ISSN: 1692-7257 - Volume 1 – Issue 47 - 2026

ORIGINAL

RCTA
Revista Colombiana de Tecnologías de Avanzada
UNIPAMPLONA

Experimental assessment of a Gorlov hydrokinetic microturbine for rural low-flow use

Evaluación experimental de una microturbina hidrocinética Gorlov para uso rural de bajo caudal

Jorge Enrique Meneses Flórez[1]
Kevin Alexander Ramírez Rodríguez[1]
Henry David Méndez Chávez[1]

[1] **Universidad Industrial de Santander (UIS), Escuela de Ingeniería Mecánica, Grupo de Investigación en Conectividad y Procesado de Señales - CPS, Bucaramanga, Santander, Colombia.**

Received: 10 August 2025. Revised: 10 September 2025. Accepted: 20 December 2025. Published: 01 January 2026.
Corresponding Author: Jorge Enrique Meneses Flórez

How to cite: J. E. Meneses Flórez, K. A. Ramírez Rodríguez, and H. D. Méndez Chávez, "Evaluación experimental de una microturbina hidrocinética Gorlov para uso rural de bajo caudal", *Revista Colombiana de Tecnologías de Avanzada (RCTA)*, vol. 1, no. 47, ene. 2026, art. no. 4295, doi: 10.24054/rcta.v1i47.4295

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Abstract:

This study develops and evaluates a Gorlov-type hydrokinetic microturbine for electricity generation in low-flow rivers in rural Colombia. A river in Santander was hydraulically characterized, and a NACA 0015 rotor was designed and 3D-printed. Experimental tests delivered 3.3 W of power and 8.8 % efficiency, with a 40 % increase in extracted energy when channeling the flow through a 2.5 m pipe. The stable rotor behavior and gearbox-based transmission confirm its technical and educational feasibility as a low-cost renewable solution for decentralized electrification.

Keywords: hydrokinetic microturbine, Gorlov rotor, additive manufacturing, rural electrification.

Resumen:

El estudio desarrolla y evalúa una microturbina hidrocinética tipo Gorlov para generar electricidad en ríos de bajo caudal en zonas rurales de Colombia. Se caracterizó hidráulicamente un cauce en Santander y se diseñó un rotor NACA 0015 fabricado por impresión 3D. Las pruebas experimentales registraron 3.3 W de potencia y 8.8 % de eficiencia, aumentando 40 % la energía captada mediante canalización del flujo con una tubería de 2.5 m. El desempeño estable del rotor y la transmisión por caja de engranajes validan su viabilidad técnica y educativa como alternativa renovable de bajo costo para electrificación descentralizada.

Palabras clave: microturbina hidrocinética, rotor Gorlov, manufactura aditiva, electrificación rural.

INTRODUCTION

Electricity supply in rural areas of Colombia faces long-standing challenges, even though 70 % of the energy comes from large hydropower plants with high environmental and social impact[1]. UPME[2]reports that more than 500,000 people in non-interconnected zones lack continuous access to electricity or depend on fossil fuels, which limits development. Distributed generation solutions based on micro renewable sources offer a sustainable way to address this problem. Free-stream flow hydraulic microturbines (hydrokinetic systems) are a viable alternative in particular, since they convert the kinetic energy of river currents into electricity without requiring dams or diversion channels, which reduces costs and minimizes environmental impact.

Energy context and rural challenge

Unequal access to electricity limits human development, education and health in rural communities. In Colombia, CREG[1] and UPME[3]point out that conventional electrification in dispersed areas entails high costs and low economic viability, which is why autonomous hybrid systems (solar, hydraulic and wind) emerge as an alternative for Non-Interconnected Zones (ZNI). Their implementation requires modular, economical, low-maintenance solutions adapted to local conditions. In Colombia, recent studies on distributed generation through self-consumption photovoltaic systems demonstrate the feasibility of integrating renewable sources in urban and rural environments, supporting the transition toward decentralized energy schemes[4].

Small-scale use of hydraulics is viable because rivers and streams are abundant. According to the Hydrological Atlas of Colombia[2]and the IDEAM Flow Rate Measurement Manual[5], typical flows have velocities between 0.3 and 2.5 m/s, a range suitable for operating hydrokinetic microturbines if design and channeling are optimized.

