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Analysis of geometric design criteria for the inlet channel and basin for gravity vortex turbines

Análisis sobre criterios de diseño geométrico del canal de entrada y cuenca para turbinas de vórtice gravitacional

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Resumen: Este artículo presenta una revisión de los estudios más relevantes sobre los canales de entrada y las cuencas empleadas en turbinas de vórtice gravitacional, con el propósito de identificar los parámetros geométricos y operativos que controlan la formación, estabilidad y eficiencia del vórtice. Se analizan configuraciones cilíndricas y cónicas, así como variaciones en la geometría e inclinación del canal de entrada, integrando resultados experimentales y numéricos para comparar su influencia en el desempeño hidráulico. Estos hallazgos permiten reconocer las tendencias de diseño más eficientes e identificar propuestas innovadoras que buscan optimizar la generación del vórtice y el rendimiento global de la turbina.

Palabras clave: Energía, canal, cuenca, turbina, vórtice.

Abstract: This article presents a review of the most relevant studies on inlet channels and basins used in gravitational vortex turbines, with the aim of identifying the geometric and operational parameters that control the formation, stability, and efficiency of the vortex. Cylindrical and conical configurations are analyzed, as well as variations in the geometry and inclination of the inlet channel, integrating experimental and numerical results to compare their influence on hydraulic performance. These findings allow the recognition of the most efficient design trends and the identification of innovative proposals that seek to optimize vortex generation and the overall performance of the turbine.

Keywords: Energy, channel, basin, turbine, vortex.

1. INTRODUCTION

The electrical generation in Colombia depends significantly on hydropower; however, in order to reduce interdependence and diversify the energy matrix, the government promotes the development of renewable energy sources, including small hydropower plants (SHP), as well as solar, wind, and biomass energy [1]. Small hydropower plant (SHP) projects enable distributed generation, support regional electrification, and contribute to a resilient and environmentally sustainable energy transition, and this distribution in power generation is illustrated in Fig. 1 [2].

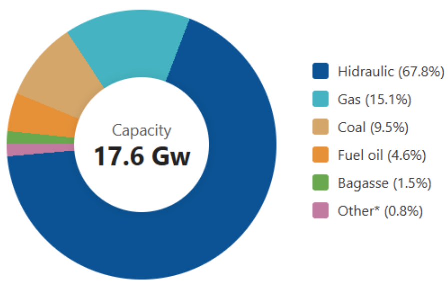

Fig. 1. *Types of energy sources according to the national energy matrix.* ***Source:*** *BBVA Research 2024 [1].*

The gravitational vortex hydraulic turbine (GVHT, by its acronym) is a low-head hydroelectric generation technology that extracts kinetic and potential energy from a water vortex that is artificially induced in a basin. A critical aspect of GVHT performance is the geometry and configuration of the inlet channel, which conveys the water flow from the source tangentially into the vortex chamber or basin, thereby ensuring efficient vortex formation and maximizing energy conversion [3].

The water from the source is channeled from the bank and conveyed to the basin through an open inlet channel, which is responsible for directing the water flow tangentially into the basin. In the basin, a gravity-induced hydraulic vortex is generated, from which kinetic energy is extracted by means of a vertical-axis turbine whose rotor rotates coaxially with the vortex [4].

The inlet channel can be constructed as a horizontal or inclined channel, and in some cases, it may be replaced by a pipe to facilitate its transport and installation. The channel width at both ends, namely at the channel inlet and at the outlet towards the basin, may either vary or remain constant [5].

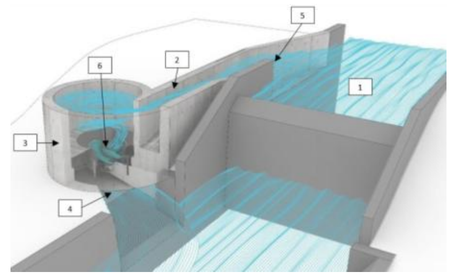

Fig. 2. *Parts of a gravitational vortex turbine.*
Source: *Velásquez, L., Chica, E. and Posada, J. [4]*

Fig. 2 shows the GVHT system: numeral (1) indicates the approach channel, where the flow is guided in a controlled manner toward the structure. Numeral (2) shows the inlet channel, which directs the flow tangentially into the basin, regulating direction and velocity. Numeral (3) identifies the basin that ensures proper transition toward the vortex formation zone, while numeral (4) marks the discharge orifice through which the water leaves the basin after transferring its energy to the rotor. Numeral (5) shows the intake from the channel, and finally, numeral (6) shows the rotor responsible for converting hydraulic energy into mechanical energy of rotation [6].

