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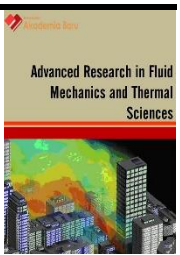

Numerical and Experimental Evaluation of Concave and Convex Designs for Gravitational Water Vortex Turbine

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ABSTRACT

The small hydroelectric power plants have become a great solution to the energy problem in the non-interconnected zones that have a low flow river. The gravitational vortex turbine is a small power plant easy to install, low maintenance and economically viable for these areas. However, the turbine has a low efficiency. Although changes in geometry could increase it. In this study, concave and convex designs are proposed for the gravitational vortex turbine tank which are studied numerically and experimentally. The numerical study was developed in ANSYS CFX V19.1 software and the experimental phase was carried out in the fluid's laboratory of the Instituto Tecnológico Metropolitano. The numerical and experimental results of the concave and convex design show a difference of 62% and 60%, respectively. The vortex formation and output velocity are the numerical parameters analysed with the software, and the electric power and torque are the parameters on the experimental phase. The tank geometry is the most important parameter to increase the turbine's efficiency, so it is recommendable to select a suitable design.

1. Introduction

One of the key points of the United Nations conference on sustainable development was the access to electricity. In the report it can be evidenced that the rural communities in Latin America are located where less electricity coverage is. Therefore, the United Nations has provided guidelines to guarantee energy to these communities. Among the guidelines are: "Establish and grant access to minimum energy consumption for lower income groups", and "Develop a regulatory framework to promote lower carbon emissions through the efficient use of energy and the development of renewable energies ..." [1].

Colombia faces the challenge of satisfying its energy demand in terms of quality and opportunity with criteria of technical efficiency and at affordable prices to its users. Especially in geographically

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isolated areas, difficult to access, and distant from the interconnected system (Non-Interconnected Zones - NIZ). Hence, the use of water resources by small hydroelectric plants (SHP's) becomes a good option to solve its energy requirements [2]. Colombia also aims to implement 30% of renewable energy in the NIZ, to date it has only 12% of them installed [3].

The extension of electricity networks in rural areas is often limited by geographical and economic aspects. Due to this situation, the use of renewable energy has been promoted, in which its generation can be carried out on site [4]. The SHP's are a good example of renewable energy, the application for the future and its generation of power cannot be overestimated [5, 6]. In recent years the implementation of micro-hydroelectric plants has increased because they have shown good performance and low implementation costs. It is estimated that the implementation of this kind of energy will continue increasing in order to reduce carbon emissions [7].

The gravitational water vortex turbine (GWVT) is one alternative of the renewable energies. It does not pollute the environment, is affordable, and has a very similar performance to a conventional hydroelectric power plant. The surface of the GWVT is a mini/micro hydro system and can be considered as a harmful (conventional reservoirs) or useful (gravitational vortex turbine) source [8].

The incidence of the cylindrical and rectangular tanks in the generation of vortex velocity was determined by a numerical study using the ANSYS Fluent software [9]. The study concluded that the optimum depth corresponds to the turbine configured with a height of 600 mm, and a cylindrical chamber; which presented a maximum velocity of approximately 0.73 m/s.

Shabara *et al.,* compared numerical and experimental results of a GWVT [10]. This investigation determined that the numerical results delivered by the software are similar to the experimental results. They argued that the variation in the turbine height is not a parameter that influences the efficiency, while the tank geometry greatly influences the efficiency of the turbine.

Wanchat *et al.,* determinated the influence of the outlet diameter for the GWVT electric power production. The authors concluded that the range of the diameter of the exit orifice should be between 200-300 mm, with a velocity for the rotor of 200 and 180 rpm with a power of 60 and 50W, respectively. They found that the water does not move small diameter rotor blades, while large diameter blades generate little torque, which translates into low velocity and low power [11].

Dhakaln *et al.,* compared conical and cylindrical tanks for GWVT. The increase in velocity was greater for the conic due to the reduction in the area. By increasing the angle of the cone the velocity is increased and more power is delivered [12]. Sagar *et al.,* determined the effect of the main GWVT parameters of a conical tank [13].

The GWVT efficiency varies with tank geometry. In previous research; cylindrical, conical, and rectangular tanks have been studied. Where the conic tanks have shown greater efficiency. Although there are several numerical and experimental studies that focus on increasing the efficiency of the GWVT with changes in geometry, the study of the tank design has shown greater change in efficiency. This continues to be the one with the greatest potential for improvement, because it directly affects the formation of the vortex and therefore the fluid outlet velocity. The objective of this study is to evaluate the efficiency of two different tank geometries: convex and concave designs, by numerical simulations and experiments.

