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Review Paper

Review: Gravitational Vortex Turbines as a Renewable Energy

Jorge Sierra[1,2], Alejandro Ruiz[1], Angie Guevara[1] and Alejandro Posada[2]

[1]Department of Mechatronics Engineering, Instituto Tecnológico Metropolitano, Medellín, Colombia.
jorgesierra@itm.edu.co*, alejandroruiz190787@correo.itm.edu.co,
angieguevara220191@correo.itm.edu.co
Research group: Materiales Avanzados y Energía (MATyER)
[2]Department of Mechanical Engineering, Institución Universitaria Pascual Bravo, Medellín, Colombia.
alejandro.posada@pascualbravo.edu.co
Research group: Grupo de Investigación e Innovación Ambiental (GIIAM)

Abstract

As result of the negative environmental impact of large hydroelectric dams and conventional diesel power plants, new renewable energy sources should be studied. Gravitational Vortex Turbines (GVTs) can provide clean energy to off-grid areas, known as Non-Interconnected Zones in Colombia, by inducing a water vortex in a turbine-generator set. The implementation of these turbines in the world has expanded due to demographic growth in remote areas, and new studies have enhanced their efficiency. However, there is not enough literature about the estimation of the incidence of their geometric and operating parameters on their performance. This paper presents a global overview of GVTs through a literature review that explores their operation as well as numerical, experimental, and analytical studies that have been conducted to improve their efficiency.

Keywords: Gravitational vortex turbine, Renewable energy, Efficiency, Pico hydroelectric power plants.

1. Introduction

Energy is fundamental for the social and economic well-being. Its absence or high cost makes economic progress more difficult, impacting the quality of life of communities. Moving from fossil fuels to clean energies offers an economic opportunity for sustainable growth. However, more than a thousand million people, around 13% of the world population, have limited or no access to electricity [1]. In 2015, the world adopted the 17 Sustainable Development Goals for 2030. One of them is affordable and clean energy, which has three targets:

- Ensure universal access to affordable, reliable and modern energy services.
- Double the global rate of improvement in energy efficiency.
- Increase substantially the share of renewable energy in the global energy mix [2].

According to the International Energy Association, energy production by hydroelectric power plant and other renewable sources will grow at an annual rate of 1.7% from 2004 to 2030, with an overall growth of 60% by 2030 [3], [4]. The International Renewable Energy Agency (IRENA) reports the variation in the cost per kWh generated by different sources (Fig. 1). According to the IRENA, the global weighted average cost of hydroelectric power plants increased 44% from 2010 to 2018. Table 1 shows the cost per kWh of different renewable energy sources in 2018. The hydroelectric power plants, which generated over 1 MW, are the cheapest in this comparison.

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Corresponding author: Jorge Sierra, jorgesierra@itm.edu.co

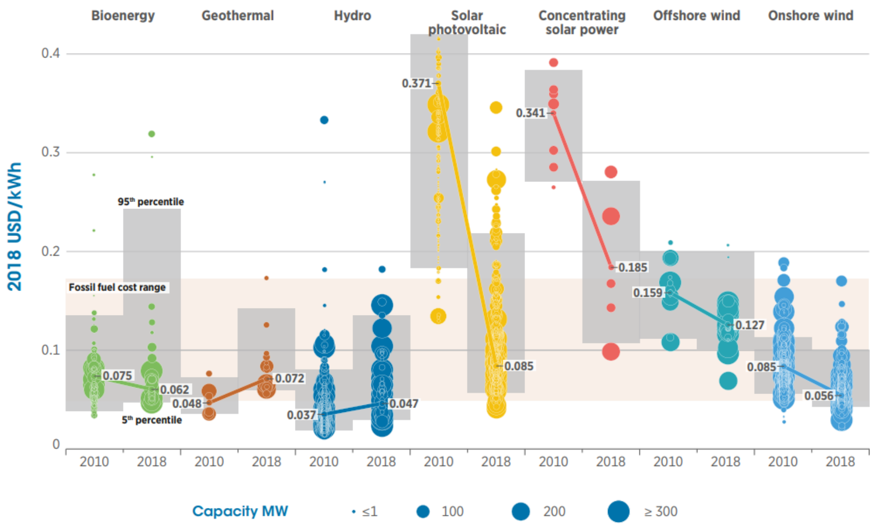


Fig. 1 Comparison of the levelized cost of energy of different renewable energy technologies between 2010 and 2018 [5].

Table 1 Cost of producing 1 kWh in USD (2018) [5].

Energy generation technology	Average cost (USD/kWh)
Hydraulic	0.05
Onshore wind	0.06
Bioenergy	0.06
Geothermal	0.07
Solar photovoltaics	0.09
Offshore wind	0.13
Concentrating solar power	0.19

Hydroelectricity is obtained by extracting energy from moving water. Such energy can be potential and kinetic: the former is produced by falling water, while the latter represents the natural or artificial current of rivers. In both cases, water moves a turbine which in turn moves a generator that transforms the energy into electricity. However, the development of hydroelectric power plants is limited by the available land (since most of them are in populated areas and used for agriculture and cattle raising), the investment, and the social and environmental impacts of dams. All of this explains why hydraulic power has been only partially exploited in developing countries [3]. Dams also become sources of Green House Gases (GHG) such as carbon dioxide (CO2), nitric oxide (N2O), and methane due to the reflection of sun's rays. The last two compounds are 34 and 295 times more contaminant than CO2, respectively [6]. Some dams and lakes generate contamination due to the oxygen reduction produced by the aerobic activity of bacteria decomposing organic material. Additionally, the affluent becomes rich in nitrogen and phosphates, which destabilizes the ecosystem and causes fish death or migration [7]. Hydroelectric power plants are classified by the power they can generate (Table 2).

Table 2 Classification of hydroelectric power plants by generated power [8].

Type	Generated Power	Application
Nano/ Pico power plants	Below 10 kW	Small communities
Micro power plants	10 kW–50 kW	Off-grid networks
Mini power plants	50 kW–1 MW	Communities close to cities
Small power plants	1 MW–5 MW	Small cities
Medium power plants	5 MW–30 MW	Big regions
Big power plants	Higher than 30 MW	Big regions / industry

In particular, small hydroelectric power plants have undergone the most noticeable technological development in recent years, specifically regarding their high efficiency [8]. Additionally, their low implementation costs make them more competitive than wind energy, which explains the increase in number of installed power plants of this kind [9]. Among the available types of hydraulic turbines are Gravitational Vortex Turbines (GVTs), which reduce the contamination due to organic material decomposition since they do not require a reservoir.

2. Features of GVTs

GVTs, also known as Zotloterer turbines, are open hydraulic systems that operate at heads between 0.5 and 2 m, flow rates of 0.1–2 m3/s, a power generation of 0.2–40 kW, and theoretical efficiencies up to 80% [10]. They do not require deep rivers, are easy and economical to manufacture and maintain, and are constructed in concrete [1]. Fig. 2 shows the operating range of a GVT compared to other hydraulic turbines: Pelton (PT), Francis (FT), Kaplan (KT) and Archimedes screw (AT). AT requires deep affluent due to their configuration and complex installation devices. Although AT and GVTs share the same operating range, the design of ATs is more complex [11], which increases their manufacturing and installation costs. Therefore, compared to a GVT, building an AT is more expensive and complex. In summary, design and total cost are the main differences between ATs and GVTs.

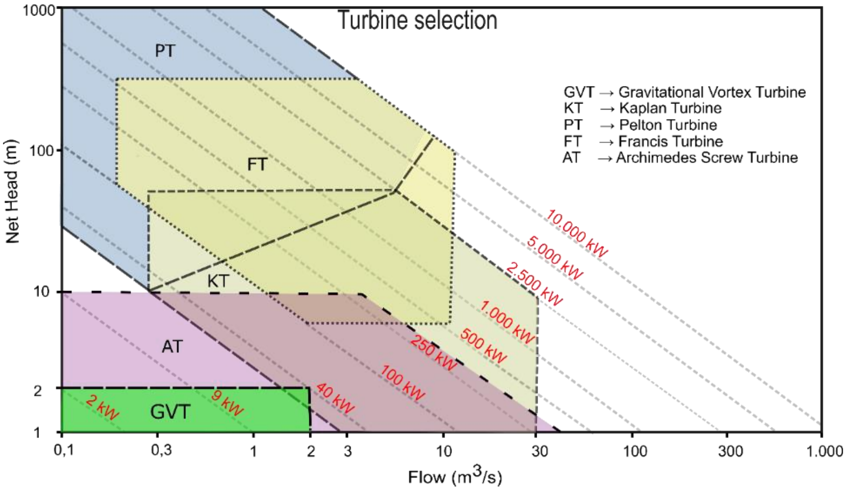


Fig. 2 Operating range of GVTs and other power plants [12].