Justification of the study

The project was developed in the La Judía village, municipality of Floridablanca, department of Santander (Colombia), located at 7.09° N and –73.05° W, at an approximate altitude of 1 200 (m a. s. l.). This rural area of the Andean foothills is characterized by small low-flow river currents used for irrigation and local supply.

The initiative arose from the need to implement a renewable energy source that would meet the basic electricity demand of a rural educational institution, in order to offer a sustainable and replicable alternative for the community. The low-flow water currents that cross the area, still without energy use, constitute an ideal natural laboratory for experimentation and technological demonstration.

The objective was to design, build and validate a functional prototype of a hydraulic microturbine capable of operating under real river channel conditions, prioritizing affordable materials and low-cost manufacturing techniques, such as 3D printing. The research sought not only to demonstrate the technical feasibility of the system, but also its potential as an educational tool in the field of renewable energy training and community technological appropriation.

State of the art of hydrokinetic microturbines

Hydrokinetic systems use axial or cross-flow rotors immersed in river currents. Among the most studied configurations are Darrieus, Savonius and Gorlov rotors, which operate on the principle of aerodynamic lift[6]. The Gorlov-type rotor (GHT – Gorlov Helical Turbine) is characterized by its helical geometry, which allows continuous flow over the blades, reducing torque pulsation and improving efficiency at low velocity regimes.

The general equation for the power available in a flow of velocity (v) is expressed as:

$$P_h = \frac{1}{2}\rho A\, v^3 \qquad (1)$$

Where ρ is the water density (≈1000 kg/m³) and (A) the area swept by the rotor. The theoretical Betz limit establishes that no turbine can capture more than 59.3 % of this power[7]. In practice, the power coefficients C_p measured for laboratory turbines range between 0.1 and 0.35, depending on the geometry, the number of blades, the aspect ratio and the flow turbulence.

Various studies have addressed the development and evaluation of hydrokinetic microturbines with consistent experimental results. Espina-Valdés et al. [8] they conducted an experimental comparison between Gorlov and Darrieus rotor configurations in low-speed flows (< 1 m/s), obtaining power coefficients C_p close to 0.25. Meanwhile, Ferraiuolo et al. [9] analyzed the performance of a 3D-printed hydrokinetic turbine, demonstrating that the geometric adjustment of the blades and flow alignment can increase operational efficiency. In the Colombian context, Pineda-Ortiz [10] he developed a numerical model for vertical shaft Darrieus/Helical turbines, highlighting the effect of aspect ratio and mechanical losses on overall performance. These works agree that friction losses, flow misalignment, and inefficient coupling with the generator are the main limitations to achieving higher efficiencies in small-scale prototypes.

Over the last decade, the international trend has moved toward the application of additive manufacturing (3D printing) for the rapid and low-cost development of experimental hydrokinetic turbines. Recent studies have shown that this technology makes it possible to adjust the rotor geometry to local flow conditions, reduce prototyping times, and decentralize production, a key aspect for rural environments. Ferraiuolo et al.[9]characterized a 3D-printed horizontal turbine operating in low velocity channels, while Rouway et al.[11]compared SLS (Selective Laser Sintering) and FFF (Fused Filament Fabrication) methods in reinforced polymer blades (Polyamide 12 - PA12), showing structural and performance improvements. Likewise, Rengifo et al.[12]optimized an Archimedes spiral turbine manufactured in PLA, and Armañanzas et al.[13]validated a turbine model in a closed pipe by means of 3D printing. These advances confirm that additive manufacturing is becoming established as a viable tool for decentralized hydrokinetic generation, although challenges persist in erosion resistance, geometric precision, and material certification, which this study addresses in the Colombian rural context.

Contribution of this research

This study provides a comprehensive experimental implementation under real conditions, integrating aerodynamic simulation, digital manufacturing and hydraulic evaluation in the field. A NACA 0015 profile was chosen for its symmetry and angular stability in bidirectional flows. The combination of parametric CAD design, QBlade simulations and additive manufacturing enabled rapid iteration between modeling and experimental tests.