2. Methodology

2.1 Governing Equations

Both fluids (air and water) are sharing the same velocity fields and turbulence. The governing equations for the unsteady, viscous and turbulent flow are the Navier-Stokes equations described in cylindrical coordinates as follows:

$$\frac{\partial V_r}{\partial r}+\frac{\partial V_z}{\partial z}+\frac{V_r}{r}=0 \tag{1}$$

$$V_r\frac{\partial V_\theta}{\partial r}+V_z\frac{\partial V_\theta}{\partial z}-\frac{V_rV_\theta}{r}=\upsilon\left(\frac{\partial^2V_\theta}{\partial r^2}+\frac{\partial V_\theta}{r\partial r}-\frac{V_\theta}{r^2}+\frac{\partial^2V_\theta}{\partial z^2}\right) \tag{2}$$

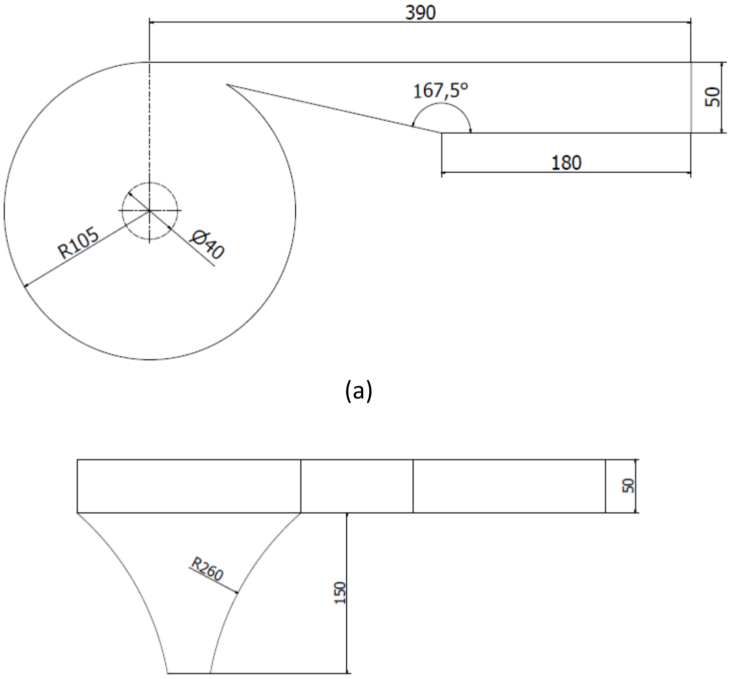
$$V_r\frac{\partial V_r}{\partial r}+V_z\frac{\partial V_r}{\partial z}-\frac{{V_\theta}^2}{r}+\frac{\partial\rho}{\rho\partial r}=\upsilon\left(\frac{\partial^2V_r}{\partial r^2}+\frac{\partial V_r}{r\partial r}-\frac{V_r}{r^2}+\frac{\partial^2V_r}{\partial z^2}\right) \tag{3}$$

$$V_r\frac{\partial V_z}{\partial r}+V_z\frac{\partial V_z}{\partial z}+\frac{\partial\rho}{\rho\partial z}=g+\upsilon\left(\frac{\partial^2V_z}{\partial r^2}+\frac{\partial V_z}{r\partial r}+\frac{\partial^2V_r}{\partial z^2}\right) \tag{4}$$

2.2 Control Volume

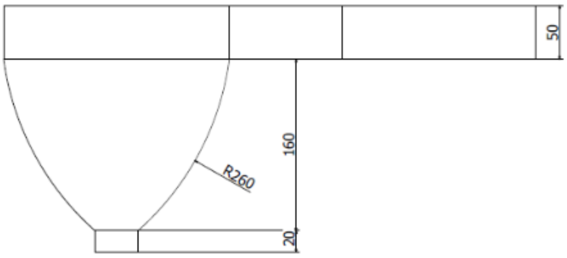
The GWVT consists of two parts: the channel and the tank. The channel counts on the parameters of length, width, height, and contraction angle. The tank has three parameters: diameter, height, and the outlet diameter. The fluid enters through the channel and stabilizes. When it reaches the contraction, its velocity increases and flows tangentially at the inlet of the tank for a smoother and faster vortex formation. The fluid in the tank forms a vortex and rise fluid velocity as it exits through the outlet at the bottom.