The geometric configuration of the inlet channel is widely recognized as a critical factor influencing hydraulic efficiency and vortex formation in gravitational vortex turbines (GVHT). Initial experimental studies and field implementations have established that the tangential flow entry, induced by the channel, is essential for forming a stable free-surface vortex within the basin, directly impacting energy extraction and turbine performance [7].

Recent advances have focused on conducting parametric analyses using both experimental setups and computational fluid dynamics (CFD) simulations to define optimal configurations between the channel and the basin. [8]. Velásquez et al. conducted a numerical study comparing tangential, enveloping, and direct pipe inlets, revealing that an enveloping tangential channel combined with a conical basin produces more symmetric and stable vortices, with higher kinetic energy in the core [9]. Similarly, studies showed that the enveloping inlet, especially when the channel width is approximately half the basin height, enhances vortex circulation [10].

Optimal geometric parameters, such as the width-to-diameter (w/D) and height-to-diameter (h/D) ratios, as well as the inlet enveloping angle, have been determined through experimental designs and response surface methodologies, providing configurations with *w/D* between 0.2 and 0.3 and enveloping angles close to 180°, which favor efficient energy transfer with minimal hydraulic losses. [4], [11]. Additionally, the basin conicity and precise alignment of the channel further influence vortex stability, as demonstrated by advanced CFD studies applying turbulence models to capture the flow structure [12].

The basin is one of the most studied components, with emphasis on modifying its geometry and evolving from cylindrical to conical configurations, adjusting the characteristic parameters of each shape. Various studies, such as Khan's [13], conclude that in cylindrical basins, reducing the diameter causes an increase in the water level inside the basin, although it simultaneously decreases the height of the air cone. Conversely, an excessive increase in the basin diameter results in significant friction losses, allowing a fraction of the flow to slide along the bottom without efficiently contributing to the energy conversion process [14].

This work conducted a review of recent studies related to gravitational vortex turbines and their design parameters, starting from research showing that the geometric design of the inlet channel and basin shape lead to improved vortex formation and energy utilization. The main goal was to study and propose an innovative model of the inlet channel and basin to optimize vortex generation by incorporating geometric improvements based on advances and findings reported in current scientific literature. This review will promote the integration of technical criteria and designs that enhance vortex efficiency and stability, thereby contributing to the development of more effective technologies for low-impact hydraulic energy generation.

2. THEORETICAL FOUNDATIONS

The operation of gravitational vortex hridaulic turbines (GVHT) is governed by open channel hydraulics and vortex dynamics within a confined basin. The geometry and alignment of the inlet channel directly induce a tangential velocity component that initiates and sustains the free-surface vortex, forming the core of the energy extraction process [4]. The channel design must ensure efficient redirection of the flow from linear to rotational motion with minimal energy losses, making it essential to optimize parameters such as channel width (*w*), height (*h*), inlet angle, channel length (*L*), and basin height (*H*), as illustrated in Fig. 3. [15]. The generation of vortices and flow behavior in hydraulic systems, such as gravitational vortex turbines, are commonly modeled using fundamental fluid mechanics equations, based on the Navier-Stokes and continuity equations. These describe the motion of viscous and incompressible fluids and form the basis of numerical simulations. Turbulence models, such as the widely used k-ε and k-ω models, are employed to approximate the effects of turbulent eddies on the mean flow and near the walls, enabling predictions of velocity distributions, vortex formation, and pressure gradients within the discharge chamber or basin and the inlet channel [16].