GVTs induce a vortex in the water free surface during operation, which offers several environmental benefits:

- Clean rivers due to water oxygenation by the spiral formation. Also, thanks to the contact of water with air in the spiral, the water temperature decreases, thereby reducing evaporation [13].
- They allow the free circulation of fish through the turbine thanks to their low rotation velocity, which range from 50 to 200 rpm [1].
- Cheaper than other small hydroelectric power plants, GVTs do not require heavy work and expensive maintenance.
- Most GVT parts can be constructed on site by locals.
- Despite their low efficiency, GVTs are a great alternative for small communities where a connection to the main grid is unfeasible.

3. Types of Papers

The standard geometry of a GVT consists of a chamber and a runner (Fig. 3). The chamber is an open rectangular channel that stabilizes the flow taken from a river. Then, the flow is accelerated as the channel funnels the water before it enters the chamber. The flow enters tangentially into the circular chamber, but, due to the difference in height between the inlet and the outlet, a gravitational vortex is formed. This vortex undergoes gravitation and Coriolis forces. The water path line is a spiral around the outlet axis.

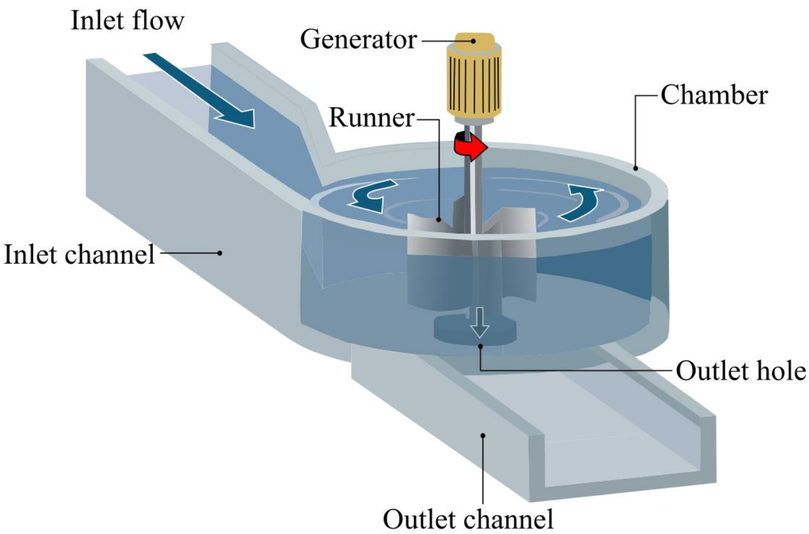


Fig. 3 GVT part and configuration.

The induced vortex is characterized using a cylindrical coordinate system. The tangential velocity increases from the inlet channel to the vortex center. This increment in tangential velocity is transferred to the turbine. Therefore, an appropriate blade geometry designed according to the velocity field can extract as much energy as possible. Once the flow pushes the runner, it continues in a spiral trajectory to the outlet by the action of gravity. This increases the axial velocity of the water to the bottom as it reaches the outlet.

4. Governing equations

In the literature, there is no standard model to characterize the vortex in GVTs, and there is no equation that relates their geometrical variables to the power they generate. Some authors do not provide enough information about the model they used, so there is no way to standardize the equation or have a reference point for future studies. Table 3 shows different mathematical correlations to characterize the vortex in the literature. Interestingly, in GVT chambers, both fluids (water and air) share the same physical properties, i.e., velocity fields and turbulence. The governing equations that describe the unsteady, viscous, and vortex formation of the turbulent flow in GVTs are continuity and Navier–Stokes eq. (14).

Table 3. Mathematical models developed to characterize the vortex generated inside GVTs and governing equation.

Mathematical models to characterize the vortex formed			
Author	**Tangential velocity equation**	**Comments**	**Number**
Mulligan et al. [15]	$v_\theta(r) \propto 1/r$	-	**(1)**
Einstein & Li [16]	$v_\theta(r) = \frac{\Gamma}{2\pi r}$	-	**(2)**
Vatistas [17]	$v_\theta(r) = \frac{\Gamma}{2\pi}\left(\frac{r}{({r_c}^4+r^4)^{\frac{1}{2}}}\right)$	when $0 \leq r \leq \infty$	**(3)**
Rosenhed [18]	$v_\theta(r) = \frac{\Gamma}{2\pi}\left(\frac{r}{({r_c}^2+r^2)}\right)$	-	**(4)**
Hite & Mih [19]	$v_\theta(r) = \frac{\Gamma}{2\pi}\left(\frac{2r}{({r_c}^2+2r^2)}\right)$	-	**(5)**
Odgaard et al. [20]	$V_\theta(r) = \frac{\Gamma}{2\Pi r}\left[1 - exp\left(-\frac{1}{4}\frac{v_z}{Hv}r^2\right)\right]$	-	**(6)**
Rankine [21]	$v_\theta(r) = \omega r = \frac{\Gamma}{2\pi}\frac{r}{r_c^2}$	when $r < r_c$	**(7)**
	$v_\theta(r) = \frac{\Gamma}{2\pi r} = \omega\frac{r_c^2}{r}$	when $r > r_c$	**(8)**
Burgers [22]	$v_\theta(r) = \frac{EC}{2\pi r}\left(e^{\frac{-Ar^2}{2\pi}}\right)$	-	**(9)**
Rahman et al. [23]	$v_\theta(r) = \frac{(\Gamma_\infty)(r_c)}{\sqrt{[8({r_c}^2)(g)(\pi^2)(H-h)+{\Gamma_\infty}^2]}}$	-	**(10)**
Marian et al. [24]	$v_\theta(r) = \frac{\Gamma d\sqrt{2(g)(H+h)}}{2(\pi)(r)}$	-	**(11)**
Governing System Equations			
Continuity	$\frac{\partial v_r}{\partial r} + \frac{\partial v_z}{\partial Z} + \frac{v_r}{r} = 0$	-	**(12)**
Navier Stokes	$\frac{\partial \pi}{\partial t} + \bar{u}\cdot(\nabla\bar{u}) = \frac{-1}{\rho}\nabla p + v\nabla^2\bar{u} + \bar{g}$	-	**(13)**

where v_θ and v_z are tangential and axial velocity, respectively; Γ is circulation; r, water radius; rc, air core radius; v, kinetic viscosity; C and E are constants; g is gravity acceleration; and H, vortex height, where

$$\Gamma = \oint_L \bar{u}.\,dl \qquad \textbf{(14)}$$

where $\vec{v}$ is velocity field and L is the vertical axis at surface. However, Stokes' theorem expresses the previous equation with a rotational velocity field.

$$\Gamma = \iint_A (\nabla_x \bar{u}) \cdot dA \qquad (15)$$

where A is the surface area and the rotational velocity filed $(\nabla_x\vec{v})$ is equal to the vector field vorticity (Ω). The Eq. $\Gamma = \iint_A \Omega\, dA$ **(16)** is expressed as:

$$\Gamma = \iint_A \Omega\, dA \qquad (16)$$

In the Navier–Stokes equation, $\bar{u}$ represents the velocity vector and is defined in Eq. $\bar{u} = (u, y, w)$ (17); additionally, ∇ reduces the partial derivation in each component (x, y, z) and is explained by Eq. $\nabla = \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}$ (18).

$$\bar{u} = (u, y, w) \qquad (17)$$

$$\nabla = \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \qquad (18)$$

To exemplify the variables in Table 3, Fig. 4 shows the physical behavior of a water particle (wp) inside a GVT chamber. Fig. 4 shows the (a) side and (b) top views of a GVT.