Unlike previous works focused exclusively on laboratory environments, this prototype was installed directly in the natural river channel, evaluating the effects of partial flow channeling by means of a 2.5 m long, 0.2 m diameter pipe. This made it possible to analyze how the channel geometry and the local acceleration of the fluid influence the actual power coefficient and rotational stability.

Problem formulation and research question

The research centers on the question: What design and construction parameters does a hydraulic microturbine prototype need in order to be used as an alternative energy source in rivers with modest flow rate? To answer this question, five specific, sequential objectives were defined: first, hydraulically characterize the selected river channel in the La Judía village; second, design a Gorlov rotor optimized for velocities below 0.5 m/s; third, manufacture the prototype by 3D printing and modular assembly; fourth, experimentally evaluate the overall efficiency of the system under two scenarios (free-stream flow and channeled flow); and finally, analyze the results obtained against the theoretical Betz limit and against comparable research in the field.

Environmental and educational relevance

The use of low-power hydrokinetic technologies not only contributes to emission reduction but also promotes an active learning model in rural communities. Installing the prototype at a local educational institution made it possible to integrate applied science with environmental awareness, showing how a natural resource can be tangibly transformed into clean energy.

Likewise, the constructive simplicity and the accessibility of the material, mainly 3D-printed PETG and industrial PVC, facilitate its replicability in low-resource settings. Its low environmental impact, since it requires neither damming nor alterations of the river channel, reinforces the compatibility of this type of technology with the Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and clean energy) and SDG 13 (Climate action).

METHODOLOGY

The methodology used in developing the hydraulic microturbine prototype was structured in five main phases: (1) hydraulic characterization of the river, (2) aerodynamic design and calculation of rotor parameters, (3) manufacturing and assembly of the system, (4) experimental implementation in the field, and (5) data processing and analysis. The complete process is summarized in Figure 1, which illustrates the stages followed from the initial characterization of the environment to the validation of the prototype.

The methodological approach was experimental and analytical, grounded in the principles of hydraulic engineering, fluid mechanics, and computer-aided design (CAD), ensuring consistency among the numerical results, the observed physical behavior, and the actual operating conditions.

The study was conducted in the La Judía village, municipality of Floridablanca (Santander), selected because it presents a steady free-stream flow with an average velocity of 0.38 m/s and an approximate flow rate of 0.49 m^3/s. The measurements were made using a SEBA F1 current meter, applying the Ven Te Chow method[14], which considers the velocity at 0.6 of the total depth to estimate the representative mean of the flow.