According to Dhakal *et al.,* [13] the parameters were selected for a higher performance. These parameters are the channel, the turbine height and the notch angle. The relation between the tank diameter and the outlet is 18%, as suggested by [11]. Figure 1(a) shows the geometry and dimension in millimeters used for the channel design and outlet diameter. Which were used for both designs of the turbine. The geometry was designed in ANSYS V18.1 software in its "Design Modeler" module [14]. Figure 1(b) and Figure 1(c) show the concave and convex dimension respectively.



(a)

(b)



(c)

Fig. 1. Geometry and (a) channel dimension for concave and convex designs (b) concave tank and (c) convex tank dimensions in millimeters

2.3 Mesh and Boundary Conditions

The discretization of the turbine control volume was done in the "Meshing" module of ANSYS V18.1 software. Tetrahedral elements were implemented, which compose the volume of the fluid inside the turbine. In the discretization process to achieve grid independence with respect to the outlet velocity at the turbine were used 1.2E6 and 6.4E5 elements for the concave and convex tank, respectively, as shown in Figure 2. Six meshes were configurated for each case to reach grid independence [15, 16]. The statistics of the meshes are shown in Table 1 for each design in order to ensure a well accuracy according to Hasannasab *et al.,* [17].

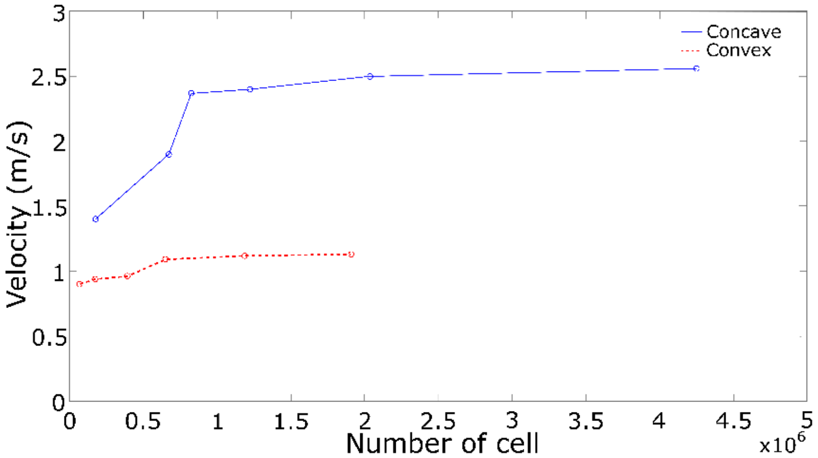
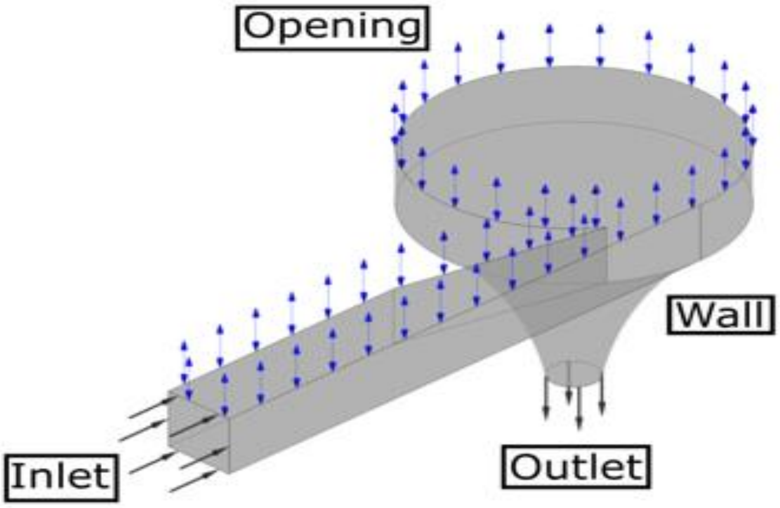


Fig. 2. Mesh independence study for concave and convex designs: number of cells vs. velocity