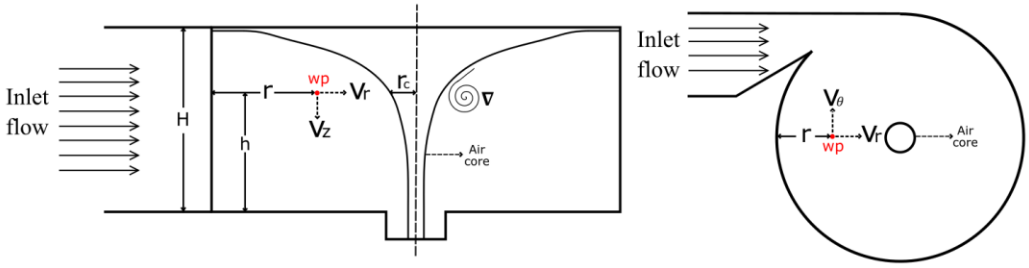


Fig. 4 Velocity profiles and variables for water particle inside GVT chamber.

5. GVT Research

The efficiency of GVTs is lower than that of conventional turbines, such as Francis, Pelton, and Kaplan. Therefore, research has focused on optimizing their geometry to increase their hydraulic efficiency. Different chambers have been used to increase the outlet velocity and form a rapid and stable vortex. The studies into GVTs have been focused on two fields: numerical and numerical-experimental research. Only a few studies have investigated their economic viability.

5. 1 Numerical Studies

Li et al. [25] analyzed the effect of chamber height and inlet velocity on three different chamber geometries in Ansys Fluent. They reported that Coriolis force is the predominant factor in vortex formation and acceleration is generated by said Coriolis force, while viscosity force can be neglected.

Wanchat et al. [26] stablished the incidence of water level and chamber geometry on the vortex's tangential velocity in Ansys Fluent. They studied two chamber designs: standard and rectangular. They also determined the tangential velocity along the radial direction with different water heights. They found the best design to be the standard chamber due to the vortex symmetry it produced. The rectangular chamber presented turbulence on the corners, which affected the vortex and its performance.

Gheorghe et al. [27] analyzed the radial, axial, and tangential velocity in a GVT with a conical chamber and a runner. They concluded that tangential velocity increases from the walls, and the maximum values are close to the vortex nucleus.

Dhaka et al. [28] determined the effect of chamber geometry on the outlet velocity in a conical chamber. They modified several geometrical parameters: chamber diameter, conical angle, width at the chamber inlet, and notch angle. As a result, they obtained a maximum outlet velocity with a chamber diameter of 0.52 m, a conical angle of 23°, a width of 0.1 m, a height of the water inside the chamber of 0.4 m, and a notch angle of 43°.

A numerical study by Sreerag et al. [29] determined the effect of the conical angle and outlet diameter on the vortex's tangential velocity. They evaluated different configurations changing the angle and, then, the outlet diameter in proportion to the chamber diameter. As a result, they obtained a maximum tangential velocity in the vortex with a conical angle of 14° and an outlet diameter of 0.3D.

In turn, Rehman et al. [30] evaluated the influence of the chamber's geometrical parameters on vortex formation and outlet velocity using a numerical analysis. They evaluated nine configurations with different parameters (ratio between chamber and outlet diameters, inclination of inlet channel angle, and notch angle) with constant operating conditions and an inlet velocity of 3 m/s. In their case, the best chamber geometry for outlet velocity and vortex formation was a configuration with a 2.5 ratio between diameters, a 60° inlet channel angle, and a 30° notch angle.

Furthermore, Wardhana, et al. [31] studied the effects of 8 runners with different profiles, chord lengths, and blade numbers under the same operating conditions on the power generated by a GVT. The highest efficiency they found was 55%.

5.2 Numerical and Experimental Analyses

The same authors, Wanchat et al. [32], found a relation between the outlet diameter and the power generation in a cylindrical chamber. They implemented a runner with 5 blades in their study. They configured the inlet velocity and varied the outlet diameter. They concluded that an outlet diameter between 14% and 18% of the chamber diameter offers the best performance. Fig. 5 shows the laboratory where the experimental phase of their study was completed.

Fig. 5 Experimental setup used in [32].

Mulligan et al. [15] studied an analytical, numerical (Ansys CFX), and experimental case of vortex formation in a standard chamber. Their main objective was to stablish a turbulence model that represented the vortex and its tangential velocity. They compared the numerical results they obtained with turbulence models and their experimental results. The most accurate results were obtained with the BSL RSM turbulence model, although there were errors at the chamber inlet and in the vortex nucleus. Once they defined the turbulence model, they compared the vortex formation in the study by Vatista [17] with the experimental study. Their numerical and experimental results showed a difference of 26% in vortex formation. They emphasized that Vatista's model showed a high similarity with experimental results.

Dhakal et al. [33] evaluated the efficiency of three runners in two types of GVT: conical and cylindrical chamber. The 12-blade runner in the conical chamber was more efficient (30%) than the other runners in the cylindrical chamber. They concluded that the best runner position was at the bottom of the chamber, due to higher velocities in that region.

Shabara et al. [34] conducted a numerical study in Ansys Fluent with experimental measurements. They used the GVT geometry proposed by Franz Zotlöterer [10]. The difference between the numerical and experimental error (2-7%) proved the validity of their numerical. They concluded that water inlet height is less influential than chamber geometry in GVT performance.

Dhakal et al. [35] experimentally validated a numerical study carried out in Ansys Fluent. They investigated the efficiency of two GVTs under the same operating conditions but with two different chamber geometries: conical and cylindrical. Their numerical and experimental results showed that the conical chamber was more efficient. In their experimental study, the conical chamber presented a higher efficiency (36.84%) than its cylindrical counterpart (20.94%) measured with respect to the generated electrical power.

Ankit et al. [36] studied the effect of adding another runner at the bottom of the GVT on power generation. Their runner, called booster runner, uses the water that falls after leaving the main runner. They used three types of pressure boosters; two of them had three blades but different blade profiles. Their results showed that the main runner combined with the pressure booster achieved a higher efficiency (79%) than the main runner by itself (76%). They concluded that the performance of the GVT can be improved if a booster runner is added.

Rahman et al. [23] experimentally compared the relationship between GVT efficiency, operating conditions, and some geometrical parameters. They studied different water inlet heights and mass flows. The geometrical GVT parameters they investigated were chamber diameter, blade radial length, and number of blades in the runner. The highest efficiency they obtained experimentally was 42.1% with three blades in a chamber with an outer diameter of 00.027 m.

Wichian et al. [37] studied the effects of blade thickness in a standard GVT. They increased blade thickness from 0% to 100% (Fig. 6). The runner's diameter and height were 0.45 m and 0.32 m, respectively. The turbine with a thickness of 50% presented the highest efficiency and was experimentally compared with a 0%-thickness runner at three flow rates. Their experimental results showed that the turbine with a 50%-thickness produced a higher torque (45.78 Nm) and efficiency (38.6%) than the 0%-thickness runner (42.12 Nm in torque and 37.8% in efficiency). Thus, they corroborated their numerical results.

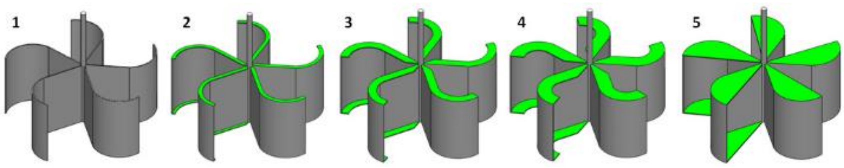


Fig. 6 Blades of different thicknesses studied in [37].

Dhakal et al. [38] carried out a numerical and experimental study to evaluate three different runners (Fig. 7). They used Ansys CFX to investigate the flow through the channel, the turbine, and the blades. Their numerical study showed that the curved profile was the most efficient (82%). Later, they conducted an experimental test of a GVT prototype to validate the analysis. Their tests proved the numerical study was right, and the maximum efficiency was 71%.