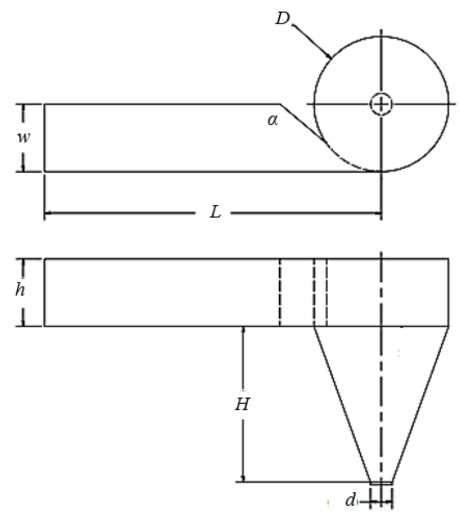

***Fig. 3**. Geometric parameters of the GVHT.*
***Source:** R. Gómez. Et al. [15]*

The generation of vortices and fluid flow behavior in hydraulic systems are governed by the fundamental equations of fluid dynamics, such as the continuity equation described below.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \tag{1}$$

This equation states that the mass of the fluid is conserved over time. For incompressible fluids, it simplifies to:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{2}$$

which means that the divergence of the velocity field $\boldsymbol{u}$ is zero, thus guaranteeing incompressible flow.

On the other hand, the conservation of momentum equation for incompressible flow, which is described as follows:

$$\rho\frac{D\boldsymbol{u}}{Dt}=-\nabla p+\mu\nabla^2\boldsymbol{u}+\rho\boldsymbol{g} \quad (3)$$

where:
u= Velocity vector of the flud
t= Time
ρ= Density of fluid
p= Pressure
μ= Dinamic viscosity
g= Gravity

It represents the balance of forces acting on a fluid particle, including inertia, pressure, viscosity, and gravitational forces.

Additionally, the vorticity transport equation describes the temporal and spatial evolution of the local rotation of the fluid. This formulation expresses that vorticity not only moves with the flow but can also be amplified or attenuated due to deformation effects of the velocity field and dissipation by viscosity.

$$\frac{\partial\boldsymbol{\omega}}{\partial t}+(\boldsymbol{u}\cdot\nabla)\boldsymbol{\omega}=(\boldsymbol{\omega}\cdot\nabla)\boldsymbol{u}+\nu\nabla^2\boldsymbol{\omega} \quad (4)$$

Where $\nu=\frac{\mu}{\rho}$ is the cinematic viscosity. This is the equation that shows how vorticity is transported and diffused within the fluid. In a free vortex, the tangential velocity $v_\theta=\frac{K}{r}$ varies inversely proportional to the radius of the container where it is generated, with K being a constant related to the circulation.

In the context of a forced vortex, the fluid rotates like a solid body, so the tangential velocity varies linearly with the radius.

$$v_\theta=\boldsymbol{\omega}r \quad (5)$$

Where $\boldsymbol{\omega}$ is the angular velocity. This expresses the tangential velocity in a rotating flow. Here, v_θ is the tangential velocity at a distance r from the axis of rotation, and $\boldsymbol{\omega}$ is the angular velocity. This means that the tangential velocity increases linearly with the radius in a solid body rotation scenario. This is fundamental in vortex dynamics, illustrating how fluid velocity varies around the rotation axis in systems such as GVHT. This relation helps predict vortex behavior, energy transfer, and flow stability in hydraulic and aerodynamic applications.

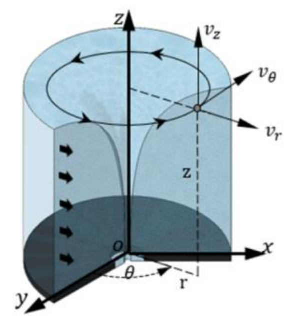

***Fig. 4**. Physics of vortex formation.*
***Source:** Dhakal, et al. [16].*

The Fig. 4 It represents a cylindrical coordinate system applied to rotational flow inside a cylinder, where the fluid motion is decomposed into radial, tangential, and axial components. The scheme shows the development of a vortex descending toward the base of the container, evidencing the transport of mass and angular momentum toward the central axis.

These behaviors govern the velocity distribution in different types of vortices found in hydraulic turbines.

The previously mentioned turbulence models (k-ε and k-ω) are widely used as two-equation turbulence models based on the Reynolds-averaged Navier-Stokes (RANS) equations. Both models introduce two additional transport equations to represent the effects of turbulence on fluid flows, enabling the closure of the RANS equations and practical simulation of turbulent phenomena in engineering applications. These models approximate how turbulent kinetic energy and its dissipation or frequency evolve in flow, allowing engineering prediction of flow behavior under turbulent conditions [17].