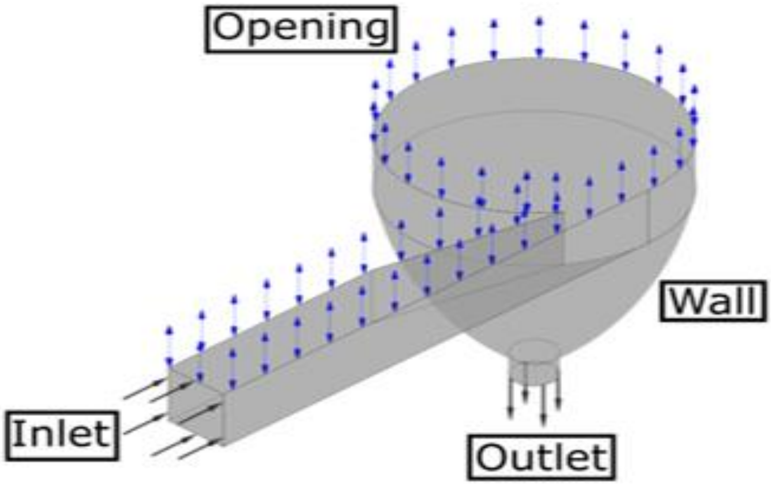
Table 1
Mesh statistics for concave and convex designs

Tank	Concave	Convex
Max. obliquity	0,69	0,66
Aspect ratio	5,16	4,87
Min. skewness	0,30	0,32
Min. quality	0,38	0,42

The boundary conditions correspond to the operations conditions: a height of 0.5 m and a flow rate of 0.38 L/s. The control volume is shown in Figure 3. A velocity inlet of 0.15 m/s at the inlet, an opening condition at the upper wall, a non-sliding wall condition at the lateral walls were configured. Finally, at atmospheric pressure outlet was stablished for the outlet opening. The system is governed by a subsonic flow (Ma <1), a relative pressure of zero Pascal (0 Pa) and a volume fraction for both (water and air) of zero gradients are configured for the boundary conditions.



(a)



(b)

Fig. 3. Boundary conditions for (a) concave and (b) convex designs

2.4 Numerical Method

The solution process for the momentum and mass conservation equation was done using the CFX module of ANSYS Workbench V18.1. The biphasic properties of the fluids were configured for water and air at 25° C with a reference pressure of 1 atm. It was configured in this way to not generate changes in the physical properties of both fluids, which were considered in continuous phase and generating an effort between both, characterized by a surface tension coefficient of 0.072 Nm-1.

The BSL RSM turbulence model was selected for the study due to greater precision in a rotation system and secondary flows, according Mulligan *et al.,* [18]. The simulation ran in a transient state with a time step of 0.001 s to visualize the behavior of the fluid in very small-time intervals, with a total simulation time of 25 s. The residuals obtained by the Root Mean Square (RMS) were below 1E-4, and the outlet velocity was monitored each time step. The convergence criterion was selected to guarantee a reliable simulation response.

3. Simulation Results

The numerical results are shown in one plane located at the middle of the tank. This plane is the same for each of the designs. Figure 4 exemplify where the view plane is in the concave and convex designs.

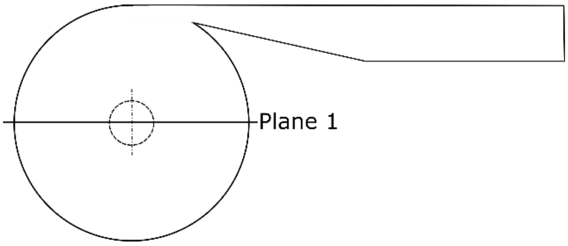
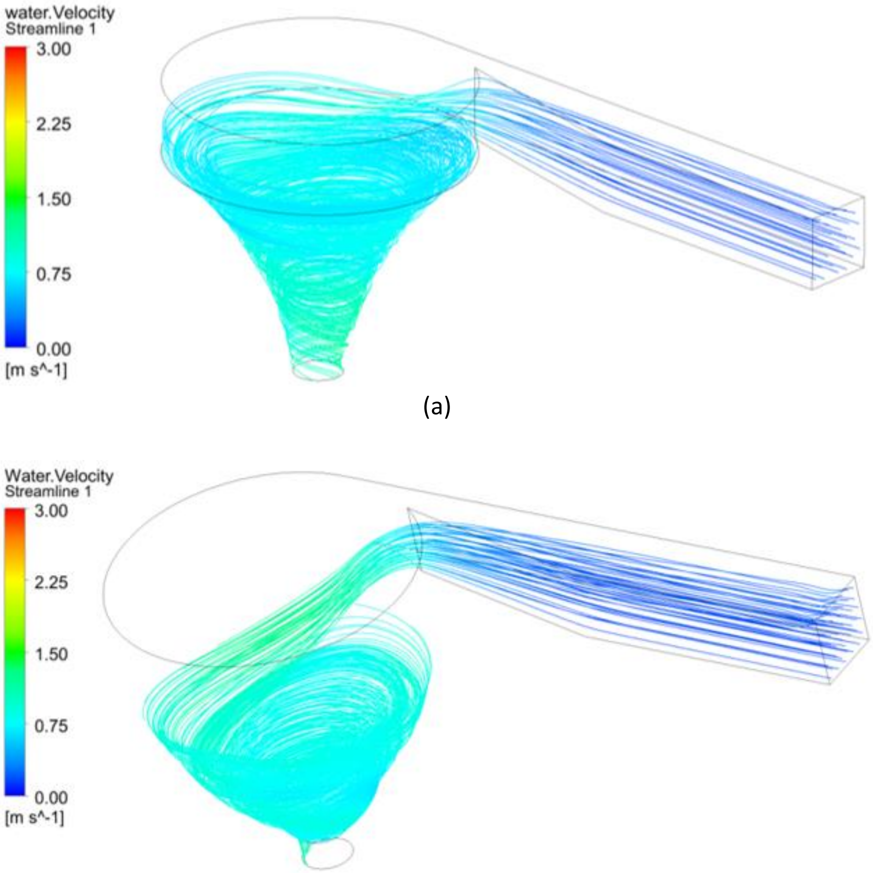