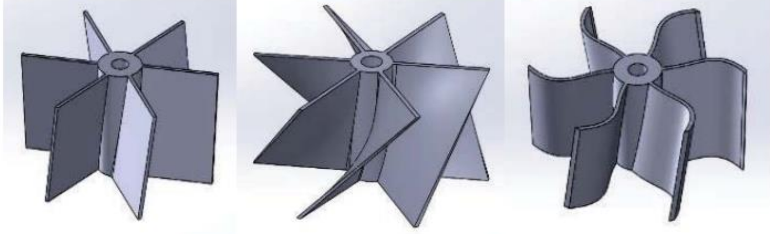


Fig. 7 GVT runner with straight, twisted, and curved blades studied in [38].

Power et al. [39] experimentally studied the operating conditions of a GVT. They recorded variations in flow rate, water inlet height, the geometry and number of blades, angular velocity, vortex height, and force generated in the runner with each configuration. They computed and compared the inlet and outlet powers and efficiency of each configuration. They found that turbine efficiency increased with the size and number of the blades. Among the three inlet heights they tested, 25 cm above the chamber bottom (35% of the chamber total height) showed the best performance.

Stritram and Suntivarakorn [40] studied the effect that deflected plates placed on top and the bottom of the chamber had on torque. They reported a system efficiency of 50%.

Hidayat et al. [41] studied the effect of different notch widths on runner velocity. The highest runner velocity they achieved was 90 rpm with a totally open notch. They reported a power generation of 27.5 with a DC battery to represent a generator.

Rizwan et al. [42] [43] experimentally studied different multi-stage runners for a GVT with conical chamber. They reported that the three-stage runner generated more electrical power and torque than the two-stage or single runners. They also concluded that the top runner must be designed for minimal vortex distortion. Fig. 8 shows the GVT system and multi-stage runner they implemented.

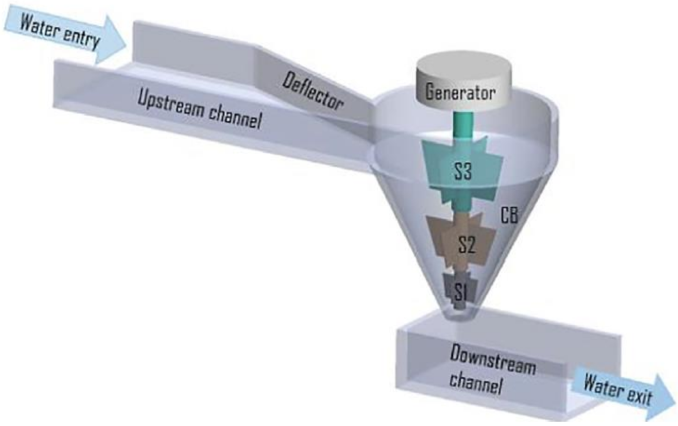


Fig. 8 GVT system and multi-stage runner studied in [42] [43].

We summarized the main geometric parameters obtained from this literature review in Table 4. Such parameters are presented in a non-dimensional form due to the different dimensions they use. The chamber diameter (D) will determine the other parameters.

Table 4 Parameters investigated in GVT literature.

Main Parameter	Study	Major findings	Reference
Water inlet height	CFD and experimental	Result differences between 0% and 7%	[34]
Turbulence model	Analytical, CFD, and experimental	BSL RSM	[15]
Chamber geometry	CFD and experimental	Cylindrical Conical Concave and convex	[26] [35] [44]
Chamber diameter Angle of the area reduction zone Width of the inlet channel Angle of the cone Channel height	CFD	0.8 m 70° 0.125 D 23° 0.2 D	[28]
Outlet diameter for a conical chamber	CFD	0.3D	[29]
Ratio between the chamber diameter and the outlet diameter (D/d) Inlet channel slope angle	CFD	2.5 60°	[30]
Outlet diameter	CFD and experimental	0.14D–0.18D	[32]
Number of blades in the runner	CFD and experimental	12	[33]
Thickness of runner blades	CFD and experimental	Blade thickness	[37]
Blade profile in the runner	CFD	Curved profile	[38], [31], [45]
Multi-stage runner	experimental	Multi-stage runner	[42] [43]

It can be seen from Table 4 that there is no optimal geometry reported in numerical or experimental studies, which might be due to a lack of knowledge about the effect of GVT geometry on its efficiency. Additionally, the methodology used by some authors is not very clear in the studies mentioned above or their mathematical models. Also, there is no consensus regarding parameters selection. Most authors did not detail their numerical study [22-34]. Mesh quality, convergence criteria, simulation type and total time are omitted, although are important to replicate the studies [46].

One of the main parameters that should be determined is GVT efficiency. Some authors have reported a GVT efficiency higher than 70% [36],[38]; others authors, under 55% [23], [31], [33], [35], [37], [40]; and yet some others did not report it [32], [34], [41], [44]. However, only Zötloterer [10] reported how to determine the GVT efficiency, but the equation do not apply for every geometry turbine. As mentioned in previous paragraph, the principal parameter studied is according to chamber design (geometry, diameter, angles, etc.). Only few researches studied the GVT system (with runner) [23], [31], [32-34], [36-39]. Even the design runner represents a significant increase or decrease in GVT efficiency.

6. GVT Patents

The technology of generation systems that use renewable energy sources is constantly developing and growing. The main reason behind it is the need to improve current generation systems based on fossil fuels. Fig. 9 shows the number of patents between 2006 and 2016 classified by the technology they use to generate electricity from renewable sources. There is a significant increase in the number of patents of hydraulic technologies. However, there are only three patents related to GVTs, and all of them belong to the engineer Franz Zotlöterer.

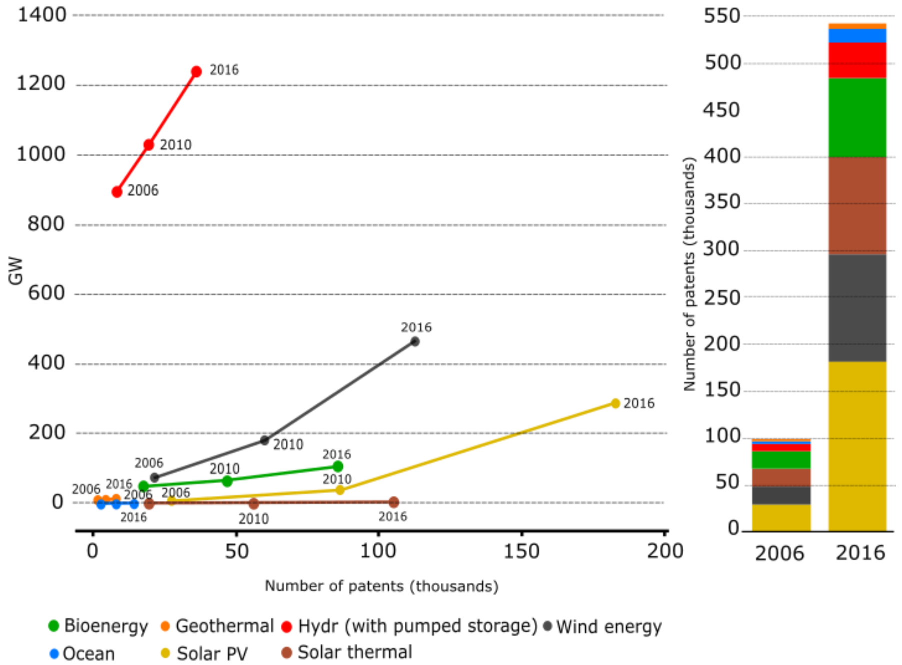
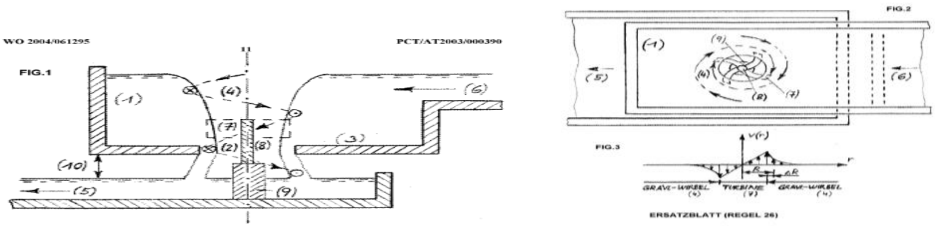
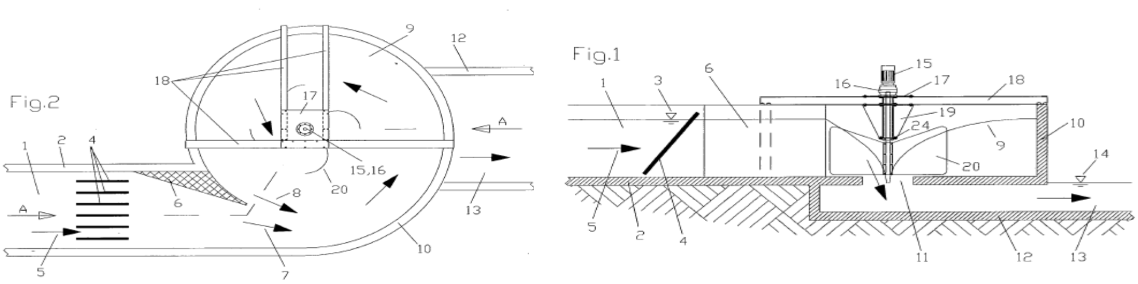


Fig. 9 Number of registered patents by type of renewable energy. Taken from [47].