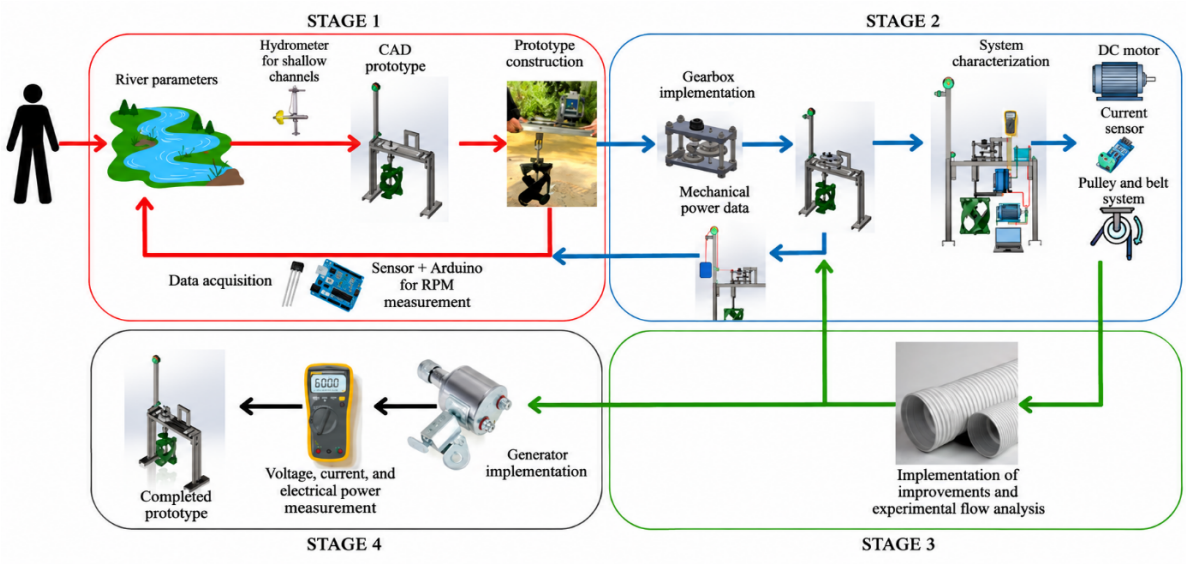


Fig. 1. *Stages followed from the initial characterization of the environment to the validation of the prototype.*
Source: own elaboration

The available hydraulic power was calculated from the kinetic energy equation of the flow, which is suitable for free-stream flow systems without a head drop. This yields the actual average power of the river under natural conditions:

$$P_h = \frac{1}{2}\rho A v^3 \rightarrow P_h = 37.33\,W \qquad (2)$$

Where $\rho = 997\ \frac{kg}{m^3}$, $A = 1.3125\ m^2$ and $v = 0.38\ \frac{m}{s}$.

The theoretical maximum power was also calculated according to the Betz limit (59.3 %)[7], yielding a value that constitutes the upper physical threshold for any lossless hydrokinetic conversion.

$$P_{Betz} = 0.593\ x\ P_h \rightarrow P_{Betz} = 22.14\,W \qquad (3)$$

Aerodynamic design of the rotor

Selection of the profile and geometric parameters

The rotor was designed with the Gorlov Helical Turbine (GHT) configuration, using three helical blades with a NACA 0015 profile. This profile was chosen for its symmetry, stability, and low drag coefficient in laminar regimes. The final design parameters are detailed in Table 1, while the CAD design of the Gorlov-type rotor, developed in SolidWorks, is presented in Figure 2.

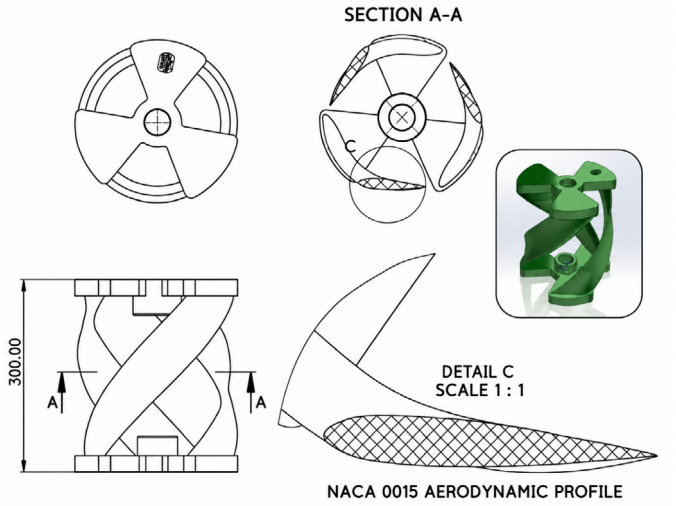


Fig. 2. *CAD design of the Gorlov-type rotor (NACA 0015) with helical inclination.*
Source: own elaboration

Table 1. Geometric characteristics of the rotor

Parameter	Value	Unit
Diameter	0.25	m
Height	0.30	m
Angle of attack	14.5	°
Helical pitch angle	48.9	°
Chord	0.105	m
Number of blades	3	
Material	PETG (3D printing)	

Source: own elaboration

Reynolds number

The Reynolds number (Re), calculated using the values shown below, indicated that the predominant flow regime is low turbulence, which is characteristic of natural flows in shallow rivers.

$\rho = 997\ \frac{kg}{m^3}$, $U = 0.38\ \frac{m}{s}$, $L_c = 0.105\ m$, $\mu = 1.002\ x\ 10^3\ Pa - s$

$$Re\ = \frac{\rho U\ L_c}{\mu}\ \rightarrow\ Re\ \approx 39900 \quad (4)$$

Tip Speed Ratio (TSR)

The Tip Speed Ratio (λ) was determined according to:

$$\lambda = \frac{\omega R}{v} \quad (5)$$

where ω is the angular velocity (rad/s), R = 0.125 m and $v = 0.38\ \frac{m}{s}$.

