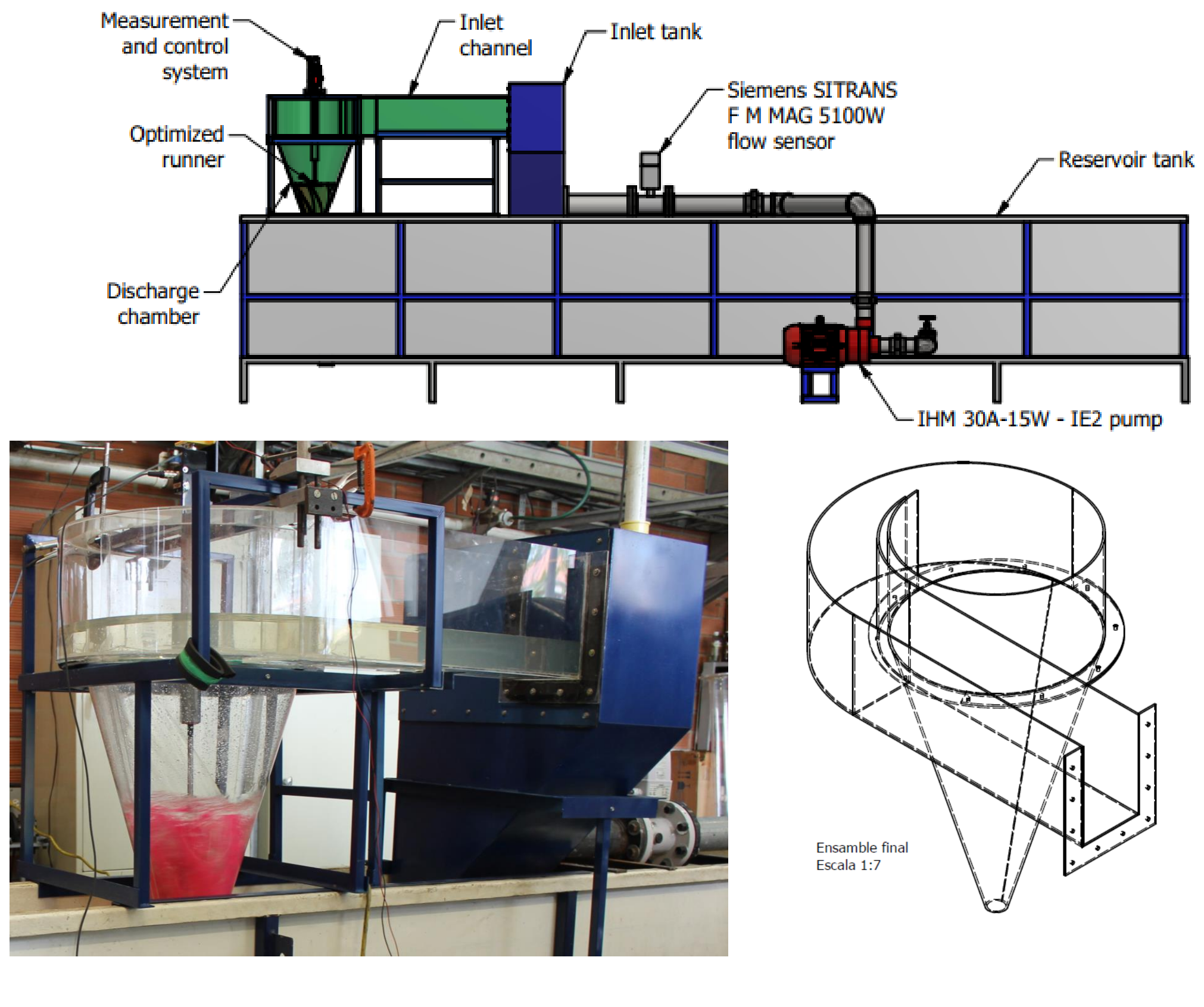
Fig. 2. Computational domain and mesh used in the study.