The k-ε model fundamentally calculates turbulent viscosity based on turbulent kinetic energy (k) and the turbulent energy dissipation rate (ε), assuming isotropic turbulence and using empirical constants. This model is robust and generally suitable for fully developed flows, free shear layers, and flows away from walls. However, its accuracy decreases in cases with adverse pressure gradients, strong separations, or near-wall regions, unless wall functions or improved variants (such as realizable k-ε or RNG k-ε) are used. The two additional equations for the model are described as follows.

$$\frac{\partial k}{\partial t}+(\boldsymbol{u}\cdot\nabla)k=P_k-\epsilon+\nabla\cdot\left[\left(\nu+\frac{\nu_t}{\sigma_k}\right)\nabla k\right] \quad (6)$$

$$\frac{\partial \epsilon}{\partial t}+(\boldsymbol{u}\cdot\boldsymbol{\nabla})\epsilon=C_{1\epsilon}\frac{\epsilon}{k}P_k-C_{2\epsilon}\frac{\epsilon^2}{k}+\boldsymbol{\nabla}\cdot\left[\left(\nu+\frac{\nu_t}{\sigma_\epsilon}\right)\nabla\epsilon\right] \quad (7)$$

Where P_k is the turbulent kinetic energy production term and ν_t is the turbulent viscosity, while the other terms are empirical constants.

On the other hand, the k-ω model, where ω is the specific dissipation rate of turbulent energy, generally offers greater accuracy near the wall region compared to the k-ε model, since ω is less affected by the distance to the wall and remains valid close to boundaries. It is especially effective for simulating flows with significant phenomena in their boundary layer, separation, and complex surfaces. For broader applicability and enhanced stability in free shear flows, the Shear Stress Transport (SST) k-ω variant combines the k-ε and k-ω approaches, achieving optimal performance across the entire flow domain [17].

The transport equations for this model are:

$$\frac{\partial k}{\partial t} + (\boldsymbol{u}\cdot\nabla)k = P_k - \beta^*\, k\, \boldsymbol{\omega} + \boldsymbol{\nabla}\cdot[(\nu + \sigma_k\, \mu_t)\,\boldsymbol{\nabla} k] \quad (8)$$

$$\frac{\partial \omega}{\partial t} + (u\cdot\nabla)\omega = \alpha\left(\frac{\omega}{k}\right) P_k - \beta\, \omega^{\wedge}2 + \nabla\cdot[(\nu + \sigma_\omega \mu_t)\,\nabla\omega] \quad (9)$$

Where $\alpha, \beta, \beta^*, \sigma_k, \sigma_\omega$ are empirical constants of the model, and the turbulent kinetic energy production term (P_k) and the turbulent viscosity (μ_t), they are defined in a similar manner as in the previously explained k-ε model [18].

3. METHODOLOGY

Rahman et al. [19] They conducted a comprehensive analysis on the effect of channel inclination on flow behavior in gravitational vortex systems, evaluating three inclination angles at 0°, 30°, and 60°, as shown in Fig. 5. Their study included both experimental observations and numerical simulations to analyze how these angles influenced key hydraulic variables, such as flow velocity profiles, vortex formation, and overall turbine efficiency.

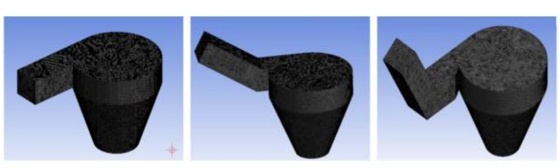

Fig. 5*. Inlet channels with inclination at different angles.* ***Source:*** *Rahman et al. [19].*

By progressively increasing the angle of inclination, significant changes occurred in the development and intensity of the vortex; for example, larger inclination angles tended to promote a more concentrated inlet jet and higher tangential velocity at the vortex core, while smaller angles resulted in a wider and less concentrated inlet flow.

The results demonstrated that the proper selection of the channel inclination angle can be a decisive factor to optimize vortex stability and maximize hydroelectric generation, as each angular configuration modifies the velocity distribution and pressure field within the vortex chamber. These findings provide valuable geometric criteria for the optimal design of gravitational vortex turbines [19].