Under test conditions, 130 RPM (channeled flow) were recorded, equivalent to $\omega = 13.61\ \frac{rad}{s}$. Substituting:

$$\lambda = \frac{13.61\ x\ 0.25}{0.38}\ \rightarrow\ \ \lambda = 4.47$$

This value lies within the optimal range ($3 \leq \lambda \leq 5$) for Gorlov-type rotors, ensuring stability and good dynamic response.

Rotor solidity

Solidity (σ) expresses the ratio between the total blade area and the area swept by the rotor. From the values $n = 3$, $C = 0.105\,\mathrm{m}$ and $D = 0.25\,\mathrm{m}$, a value of $\sigma = 0.4$ was obtained. This solidity level is considered moderate, as it provides an adequate balance between starting torque and the aerodynamic efficiency of the Gorlov-type rotor.

$$\sigma = \frac{n\ C}{\pi D}\ \rightarrow \sigma = \frac{3\ x\ 0.105}{\pi x\ 0.25}\ \rightarrow\ \sigma = 0.40 \quad (6)$$

Manufacturing and assembly

The prototype was manufactured by FDM 3D printing with high-strength PETG filament, at a density of 1.27 g/cm³, an extrusion temperature of 240 °C and a layer height of 0.2 mm. The parts were then treated with epoxy putty and waterproof paint to improve surface resistance.

The modular design allowed easy transport and field assembly, as well as rapid replacement of components in the event of failure. The final assembly (see Fig. 3) integrated:

- Helical rotor of 0.25 m in diameter.
- 1:12 gearbox manufactured in PETG.
- 12 V, 6 W AC generator, dynamo type.
- AISI 304 stainless steel support structure, with 4.5 mm thick reinforcements.
- AISI 304 steel main shaft, Ø10 mm, with water-sealed bearings.



Fig. 3. *Manufactured module, 3D-printed rotor and free-stream flow tests (without channeling)*
Source: own elaboration

Experimental implementation

The tests were carried out in the natural river channel under two configurations:

- Free-stream flow, i.e., without channeling (see Fig. 3).
- Channeled flow through a PVC pipe 2.5 m long and 15 inches in diameter, which concentrated the flow and reduced lateral losses (see Fig. 4).



Fig. 4. *Tests with channeling through a PVC pipe for flow stabilization.*
Source: own elaboration

The experimental data, averaged from 30 consecutive measurements to minimize statistical dispersion, included records of flow velocity both upstream and downstream, rotor RPM measured with an optical tachometer, generator output voltage and current (measured digitally), and temperature and environmental conditions. Comparing the results, the average RPM with channeling was 129.8, exceeding the 114 RPM obtained without channeling, which means a 13.9% increase in angular velocity.

The overall system efficiency (η_{total}) was determined by comparing the electrical power obtained with the available hydraulic power.

Processing and efficiency analysis

$$\eta_{total} = \frac{P_{electrica}}{P_h} x\ 100 \qquad (7)$$

Where $P_{electrica} = 3.3\ W$ and $P_h = 37.33\ W$.

Therefore:

$$\eta_{total} = 8.84\,\%$$

This value agrees with the experimental power coefficient $C_p = 0.088$, within the range reported for low-velocity experimental microturbines.

To strengthen the reliability of the results, a qualitative analysis of the measurement uncertainty was performed. The SEBA F1 current meter has an accuracy of ±2 % in velocity, while the digital multimeter records voltage and current with an accuracy of ±0.5 % and ±1 %, respectively. The variation in water temperature (±1.5 °C) was also considered, since it slightly affects the density and viscosity of the fluid. The combined effect of these error sources is estimated at less than 5 % of the measured value, so it does not significantly alter the efficiency or the comparison between free-stream flow and channeled flow.

Laboratory validation



Fig. 5. *Laboratory tests in a hydraulic channel.*
Source: own elaboration

The system was also tested in the hydraulics laboratory of the Universidad Industrial de Santander, using a test channel (see Fig. 5). However, the flow available in that channel had insufficient depth and velocity to fully cover the rotor, which limited the possibility of performing a comprehensive validation under controlled conditions. Even so, the tests proved valuable for verifying the structural rigidity, the dynamic balance of the rotor, and the mechanical coupling of the system, confirming the stability of the assembly during free rotation.