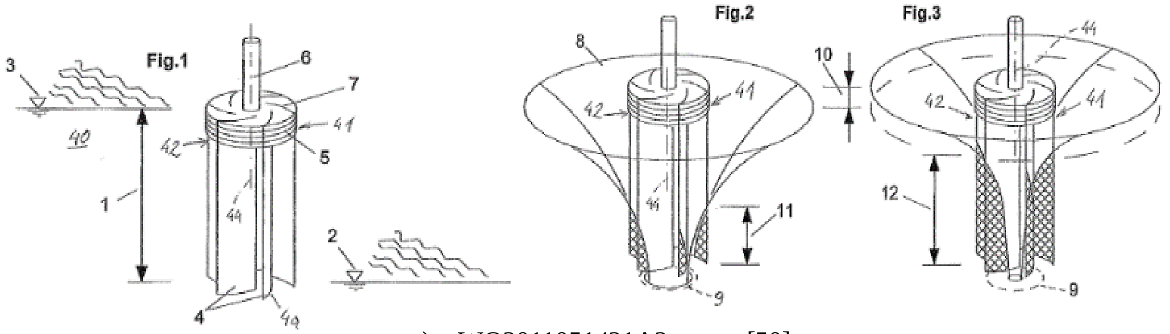
The first GVT patent [48] claims the invention of a system using the kinetic energy of a fluid to generate electricity (Fig. 10 (a)). It consists of an inlet channel (6) connected to a circular chamber (1), which induces a vortex that moves a runner (8), and the fluid is returned to the original affluent through an outlet (9). The second patent [49] (Fig. 10 (b)) claims the invention of flow wedge the entrance channel (6) described in the first patent, which allows the fluid inlet to be tangential and increase its velocity. The third patent [50] claims (Fig. 10 (c)) the invention of a cylindrical runner with a number of blades around the circumference, where runner is placed vertically.



a) WO2004061295A2 Patent [48].



b) WO2008141349A2 patent [49]



c) WO2011051421A2 patent [50].

Fig. 10 GVT patents.

7. GVT in the world

Table 5 lists Gravitational Vortex Turbines (GVTs) installed worldwide sorted by installation date. We obtained this information from our literature review and commercial web sites. Most GVTs (19 projects) are installed in Europe and have 154.3 kW of installed generation capacity, followed by Asia (55.1 kW installed capacity in five projects), America Latina (22.2 kW in two projects), and Oceania (0.2 kW in one project). All the GVTs installed worldwide between 2004 and 2018 have a combined capacity of 231.8 kW. The trend shows an increase in GVT installed and they have higher performance (less flow rate or head) with output power of 15 kW with lower flow rate (*). However, we could not determine the installation date of 9 projects because references [10], [51], [52] mentioned the operating condition but not the installation date.

Two GVTs were installed, one in Schöftland and one in Suhr (Switzerland), with the same capacity but different flow rates. We could not determinate their geometry differences (in chamber, runner and/or generate) but unit in Schöftland outperforms the GVT in Surh.

Table 5 GVTs installed worldwide.

Country	City	Year	Head (m)	Flow rate (m^3/s)	Capacity (kW)
Australia [53]	Kalorama	2004	0.8	0.05	0.2
Austria [10]	Obergrafendorf	2005	0.9	0.9	10
Australia [53]	Marysville	2008	0.6	0.11	11
Switzerland [54]	Schöftland*	2009	1.5	1	15
Switzerland [51]	Suhr, Aargau	2009	1.5	2.2	15
Lithuania [55]	Kaunas	2010	1.5	0.5	4.4
Austria [55]	St. Veit an der Glan	2011	0.9	0.7	3.3
Germany [55]	Niedersfel, Winterberg	2012	1.4	0.5	4.7
Germany [55]	Wesentz, Sachsen	2013	1.2	0.5	6
Thailand [55]	Taksinmaharat	2014	1.5	1	8.5
Italy [55]	San Vito	2014	0.4	0.9	4
Indonesia [56]	Bali	2015	1.8	1	15
Peru [55]	Junín	2016	1.4	0.9	7.2
Nepal [57]	Katmandú	2016	1.5	2	1.6
Chile [52]	Doñihue	2017	2.1	2	15
Italy [55]	Sesto Campano	2017	1.5	1	9
Italy [55]	Bivio Mortola	2017	1.8	0.8	9
India [51]	Kerela	2018	1.5	1	10
Estonia [52]	Otepää	-	1.6	0.75	5.5
Austria [10]	-	-	1.8	1	10
Austria [10]	-	-	1.5	0.9	8.3
Austria [10]	-	-	1.2	1.2	7.5
Austria [10]	-	-	1.4	0.6	5
Austria [10]	-	-	1	0.9	4.6
Austria [10]	-	-	1.4	0.5	4
Austria [10]	-	-	1.6	2	18
India [51]	Dabka, Nainital	-	2	1.5	20

Fig. 11 summarizes the installed capacity per year and accumulated installed capacity between 2004 and 2018 of all the GVTs worldwide. Most capacity was installed in 2017. However, the undated installed turbines represent 36% of the total installed power, which does not allow us to determine if recent years (2015 to present) have presented an in increase in GVT installed capacity. This is because most studies to improve their performance have been carried out in those years and could had been applied to them.

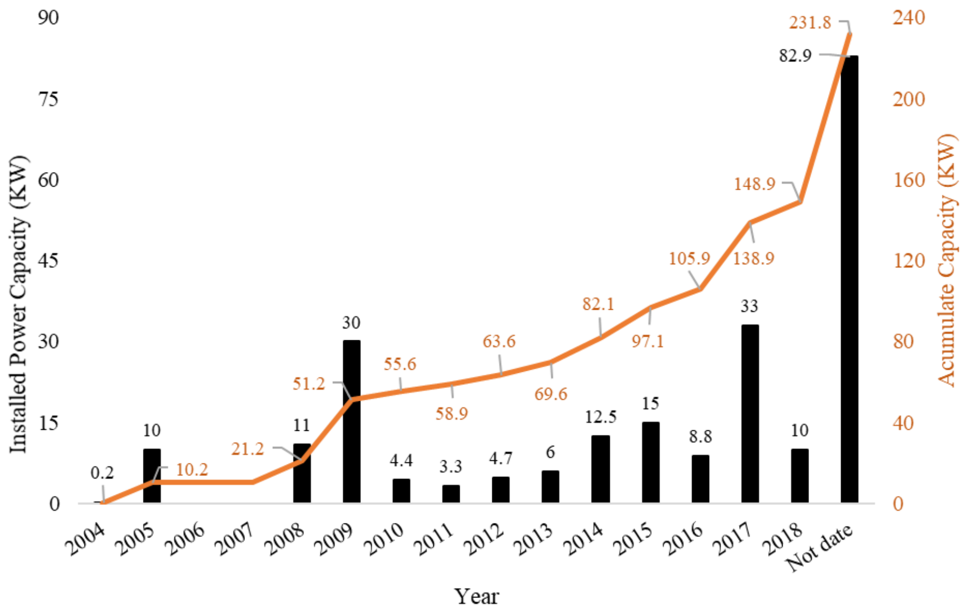


Fig. 11 Annual variation in installed power capacity of the GVTs worldwide.