Fig. 4. Top channel plane view

Figure 5 shows the velocity streamlines for each design. The trajectory followed by the fluid can be seen from the inlet to the outlet (right to left in the pictures). The axial vector rises velocity as it approaches the outlet diameter. Meanwhile, the tangential vector has the highest velocity at the upper part of the tank. It depends on the air core vortex and the radius of the water vortex as shown by Vatista [19] in the following equation

$$V_\theta(r) = \frac{\Gamma}{2\pi}\left(\frac{r}{(r_c{}^{2n} + r^{2n})^{\frac{1}{n}}}\right) \tag{5}$$

In the concave design, the vortex formation is rapid and clear. The contraction in the concave tank generates a velocity gain at the outlet. Contrarily, the convex tank does not form a strong vortex due to form a bigger tank. The axial vector velocity decreases neat the outlet, which causes a low water retention. In the convex design the area keeps almost constant and it is reduced at the outlet. In this case the water does not gain a significant velocity. This behavior is similar with the results shown by Dhakal [12], where the streamlines increase their velocity when the area is reduced near the outlet.

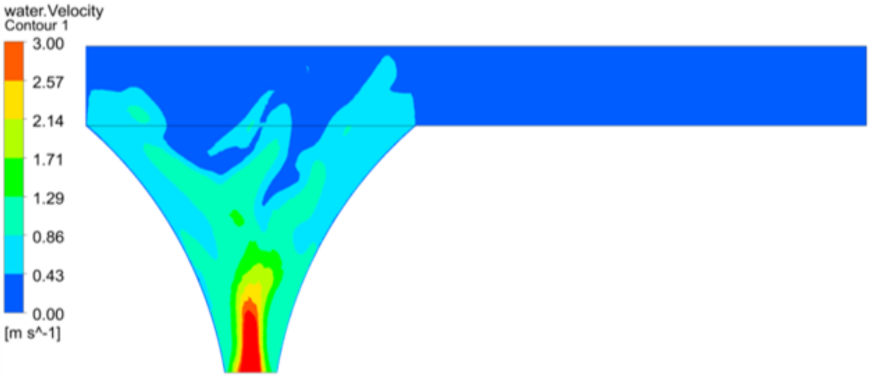


(a)

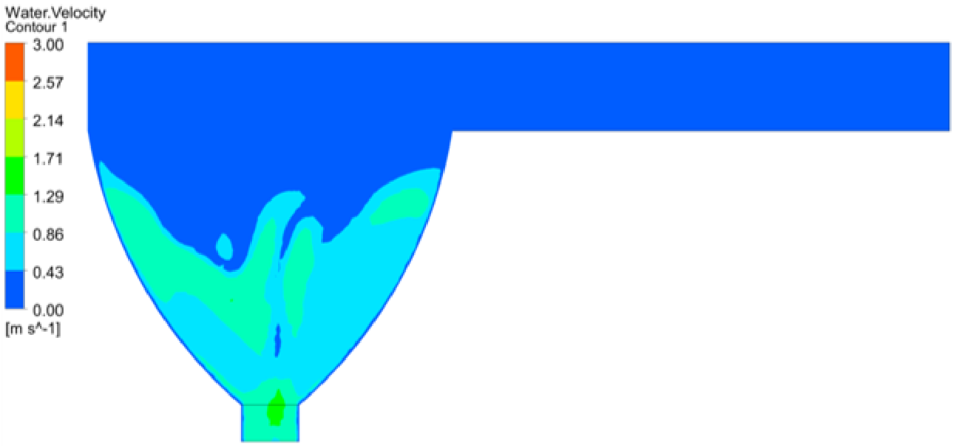
(b)

Fig. 5. Velocity streamlines in the (a) concave and (b) convex designs

Figure 6 shows velocity contours for concave and convex designs. It shows clearly the highest velocities points. The fluid increases the velocity as it goes down the tank. It reaches the maximum velocity value (as mentioned in Figure 5) thereby increasing its kinetic energy at the outlet, as mentioned in [10]. The contours also show a higher velocity average in concave than convex design. Thereby, generating a higher and stable torque, and more electrical power.