RESULTS AND DISCUSSION

The experimental evaluation of the prototype made it possible to characterize the behavior of the system under real operating conditions and to compare the results obtained with the estimated theoretical values and with previous studies on small-scale hydrokinetic turbines. The analysis was structured into three complementary levels: first, the hydraulic and rotational performance of the rotor was examined; then, the energy efficiency and the power generated were determined; and finally, a theoretical comparison was carried out to identify the factors limiting the overall performance.

Hydraulic and rotational performance

The experimental tests were carried out in two distinct scenarios: in free-stream flow, without channeling, and in channeled flow by means of a PVC pipe 2.5 m long and 15 inches in diameter. In both cases the revolutions per minute (RPM) of the rotor were recorded, and a notable increase in stability and in rotation velocity was observed when the flow was channeled, due to the reduction of turbulence and lateral losses. Table 2 presents the average values obtained from the 30 repetitions carried out in the field, which reflect the dynamic behavior of the rotor under both test conditions.

The pipe not only increased the angular velocity but also markedly reduced the RPM fluctuation between consecutive measurements. This behavior is attributed to a decrease in the transverse velocity gradient and to the development of a more uniform flow in the inlet section, as proposed by studies on flow channeling in hydrokinetic turbines[14]. In addition, the partial Venturi effect induced by the section reduction accelerated the fluid downstream, which increased the local Reynolds number and favored the turbulent regime desired for stable rotor operation.

Table 2. Experimental resultTable 2. Experimental results of angular velocity

Flow condition	Average RPM	ω (rad/s)	Variation (%)
Free-stream flow	114.2	11.94	—
Channeled flow	129.8	13.61	+13.9

Source: own elaboration

The output voltage of the alternating current (AC) generator was recorded at 10-second intervals using a digital multimeter. Under channeled flow conditions, the average values obtained were $V = 2.9\,\mathrm{V}$ and $I = 1.14\,\mathrm{A}$, which corresponds to an effective electrical power of 3.3 W. This result is significant considering the small dimensions of the rotor (0.25 m in diameter) and the low velocity of the flow (0.38 m/s). In contrast, under free-stream flow, the average power reached was 2.1 W, a 57 % increase when the flow is channeled, associated with a better concentration of kinetic energy and a reduction in local turbulence.

Overall hydraulic efficiency

The overall efficiency of the system was calculated as the ratio between the electrical power obtained and the available hydraulic power (Equation 7). The results are summarized in Table 3.

Table 3. System efficiency under different configurations

Condition	Hydraulic power (W)	Power electrical (W)	Efficiency total (%)
Free-stream flow	37.33	2.1	5.6
Channeled flow	37.33	3.3	8.8

Source: own elaboration

The experimental power coefficient (C_p) obtained for the prototype reached a maximum value of 0.088 under channeled flow conditions, equivalent to an overall efficiency of 8.8 %. The value obtained falls within the expected ranges for small-scale hydrokinetic microturbines, which supports the validity of the design and the consistency of the experimental measurements. Although the efficiency is modest compared with the theoretical Betz limit ($C_{p,\mathrm{Betz}} = 0.593$), this difference is explained by the mechanical and electrical losses of the system, the low Reynolds number (≈ 39 900) and the limited flow velocity (0.38 m/s), factors that restrict momentum transfer and lift generation on the blades. In higher-velocity flows (> 0.6 m/s), a proportional increase in C_p and in the generated power would be expected, which suggests a relevant margin for improvement for future geometric and operational optimization of the rotor.

$C_p - \lambda$ relationship

The aerodynamic behavior of the rotor was analyzed from the relationship between the power coefficient (C_p) and the tip speed ratio (λ), a key parameter for evaluating the energy conversion efficiency in hydrokinetic turbines.

The experimental values obtained (Table 5) show a progressive increase in C_p until reaching a maximum of $C_p = 0.088$ for $\lambda_{opt} = 4.5$ (see Fig. 6), in agreement with the typical trend of lift-type turbines. This behavior coincides with the numerical predictions obtained through QBlade simulations, which validates the geometric design of the rotor and the selection of the NACA 0015 profile.