Another configuration of the upper inlet channel of fluid to the basin studied by Havaldar involved analyzing two geometric configurations: a straight and inclined channel, and a curved channel, as shown in Fig. 6. In particular, the curved channel followed a brachistochrone curve within a vertical plane [20].

This curve, also known as the "brachistochrone curve," optimizes the flow path by minimizing the travel time of fluid particles moving from the highest point of the channel inlet to the basin. This optimized trajectory allows fluid particles to reach higher velocities on their way to the basin, which promotes vortex formation and enhances energy extraction efficiency in gravitational vortex systems.

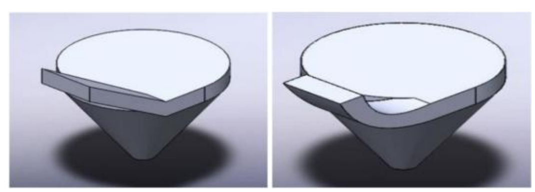

Fig. 6*. Geometric configurations of inlet channels with straight and curved inclinations.* ***Source:*** *Havaldar et al. [20].*

Thapa and his collaborators conducted a detailed study to investigate the influence of inlet channel geometry on vortex formation in a low-head gravitational vortex turbine (GVT). In their numerical analysis, they used ANSYS Fluent® software to simulate flow behavior under different geometric configurations. The study evaluated four inlet channel shapes: triangular, rectangular, circular, and curved. Results from experimental and numerical analyses revealed that vortex formation induces forces on the turbine shaft, negatively impacting operational efficiency. Notably, the rectangular channel generated a highly symmetric pressure field with elevated pressure values, suggesting its suitability for low-head systems. However, under high-head conditions, this pressure distribution could cause unexpected bending moments on the turbine shaft, increasing the risk of structural failure.

Conversely, the triangular inlet geometry demonstrated superior efficiency by promoting a symmetric vortex pattern that minimizes radial forces. These radial forces are primarily responsible for inducing bending moments on the shaft, which can compromise structural integrity. Therefore, the triangular geometry represents a promising design approach to improve the mechanical stability and performance of gravitational vortex turbines; Fig. 7 presents four streamline patterns showing the formation and evolution of a vortex as flow enters a domain. In each case, the curvature and flow distribution determine the vortex structure, its intensity, and the way the fluid wraps around the rotational center [21].

In terms of the basin or discharge chamber, as some studies indicate, research by Sharif has shown that in cylindrical basins, reducing the diameter causes an increase in the water level inside the basin, which represents a decrease in the height of the air cone. Conversely, an excessive increase in diameter generates losses due to friction, leading to a fraction of the flow sliding along the bottom without efficiently contributing to energy conversión [22].

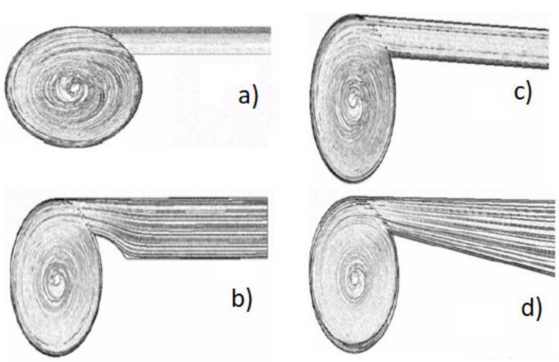

***Fig. 7**. Geometric configurations of the inlet channel and vortex formation in terms of flow. **Source:** Thapa et al. [21].*

Similarly, Chattha conducted studies based on numerical simulations and experiments with conical geometry basins, which helped demonstrate that the best operational results are achieved when the vortex and the generated air cone reach the same height as the basin, that is, when it extends to the bottom of the basin [23].