Fig. 12 shows the distribution of GVTs per country. Austria has the highest installed capacity with 70.7 kW, which represents 31% of the total installed capacity. This trend is ratified by Manzano et al. [58] who reported that, in 2011, Austria's installed capacity was 1284 MW, generated by 2993 small hydro power plants, which makes it one of European countries with the highest generation capacity by said power plants.

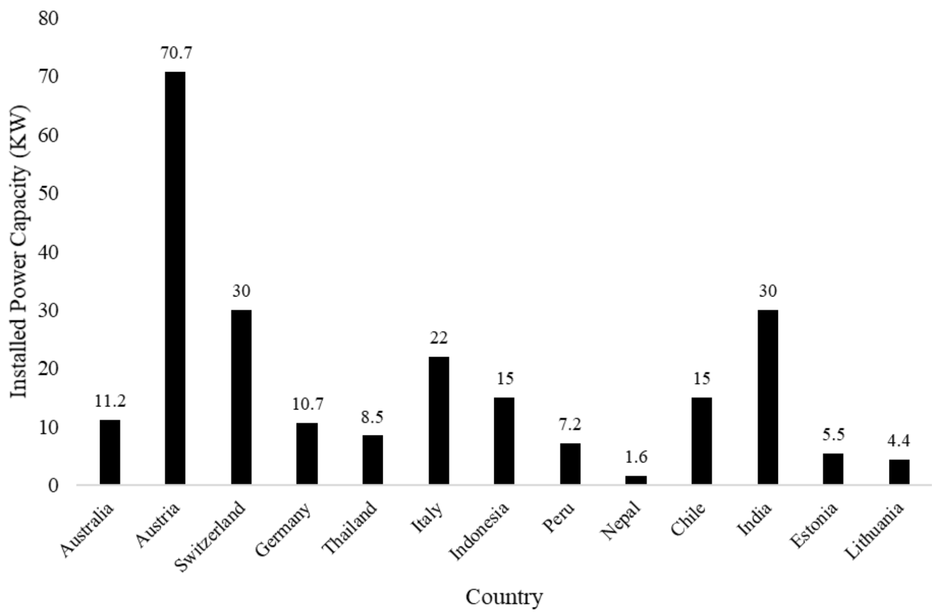


Fig. 12 Distribution of the installed capacity of GVTs per country.

8. Economic viability

In the literature, there are a few economic studies into GVTs. The main costs in the installation of the system are labor and licensing. For example, Vladimir et al. [31] reported a total labor cost of 17,500 USD to build a GVT in Peru (a 10-kW system). Dhakal et al. [59] reported a labor cost of 10,000 USD in their case study in Nepal in 2015. Zotlöterer [60] mentioned a construction cost of 110,000 USD (for a 10-kW system, 1 EUR = 1.1 USD). Labor costs are significantly lower in developing countries, which reduces the total investment. However, Vladimir et al. and Zotlöterer mentioned payback times of 16 and 7 years, respectively (with different costs of domestic electricity: ~0.1 USD/kWh in Peru and ~0.22 USD/kWh assumed by Zotlöterer). In the case of Peru, the authors concluded that their system could reduce the payback period to 8 years, considering a runner without optimization and a basic electrical system; this period is similar to that estimated by commercial manufacturers [60]. The actual cost of GVTs depends on their type, country requirements, and labor cost. Fig. **13** presents estimated breakdown of the total cost of installing a GVT system.

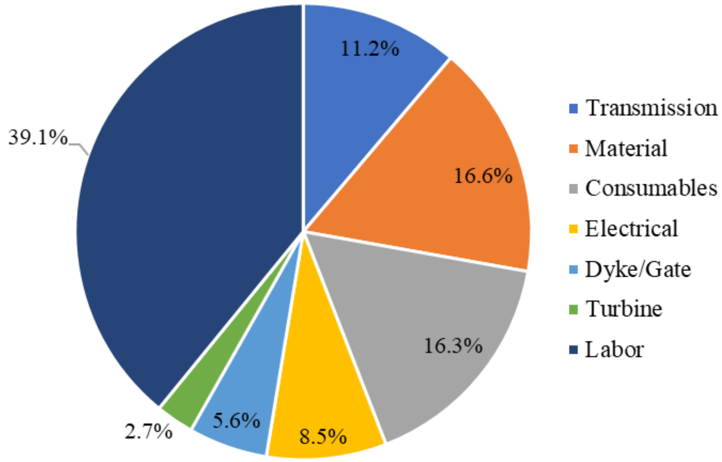


Fig. 13 Breakdown of GVT system cost. Taken from [31].

9. Companies manufacturing GVTs worldwide

Only five companies in the world design and install GVTs:

- Zotlöterer [10] is a company is located in Obergrafendorf, Austria. Established in 2004, it plans and designs GVTs in different countries. Additionally, it optimizes wind turbines at low wind speed. In 2005, the company constructed its first GVT, which supplies 60,000 kWh per year to around 15 households.
- Kourispower PTY. LTD. [53] is an Australian company that designs and makes GVT and improves electrical transmission and hydroelectric storage. In 2008, they conducted a test in Australia with a generated power of 12kWh per day.
- AquaZoom (previously known as Green Renewables) AG [51] is a Swiss company founded in 2015. Its first GVT was constructed in Suhr, Switzerland under the name Green Renewables. Their first GVT as AquaZoom was installed in Kerela, India, with a total installed capacity of 10 kW.
- Wasserwirbelkraftwerke Schweiz [55] is a partnership of FLS Biobau GmbH, Ingenieurbüro Arnet GmbH, and Tree Engineering GmbH. It was established in 2011 in Schöftland, Switzerland. It designs, plans, and constructs GVTs. In 2011 they installed a test GVT whose capacity was 10–15 kW.
- Turbulent Hydro [52] is a Belgian company founded in 2015. It researches, designs, and constructs GVTs. Its first turbine was implemented in Doñihue, Chile, in 2017. That turbine supplies energy to around 60 rural households and generates 15 kW.

10. Future trends

According to this literature review, a better runner configuration for the chamber geometry should be investigated. Hydrodynamic profiles like NACA have not been implemented in the runner, which might result in studies into multi-stage runner blades. An important parameter that should be numerically and experimentally studied is the angle of attack between the fluid and the blade in order to produce the best possible interaction. Additionally, new chamber designs should be explored.

According to several companies [51], [52], [61], they have planned to build some GVTs or are building them (Table 6). However, said companies do not provide an estimated date for completion. According to Alzamora et al. [31], heavy machinery or special labor are not necessary to build a GVT. Therefore, we can estimate 8 months to finish the GVTs in progress. Remarkably, the GVTs in Taiwan (in progress) and Philippines (proposal) will have the highest installed capacity in the world.

Based on Table 6, we can determine that the general interest in GVTs has increased in recent years, with 15 future projects (4 in progress) that implement this technology. This is because GVTs are great alternatives for environmentally friendly electricity generation and are not expensive to build.

Table 6 GVT projects worldwide.

Country	City	State	Head (m)	Flow rate (m^3/s)	Capacity (kW)
UK [51]	Chester	In progress	1.5	1000	100
Taiwan [52]	Ylang	In progress	3.3	5.8	600
France [52]	Versalles	In progress	3.2	0.7	5.5
Chile [52]	Cunco	In progress	1.5	0.9	5
Philippines [52]	Mindanao	Proposal	-	-	120-150
USA [61]	New York	Proposal	-	-	10-100
UK [51]	Haughton	Proposal	1.1	2	28
UK [51]	Frome	Proposal	1.5	1	28
UK [51]	Northampton	Proposal	2.2	2	28
UK [51]	Otterburn	Proposal	1.9	2	25
India [51]	Karbi Anglong	Proposal	-	-	13
India [51]	Heng Bung	Proposal	1.5	1.5	12
UK [51]	Warmingham	Proposal	1.9	0.9	12

UK [51]	Milton Keynes	Proposal	1.2	1.2	10
India [51]	Chereerapunji	Proposal	-	-	9

11. Conclusions

GVTs are economic, off-grid energy solutions because they are easy to manufacture and implement. GVTs constitute a new alternative for renewable energy generation. They can be installed in homes far from the national grid system, in rivers, and channels with low flow rates and heads. For those reasons, the use of GVTs has increased worldwide, especially in Europe. However, considering their hydrographic richness, South American countries should consider this type of turbine as well.