Table 5 presents the experimental values obtained for different tip speed ratios. It shows the point of maximum aerodynamic performance followed by a progressive decrease associated with increased drag and separated-flow losses, a behavior characteristic of vertical-axis lift-type rotors.

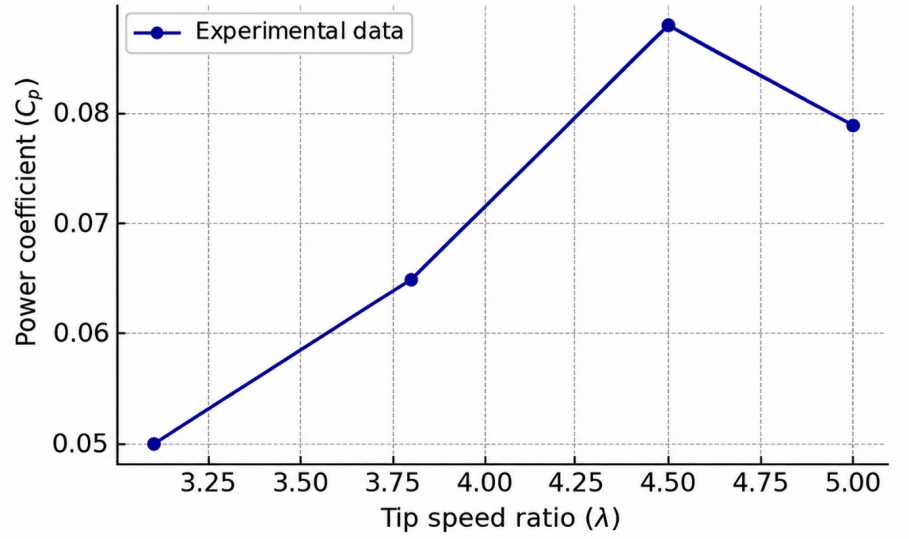


Fig. 6. *Experimental curve of the C_p-λ relationship for the Gorlov-type rotor.*
Source: own elaboration

Table 5. Experimental $C_p - \lambda$ relationship

λ	C_p
3.1	0.050
3.8	0.065
4.5	0.088
5.0	0.079

Source: own elaboration

Influence of channeling and system losses

Channeling through a pipe had a direct effect on flow stability, reducing transverse turbulence and improving the uniformity of the velocity field. This was reflected in an increase in RPM and in C_p, but it also introduced new head losses from friction at the pipe wall, which were estimated using the Darcy-Weisbach equation:

$$h_f = f\frac{L}{D}\frac{v^2}{2g} \qquad (8)$$

where f = 0.03, L = 2.5 m, D = 0.381 m, v = 0.38 m/s, and g=9.81 $\frac{m}{s^2}$.

The result was $h_f = 0.0114\,m$, a negligible loss compared with the hydraulic benefit obtained.

On the other hand, the mechanical coupling between the shaft and the generator showed power losses close to 15%, mainly from friction in bearings and angular play in 3D-printed gears. These losses could be reduced through precision CNC machining, sealed lubrication, and optical alignment of the transmission system.

Comparison with other studies

The results obtained were compared with recent research on low-velocity hydrokinetic microturbines, published between 2019 and 2025. In general, these studies agree that conversion efficiency (C_p) depends mainly on the incident flow velocity, the degree of hydraulic confinement, and the rotor geometry.

Yosry et al. experimentally analyzed a small-scale vertical-axis turbine through VOF-3D simulations considering the variation of the channel free surface, demonstrating that hydraulic blocking can increase C_p by up to 20 % relative to free-stream flow[15]. Complementarily, Espina-Valdés et al. compared the Gorlov and Darrieus configurations in a hydrodynamic tunnel, finding greater stability and torque in the helical rotor, although they warned of an overestimation of C_p in confined channels[8].