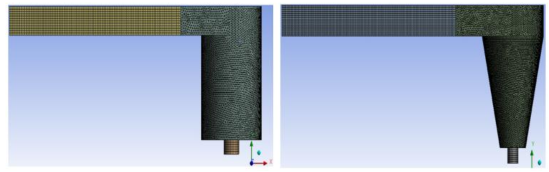

***Fig. 8**. Geometric configurations of inlet channel and vortex formation in terms of flow.*
***Fuente:** Dhakal et al. [24].*

Dhakal and his team conducted simulations in both conical and cylindrical basins, keeping the height and upper diameter D fixed while modifying the discharge diameter d and the cone angle, parameters that are directly related. The purpose of the study was to maintain the ratio d/D within the range of 14% to 18%, as this range favors proper vortex formation. The results showed that an increase in basin inclination produced higher flow velocities, with the highest outlet velocities reached when the d/D ratio approached 18%. Fig. 8 shows the basins studied by Dhakal [24].

On the other hand, Sánchez proposes modifications based on the premise that the basin is the most critical component within a gravitational vortex turbine (GVHT) system. Recognizing the importance of this section for the overall turbine performance, the authors implemented specific adjustments to the geometry of the discharge cone with the aim of optimizing hydraulic efficiency and the axial velocity of the fluid outlet. In particular, two distinct geometric configurations were incorporated: one concave and the other convex, as shown in Fig. 9. These modifications were evaluated through a scaled experimental setup, allowing detailed analysis of how each design influences flow characteristics and, consequently, the turbine's energy efficiency. The results provide valuable insights for GVT design and improvement, demonstrating that small changes in geometry can significantly impact overall performance [25].

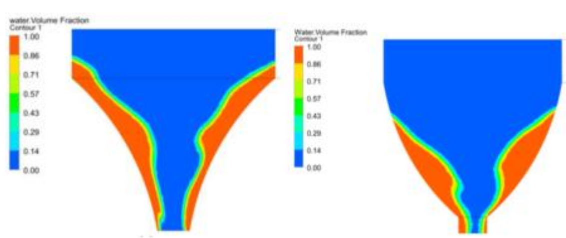

***Fig. 9**. Conical basins with concave and convex cross-sections.*
***Source:** Sánchez et al. [25].*

According to Velásquez, in a study conducted using a multi-objective methodology to optimize the geometry of the channel and basin of a gravitational vortex turbine (GVHT), advances in vortex formation and achieved circulation are shown by implementing an enveloping channel surrounding the basin inlet and an elongated conical basin, with the model evidenced in Fig. 10. They concluded in their study that circulation and volumetric flow rate were 1.6999 [m^2/s] and 0.0030 [m^3/s], respectively. Since the selected geometric parameters were dimensionless, these results allowed them to generate new geometries [26].

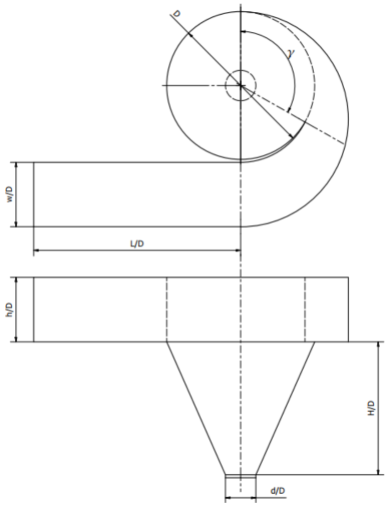

Fig. 10. *Geometry and dimensionless parameters of channel and basin.* ***Source:*** *Velásquez et al. [24].*

Fig. 10 represents the geometric design of the inlet channel and basin of the gravitational vortex turbine (GVHT) using dimensionless parameters. The geometric ratios *L/D*, *w/D*, *h/D*, and *d/D* characterize the system's proportionality and allow analysis of their influence on vortex formation, flow development, and the hydraulic performance of the turbine.

4. RESULTS

The geometric parameters involved in the design affect vortex formation, energy conversion efficiency, and flow stability within the system. These parameters include the geometry of the inlet channel, the shape and dimensions of the vortex basin, the rotor configuration, and the characteristics of the discharge channel. Table 1 shows the relationships among the geometric parameters studied for cylindrical basins; these relationships allow the construction of models that serve as the basis for improving the efficiency of GVHT.