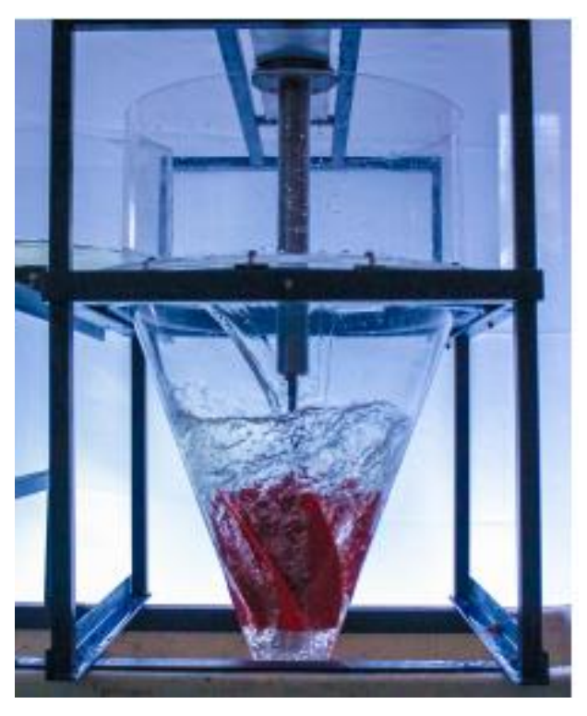
The simulation was designed to calculate the torque (T) generated by the rotor under different configurations and at varying angular speeds (ω). These data were then employed to ascertain the power produced (P_{out}) by the rotor and evaluate the efficiency of the turbine (η). The computations for the generated power and the efficiency were carried out as described by Eqs. (2) and (3), respectively.

$$P_{out} = T\omega \qquad \text{Eq. (2).}$$

$$\eta = \frac{P_{out}}{P_{dis}} \qquad \text{Eq. (3).}$$

Results and discussion





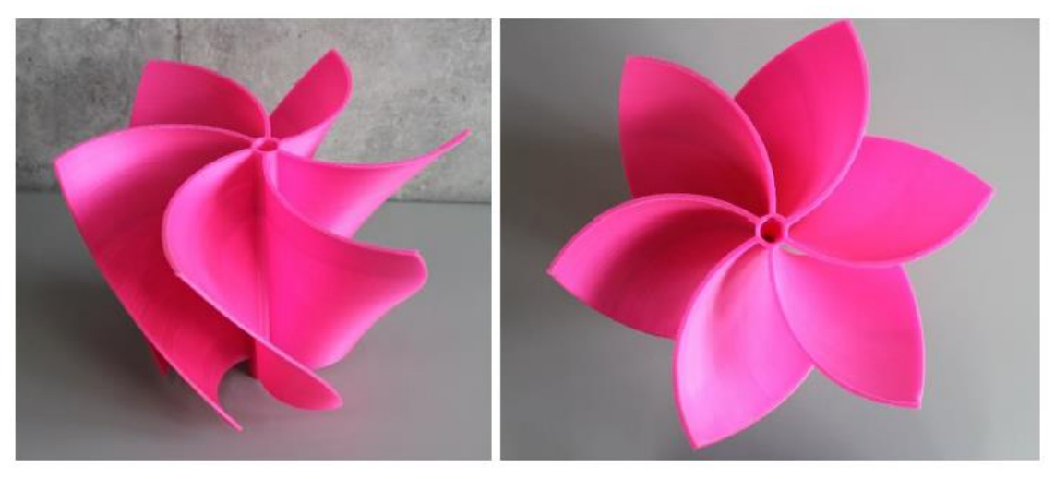


Fig. 3. Experimental installation.

A practical configuration was employed, incorporating a reservoir with a reservoir of 2 m^3 capacity, a centrifugal pump, and an inlet tank with a volume of 0.18 m^3 intended for connection to the TVG. The configuration of the experimental setup is illustrated in Fig. 3

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. 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.