According to the review of literature, patents, and companies above, GVTs represent a new technology that has not been sufficiently studied and whose reported efficiency is still low. The studies published in this field do include few details about their methodology. As a result, a mathematical model that relates their geometrical parameter cannot be established, and an optimal configuration that produces the best efficiency to extract the maximum energy from the fluid cannot be defined.

Nomenclature

v_θ	Tangential velocity (m/s)	r	Water particle radius (m)
Γ	Circulation (m^2/s)	r_c	Air vortex radius (m)
v_z	Axial velocity (m/s)	H	Vortex height (m)
v	Kinetic viscosity (m^2/s)	ω	Angular velocity (m/s)
E	Constant	C	Constant
g	Gravity acceleration (m/s^2)	h	Water particle height (m)
v_r	Radial velocity (m/s)	$\bar{u}$	Velocity vector (m/s)
∇	Partial derivation	ρ	Water density (kg/m^3)
L	Vertical axis at surface (m)	A	Surface area (m^2)
Ω	Vorticity (s^{-1})	wp	Water particle

References

[1] actclean;, "Gravitation water vortex power plant as bioreactor," 2011. [Online]. Available: http://act-clean.eu/index.php/Gravitation-water-vortex-power-plant-as-biore;100.361/1. [Accessed: 14-Jun-2018].

[2] SEforALL, "Sustainable Development Goal 7," 2015. [Online]. Available: https://www.seforall.org/sustainable-development-goal-7. [Accessed: 14-Jun-2018].

[3]UNESCO, "La energía hidroeléctrica," 2019. [Online]. Available: http://www.unesco.org/new/es/natural-sciences/environment/water/wwap/facts-and-figures/all-facts-wwdr3/fact-6-hydropower/. [Accessed: 14-Jun-2018].

[4] B. Sugiharto, S. Soeparman, D. Widhiyanuriyawan, and S. Wahyudi, "Characteristics of the savonius wind turbine using multiple guide vanes," Int. J. Fluid Mach. Syst., vol. 13, no. 3, pp. 606–614, 2020.

[5] IRENA International Renewable Energy Agency, Renewable Power Generation Costs in 2017. 2018.

[6] B. R. Deemer et al., "Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis," Bioscience, vol. 66, no. 11, pp. 949–964, Nov. 2016.

[7] G. Enio, E. M. de Andrade, M. de F. Rosa, L. de F. Araújo, and A. C. M. Meireles, Revista Ciência agronômica., vol. 38, no. 1. 2007.

[8] GIE, "Pequeñas Centrales Hidroeléctricas (PCH´s)," 2014. [Online]. Available: http://www.gie.com.co/es/productos/energias-renovables/pequenas-centrales-hidroelectricas-pch-s. [Accessed: 14-Jun-2018].

[9] J. L. Márquez, M. G. Molina, and J. M. Pacas, "Dynamic modeling, simulation and control design of an advanced micro-hydro power plant for distributed generation applications," Int. J. Hydrogen Energy, vol. 35, no. 11, pp. 5772–5777, Jun. 2010.

[10] F. Zotlöterer, "Gravitational Water Vortex Power Plants," 2003. [Online]. Available: http://www.zotloeterer.com/welcome/gravitation-water-vortex-power-plants/configuration-function/. [Accessed: 05-Mar-2018].

[11] K. Shahverdi, R. Loni, B. Ghobadian, S. Gohari, S. Marofi, and E. Bellos, "Numerical Optimization Study of Archimedes Screw Turbine (AST): A case study," Renew. Energy, vol. 145, pp. 2130–2143, 2020.

[12] Wasserkraft, "Water turbines technology." [Online]. Available: http://www.wws-wasserkraft.at/en/water-turbines-technology.html. [Accessed: 14-Jun-2018].

[13] M. M. Rahman, J. H. Tan, M. T. Fadzlita, and A. R. Wan Khairul Muzammil, "A Review on the Development of Gravitational Water Vortex Power Plant as Alternative Renewable Energy Resources," in IOP Conference Series: Materials Science and Engineering, 2017.

[14] X. Zhang, M. Zhang, W. Chen, F. Yang, and X. Guo, "Free surface vortex in a rotating barrel with rods of different heights," Int. J. Fluid Mach. Syst., vol. 9, no. 4, pp. 325–331, 2016.

[15] S. Mulligan, J. Casserly, and R. Sherlock, "Experimental and numerical modelling of Free-Surface Turbulent Flows in Full Air-Core Water Vortices," Adv. Hydroinformatics, pp. 549–569, 2014.

[16] H. A. Einstein and H. Li, "Steady vortex flow in a real fluid.," Proceding Heat Transf. Fluid Mech. institute, Stanford Univ., pp. 33–43, 1951.