Table 1: *Geometric parameters studied in the literature for cylindrical basin.*

d/D	*H/D*	*w/D*	*h/D*	*L/D*
0.19	0.23	0.31	-	-
0.20	1.00	-	-	-
0.30	1.00	-	-	-
0.28	1.38	0.28	0.43	3.90
0.20	1.00	-	-	-
0.05	1.00	-	-	-
0.20	0.20	0.40	0.30	1.00
0.05	1.40	-	-	-
0.06	0.83	0.23	0.63	0.63
0.10	0.80	0.20	0.20	0.47
0.10	0.90	0.25	0.25	0.57
0.40	0.90	0.25	0.25	0.57
0.20	1.00	-	-	-
0.18	1.25	-	-	1.28
0.16	1.00	-	0.02	-

Source: *Velásquez et al. [27]*

Like Table 1, Table 2 summarizes the geometric, operational, and performance parameters reported in studies analyzing conical basins used in gravitational vortex turbines. This information compiles the most commonly used dimensionless ratios in design and characterization, as well as typical values determined through numerical simulations and experimental tests. Additionally, it allows identification of trends in cone configuration, optimal operating ranges, and criteria adopted by different authors for performance evaluation.

Table 2: *Geometric parameters studied in the literature for conical basin.*

d/D	*H/D*	*w/D*	*h/D*	*L/D*
0.15	0.83	-	-	-
0.15	2.08	-	-	-
0.17	1.42	-	-	-
0.15	0.27	0.27	1.82	0.14
0.15	1.44	0.50	2.81	0.25
0.22	1.00	0.22	3.20	0.11
0.23	0.75	0.50	4.00	0.25
0.23	0.75	0.50	4.00	0.25
0.30	0.90	0.25	5.00	0.28
0.22	1.14	0.50	4.00	0.25
0.05	1.42	0.50	2.83	0.25
0.06	0.90	0.50	1.50	0.13
0.22	1.22	0.32	0.45	-

Source: *Velásquez et al. [27]*

Madrid E., Serrano J., and Florez E. have proposed innovative research lines aimed at optimizing the hydraulic efficiency of gravitational vortex turbines. This proposal involves incorporating geometries inspired by configurations traditionally used in wind tunnels, particularly those designed to induce more uniform velocity profiles, reduce energy losses, and control pressure gradients within complex flow ducts. This geometric adaptation seeks to establish a conceptual bridge between the designs of conical and cylindrical basins, integrating the advantages that each offers in terms of vortex stability, flow concentration, and reduced energy dissipation [28]. The presented approach suggests that a hybrid geometry, derived from aerodynamic principles applied in wind tunnels and adjusted to the hydraulic requirements of GVHT, can promote the generation of a more uniform and stable vortex, minimizing unwanted separation or recirculation zones. Likewise, this type of design could help reduce losses due to friction and excessive turbulence, which is particularly relevant for low and medium hydraulic load systems. Together, these developments represent a promising alternative for advanced basin design, opening the door to new configurations that combine aerodynamic and hydraulic criteria to maximize the energy performance of gravitational vortex turbines. This adaptation is shown in Fig. 11, where the design layout with contraction in the inlet channel and a basin combining cylindrical and conical shapes is observed [28].

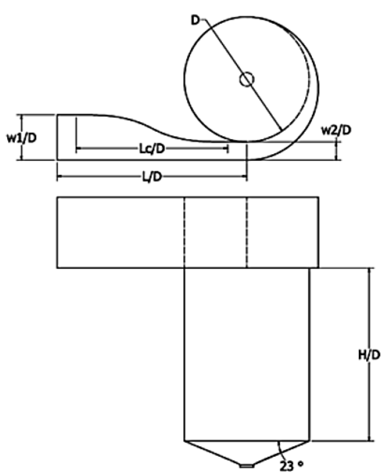

***Fig. 11**. Channel and basin geometry with contraction adaptations at the entrance and conical and cylindrical basin.*
***Source:** Madrid et al. [28].*

5. CONCLUSIONES

The analyzed studies show that configurations based on conical basins exhibit superior performance in terms of vortex stability, velocity distribution, and overall efficiency. It has also been demonstrated that certain geometric adaptations, independent of basin shape, can introduce substantial improvements in the vortex formation process. These configurations favor a more orderly inlet flow with a greater tangential component, intensifying the vortex structure and reducing energy losses due to unwanted turbulence. Overall, the results suggest that while the conical basin remains the most efficient option, its performance can be significantly enhanced with an appropriate design of the inlet channel.

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