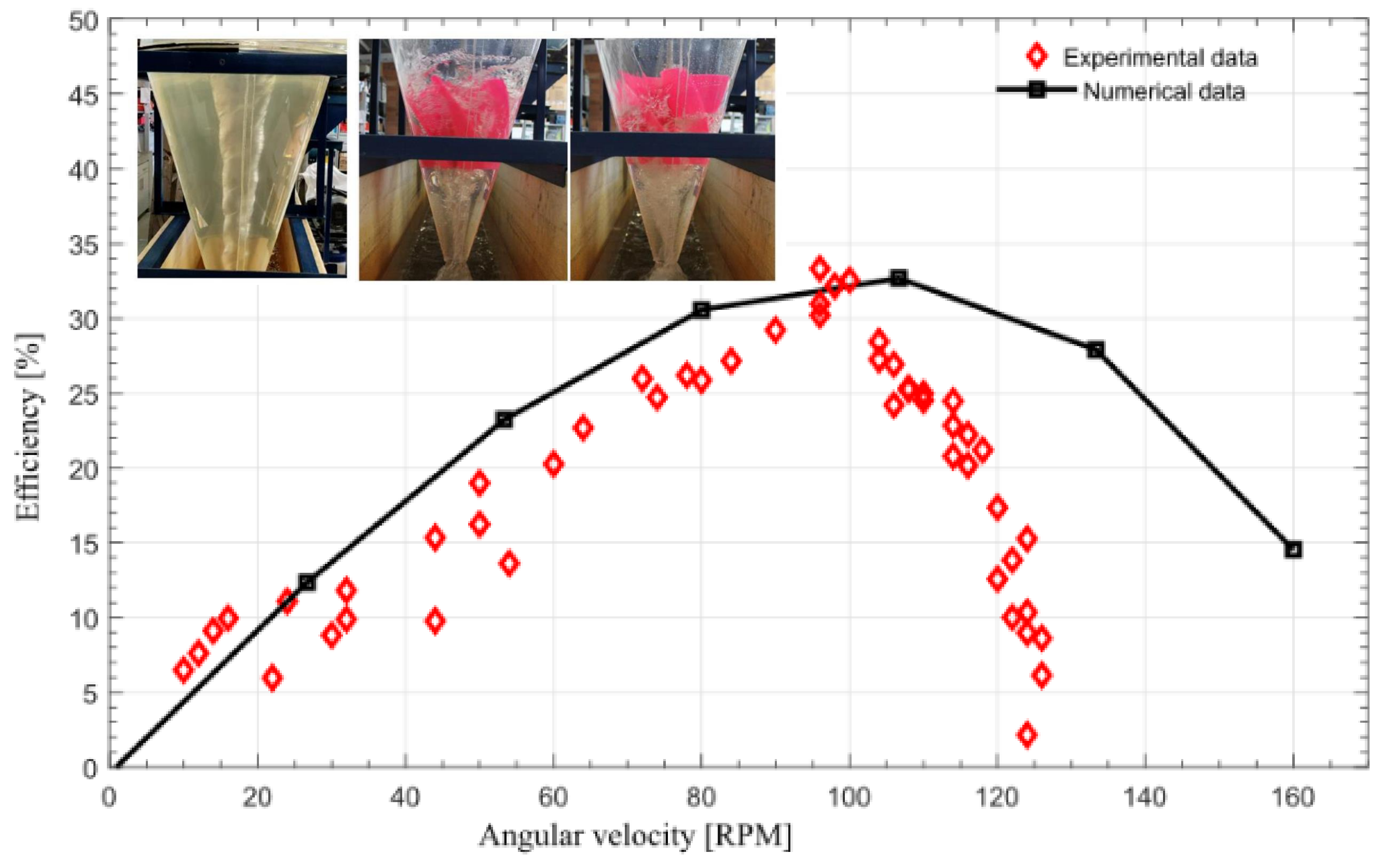


Fig. 4. Comparison between numerical results and experimental findings.

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.

Conclusion

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.

References