[17] G. H. VATISTAS, S. LIN, and C. K. KWOK, “Theoretical and experimental studies on vortex chamber flows,” AIAA J., vol. 24, no. 4, pp. 635–642, 1986.
[18] L. Rosenhead, “The spread of vorticity in the wake behind a cylinder,” R. Soc. Publ., vol. 127, no. 806, pp. 590–612, 1930.
[19] J. E. Hite Jr and W. C. Mih, “Velocity of Air-Core Vortices at Hydraulic Intakes,” J. Hydraul. Eng., vol. 120, no. 3, pp. 284–297, 1994.
[20] O. A. Jacob and M. ASCE;, “Free-Surface Air Core Vortex,” J. Hydraul. Res., vol. 112, pp. 610–620, 1986.
[21] W. J. M. Rankine, A manual of applied mechanics. London: London: R. Griffin, 1858.
[22] J. M. Burgers, “A Mathematical Model Illustrating the Theory of Turbulence,” Adv. Appl. Mech., vol. 1, no. C, pp. 171–199, 1948.
[23] M. Rahman, T. J. Hong, R. Tang, and L. L. Sung, “Experimental Study the Effects of Water Pressure and Turbine Blade Lengths & Numbers on the Model Free Vortex Power Generation System,” Int. J. Curr. Trends Eng. Res., vol. 2, no. 9, pp. 13–17, 2016.
[24] M. G. Marian, T. Sajin, and A. Azzouz, “Study of Micro Hydropower Plant Operating in Gravitational Vortex Flow Mode,” Appl. Mech. Mater., 2013.
[25] H. feng LI, H. xun CHEN, Z. MA, and Y. ZHOU, “Formation and Influencing Factors of Free Surface Vortex in a Barrel with a Central Orifice at Bottom,” J. Hydrodyn., 2009.
[26] S. Wanchat and R. Suntivarakorn, “Preliminary design of a vortex pool for electrical generation,” J. Comput. Theor. Nanosci., vol. 13, pp. 173–177, 2012.
[27] B. Gheorghe-Marius, Marian; Tudor, Sajin; Iulian, Florescu; Dragos-Iulian, Nedelcu; Constantin-Narcis, Ostahie; Catalin, “The concept and theorical study of micro hydropower plant with gravitational vortex and turbine with rapidy steps,” World energy Syst. Conf. - WESC, 2012.
[28] S. Dhakal, A. B. Timilsina, R. Dhakal, D. Fuyal, T. R. Bajracharya, and H. P. Pandit, “Effect of Dominant Parameters for Conical Basin : Gravitational Water Vortex Power Plant,” in International Conference on Technolog and Innovation Management & IOE, 2014, vol. 1, pp. 380–386.
[29] S. R. S, R. C. K, and J. B. S, “EFFECT OF OUTLET DIAMETER ON THE PERFORMANCE OF GRAVITATIONAL VORTEX TURBINE WITH CONICAL BASIN,” Int. J. Sci. Eng. Res., vol. 7, no. 4, 2016.
[30] W. Rehman, M. Ijaz, and A. Munir, “Designing of micro gravitational vortex turbine’s vortex pool,” in American Society of Mechanical Engineers, Power Division (Publication) POWER, 2017, vol. 2.
[31] V. J. Alzamora Guzmán, J. A. Glasscock, and F. Whitehouse, “Design and construction of an off-grid gravitational vortex hydropower plant: A case study in rural Peru,” Sustain. Energy Technol. Assessments, vol. 35, no. June, pp. 131–138, 2019.
[32] K. Wanchat, Sujate; Ratchaphon, Suntivarakorn; SujinWanchat; Kitipong Tonmit; Pongpun, “A parametric study of gravitational vortex power plant,” Adv. Mater. Res., vol. 805, pp. 811–817, 2013.
[33] S. Dhakal, S. Nakarmi, P. Pun, A. Bikram Thapa, and T. Ratna Bajracharya, “Development and testing of runner and conical basin for gravitational water vortex power plant,” J. Inst. Eng., vol. 10, no. 1, pp. 140–148, 2014.
[34] H. M. Shabara, O. B. Yaakob, Y. M. Ahmed, A. H. Elbatran, and M. S. M. Faddir, “CFD validation for efficient gravitational vortex pool system,” J. Teknol., vol. 74, pp. 97–100, 2015.
[35] S. Dhakal et al., “Comparison of cylindrical and conical basins with optimum position of runner: Gravitational water vortex power plant,” Renew. Sustain. Energy Rev., 2015.
[36] A. Gautam, A. Sapkota, S. Neupane, J. Dhakal, A. B. Timilsina, and S. Shakya, “Study on Effect of Adding Booster Runner in Conical Basin : Gravitational Water Vortex Power Plant : A Numerical and Experimental Approach,” pp. 107–113, 2016.
[37] P. Wichian and R. Suntivarakorn, “The Effects of Turbine Baffle Plates on the Efficiency of Water Free Vortex Turbines,” in 3rd International Conference on Power and Energy System Engineering, 2016, pp. 8–12.
[38] R. Dhakal et al., “Computational and Exerimental Investigation of Runner for Gravitational Water Vortex Power Plant,” 6th Int. Conf. Renew. Energy Res. Appl., vol. 5, pp. 365–373, 2017.
[39] C. Power, A. McNabola, and P. Coughlan, “A parametric experimental investigation of the operating conditions of gravitational vortex hydropower (GVHP),” Clean Energy Technol., vol. 4, no. 2, pp. 112–119, 2016.
[40] P. Sritram and R. Suntivarakorn, “The effects of blade number and turbine baffle plates on the efficiency of free-vortex water turbines,” IOP Conf. Ser. Earth Environ. Sci., vol. 257, no. 1, 2019.
[41] M. N. Hidayat, F. Ronilaya, I. H. Eryk, and G. Joelianto, “Design and analysis of a portable spiral vortex hydro turbine for a Pico Hydro Power Plant,” IOP Conf. Ser. Mater. Sci. Eng., vol. 732, no. 1, pp. 0–11, 2020.
[42] R. Ullah, T. A. Cheema, A. S. Saleem, S. M. Ahmad, J. A. Chattha, and C. W. Park, “Performance analysis of multi-stage gravitational water vortex turbine,” Energy Convers. Manag., vol. 198, no. May, p. 111788, 2019.
[43] R. Ullah, T. A. Cheema, A. S. Saleem, S. M. Ahmad, J. A. Chattha, and C. W. Park, “Preliminary experimental study on multi-stage gravitational water vortex turbine in a conical basin,” Renew. Energy, vol. 145, pp. 2516–2529, 2020.
[44] A. Ruiz Sánchez, J. A. Sierra-del Rio, A. J. Guevara Muñoz, and J. A. Posada-Montoya, “Numerical and Experimental Evaluation of Concave and Convex Designs for Gravitational Water Vortex Turbine,” Akad. Baru, vol. 64, no. 1, pp. 160–172, 2019.
[45] A. S. Saleem et al., “Parametric study of single-stage gravitational water vortex turbine with cylindrical basin,” Energy, vol. 200, p. 117464, 2020.
[46] F. Doussot, G. Balarac, J. Brammer, Y. Laurant, and O. Métais, “RANS and LES simulations at partial load in Francis turbines: Three-dimensional topology and dynamic behaviour of inter-blade vortices,” Int. J. Fluid Mach. Syst., vol. 13, no. 1, pp. 12–20, 2020.
[47] IRENA, “Hydropower Technology Brief,” no. February, pp. 1–18, 2015.
[48] F. Zotlöteres, “Hydroelectric power plant,” WO2004061295A2, 2003.

[49] F. Zotlöterer, "Hydroelectric power station," WO2008141349A2, 2007.
[50] F. Zotlöteres, "HYDROELECTRIC POWER PLANT," WO2011051421A2, 2009.
[51] "Aquazoom." [Online]. Available: https://www.aquazoom.com. [Accessed: 22-Mar-2020].
[52] Turbulent;, "Turbulent micro hydropower," 2019. [Online]. Available: http://www.turbulent.be/. [Accessed: 05-Mar-2018].
[53] KCT, "KOURIS CENTRI TURBINE," 2016. [Online]. Available: http://www.kcthydropower.com/.
[54] NTDTV, "Water Vortex Power Plnat debuts in Switzerland," 2010. [Online]. Available: https://www.youtube.com/watch?v=1FA2H1HiL3o.
[55] Wasserwirbe, "Genossenschaft Wasserwirbel Konzepte Schweiz," 2017. [Online]. Available: http://gwwk.ch/. [Accessed: 05-Mar-2018].
[56] Green by Jonh;, "Vortex at Green School," 2015. [Online]. Available: http://greenbyjohn.com/vortex-at-green-school/. [Accessed: 11-Apr-2018].
[57] R. Dhakal et al., "Technical and economic prospects for the site implementation of a gravitational water vortex power plant in Nepal," in 2016 IEEE International Conference on Renewable Energy Research and Applications, ICRERA 2016, 2017.
[58] F. Manzano-Agugliaro, M. Taher, A. Zapata-Sierra, A. Juaidi, and F. G. Montoya, "An overview of research and energy evolution for small hydropower in Europe," Renew. Sustain. Energy Rev., vol. 75, pp. 476–489, Aug. 2017.
[59] R. Dhakal, R. K. Chaulagain, T. Bajracharya, and S. Shrestha, "ECONOMIC FEASIBILITY STUDY OF GRAVITATIONAL WATER VORTEX POWER PLANT FOR THE RURAL ELECTRIFICATION OF LOW HEAD REGION OF NEPAL AND ITS COMPARATIVE STUDY WITH OTHER LOW HEAD POWER PLANT," vol. 1, 2015.
[60] F. Zotlöterer, "Zotloterer Smart-Energy-System." [Online]. Available: http://www.zotloeterer.com/welcome/gravitation-water-vortex-power-plants/economy/. [Accessed: 26-Mar-2020].
[61] L. Husted, "Bard Hydropower: A Pathway to Micro Hydro DER Standardization," New York.

Jorge Sierra I am a Master in Mechanics, Energy and Production Processes from the University of Lorraine, France. Mechanical Engineer from the University of Antioquia, Colombia. I have worked with Ansys software and CFD studies for 10 years. I work as a full-timeprofessor at the Instituto Tecnológico Metropolitano, Medellín, Colombia.

Alejandro Ruiz I am Mechatronics engineer from Instituto Tecnológico Metropolitano from Medellín, Colombia. Currently, I am teacher university at ITM and master student at same university. Since 2016, I have worked with Ansys and Gravitational Vortex Turbine.

Angie Guevara I am a student of the Master's Degree in Industrial Energy Management, graduated in mechatronic engineering from the Instituto Tecnologico Metroplitano ITM (2019), with training in computational fluid dynamics, with knowledge in the advanced managementof the Ansys® platform and its CFX and Fluent packages.

Alejandro Posada Dr. Posada is interested in generating electricity by renewable sources and reducing the environmental impact of transportation. He has a BSc in Mechanical Engineering, a MEng in Aeronautics, a commercial pilot license, and a PhD in Aerospace Engineeringfrom West Virginia University. His thesis was on reducing induced drag by boundary layer control on aircraft. He was a visiting professor and postdoc at WVU and now works as a full-time tenure professor at Institución Universitaria Pascual Bravo, Colombia.