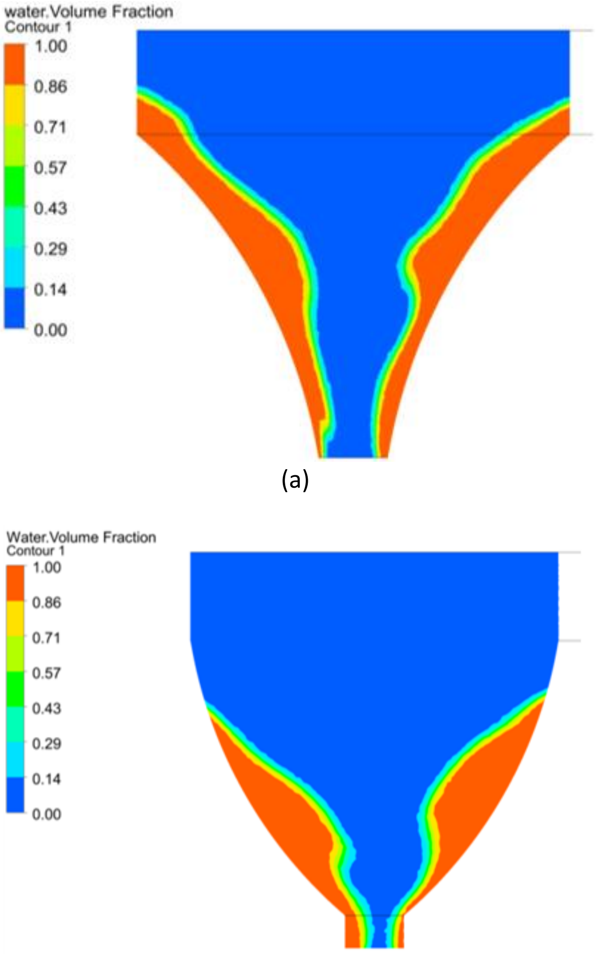
(a)



(b)

Fig. 6. Velocity contours of (a) concave and (b) convex designs

Figure 7 presents the water volume fraction for each design. It shows the interaction (interface) between air and water in the channel and tank (vortex formation). It can be seen an air vortex sharp in middle of tank and water rotates around it. In the concave case, it is possible to observe more water volume and a sharp vortex formation in the tank. The convex design shows a slight vortex and its formation in the lower part of the tank.



(a)