Along a different methodological line, Abed et al. developed an efficient hydrodynamic model to predict the performance of cross-flow turbines, experimentally validated at velocities between 0.43 and 0.73 m/s, showing high agreement with the numerical results[16]. In turn, Tunio et al. evaluated the effect of booster nozzles on Darrieus turbines, verifying that these can double the power generated, albeit at the cost of greater structural stresses[17].

More recently, Pineda et al. optimized in the laboratory a 3D-printed Gorlov turbine for river applications using the response surface methodology, reaching a C_p of 0.10 under low-velocity conditions (0.45 m/s)[18]. Likewise, Chica et al. evaluated at full scale a horizontal-axis hydrokinetic turbine for rural applications in Colombia, achieving a C_p of 0.09 and underscoring the viability of distributed generation solutions in developing countries[19].

Comparatively, the prototype developed in this study presented a $C_p = 0.088$ low channeled flow, a value consistent with the ranges reported (0.05–0.12) for low-velocity experimental systems without confinement. This result supports the validity of the approach adopted, demonstrating the technical and social relevance of low-cost hydrokinetic solutions with low environmental impact and high reproducibility for rural environments.

Social and pedagogical implications

The prototype showed its potential as an educational tool by making the conversion of hydraulic energy into electrical energy easier to understand in practice in rural schools. Its low cost, local manufacturing, and operation without environmental impact make it an appropriate technology for rural communities. Because it is modular and easy to maintain, it can be integrated into decentralized energy programs and community technical training. This type of device can be incorporated into experimental microgrid schemes and teaching laboratories, such as those proposed by Santos-Montes et al.[20], fostering practical teaching of energy conversion and management.

Low-cost technological initiatives aimed at environmental and energy education, such as the automation of anaerobic digesters for biogas production developed in the country[21], reinforce the role of local innovation as a pedagogical tool for rural sustainability.

Study limitations

The main limitation of the present study lies in the low flow velocity (≈ 0.38 m/s), which restricted the generable power and, consequently, the overall efficiency of the system. Future evaluations are recommended in scenarios with velocities between 0.6 and 0.8 m/s, where the power coefficient C_p could increase significantly.

On the other hand, the geometric precision of the blades manufactured by fused deposition modeling (FDM) 3D printing showed small deviations in the airfoil and in the twist angle, slightly affecting the lift distribution and the dynamic balance of the rotor. These imperfections can be mitigated by using higher-resolution printers, stable thermal control, fine extruder

calibration and surface smoothing post-processing that improve the finish quality and reduce edge irregularities.

Finally, the AC generator used was not designed for low revolutions, which limited the total electromechanical conversion. It is proposed in future iterations to incorporate multipole alternators or permanent magnet synchronous generators (PMSG) of low velocity, more suitable for hydrokinetic applications.

CONCLUSIONS

The development and experimental evaluation of the hydraulic microturbine with a Gorlov-type rotor demonstrated the technical and operational feasibility of harnessing the kinetic energy of low-flow river currents in Colombian rural environments. The system, designed with aerodynamic criteria and manufactured by additive manufacturing, showed stable, reproducible performance consistent with the efficiency values reported in recent literature.

Likewise, the experience in the La Judía village validated the principle that river energy can be transformed into useful electricity through simple, sustainable, and low-cost devices, without requiring large infrastructures. This approach consolidates a model of applied engineering and technological education, where innovation arises from local contextualization, creativity, and practical knowledge.

Looking ahead, the plan is to scale up the rotor design and evaluate its integration into hybrid rural microgrids, where it could be complemented with solar or wind sources to improve the reliability of energy supply in non-interconnected communities. Consequently, small-scale hydrokinetic microturbines are emerging as a strategic tool for a just and decentralized energy transition in Colombia and Latin America. As noted by Palma et al.[22], the adoption of renewable solutions and energy efficiency measures in public institutions represents a key strategy for advancing national energy sustainability, consistent with the results obtained in this study.

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FUNDING

No financing

CONFLICT OF INTEREST

None

AUTHORSHIP CONTRIBUTIONS

Drafting – original draft: Jorge Enrique Meneses Flórez, Kevin Alexander Ramírez Rodríguez, Henry David Méndez Chávez.

Writing–review and editing: Jorge Enrique Meneses Flórez, Kevin Alexander Ramírez Rodríguez, Henry David Méndez Chávez.