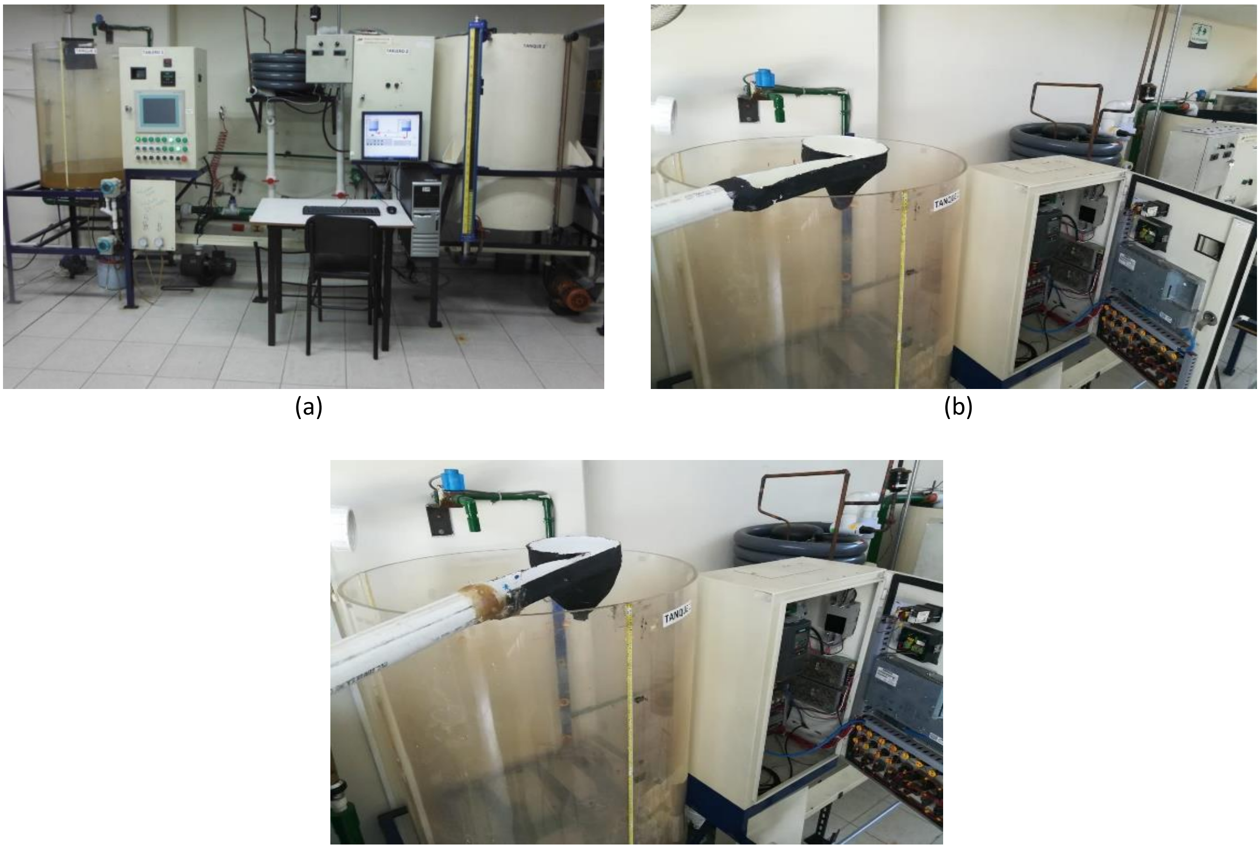
(b)

Fig. 7. Water volume fraction at plane 1 of (a) concave and (b) convex designs

In addition, the rapid and clear vortex formations increase the energy that can be extracted by the system and has a greater generation of electrical energy. The numerical results show a higher performance for concave than convex design. The highest velocity outlet in the concave design is 1.81 m/s, while the outlet velocity in convex design is 1.12 m/s with same conditions.

4. Experimental Setup

The experimental study is developed in the fluids laboratory of the *Instituto Tecnológico Metropolitano* (ITM). Which has a testing equipment, as suggested in [20], and allows to recirculate the fluid between two tanks to maintain a continuous flow. Figure 8 shows ITM laboratory (Figure 8(a)), and experimental set up for concave (Figure 8(b)) and convex design (Figure 8(c)). Table 2 describes the set characteristics.


(a) (b)

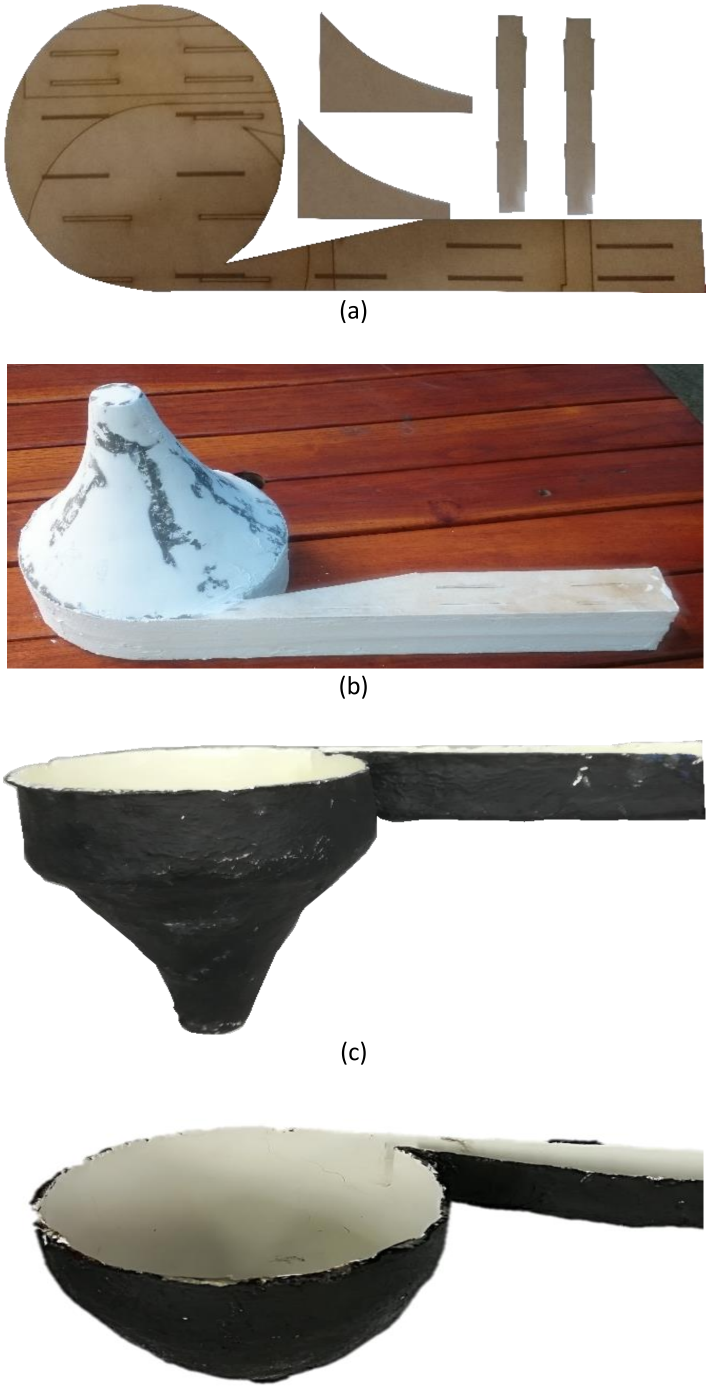
(c)

Fig. 8. Experimental set up in (a) ITM´s fluid laboratory for (b) concave and (c) convex designs

Table 2
Equipment in ITM’s laboratory

Equipment	Pump	Variable Frequency Drive
Brand	Siemens	Siemens
Power	1.8 HP	2 HP
Voltage	220-440 V	230V
Current	2.8-5.6 A	7.4 A

A wood mold was implemented to manufacture the tanks (Figure 9(a)). The geometry and dimensions shown in Figure 1 are guaranteed for each turbine. Later, a plaster cover was used to make an accurate solid cast (Figure 9(b)). Finally, fiberglass and resin were implemented for easy molding to make the specific tank design of each turbine. Figure 9(c) and Figure 9(d) show the final prototype of concave and convex designs, respectively. The same process was implemented to make convex experimental design.


(a)

(b)

(c)

(d)

Fig. 9. Manufacturing process using (a) wood mold; the use of plaster cover to make (b) a cast for concave turbine; final prototype of (c) concave and (d) convex experimental designs

A conventional rotor of 8 blades printed in a 3D printer and a 12V motor were used in the experimental phase as a rotor and generator, respectively. The rotor and the generator shaft were connected by two gears of 90 and 18 teeth for power transmission. The electrical power was measured with a UNI-T UT58C multimeter and the revolutions per minute with a digital tachometer UNI-T UT372. Figure 10 shows the rotor, the generator, and the connection between the axes. The electrical power is described in Eq. (6).

Fig. 10. Experimental rotor

$$P = V * I \tag{6}$$

5. Experimental Results

Table 3
Experimental resultTable 3 shows the voltage, current, and rpm measured in each of the turbines.

Table 3
Experimental results

Tank	Units	Concave	Convex
Revolution Per Minute	rpm	142	137
Voltage (V)	V	2.15	1.72
Current (mA)	mA	170	132
Electrical power (W)	W	0.37	0.23

The experimental results show the concave design has better performance than convex turbine, as mentioned in numerical results. In addition, the argument from [10] is validated where it promote to investigate the turbine's design tank to increase the efficiency. They also assure that it is a parameter of great influence on vortex formation and performance.

The numerical results show an increase in the outlet velocity of 1.12 m/s of convex design to 1.81 m/s of concave design. These results represent an increase of 62% in the outlet velocity of the concave design compared to the convex design. On the other hand, the experimental results show a higher electrical power generated by concave design (0.37 W) than convex design (0.23 W). These experimental results represent an increase of 60% between concave and convex design.

6. Conclusions

A concave and a convex design for a GWVT tank were evaluated numerically and experimentally. Concave design obtained the best performance with grater outlet velocity (CFD) and electrical power generated (experimental).

The experimental and numerical results show a significant increase for concave design. A superior performance in concave design with 60% in numerical results, and 62% in experimental results, corroborate it.

According to results, the tank design is one of the most important and influencer geometry parameters to increase the GWVT performance and the formation of a strong vortex. It can increase the fluid kinetic energy and generate more electrical power with this parameter.

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