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Hydrodynamic phenomena in a vertical-axis vortex turbine

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Abstract: The present work aims to develop a safely designed simulation by generating a sustainable hydraulic system coupled with energy study needs, which collaborates with less costs and more benefits. Based on simulations with the scale model using the ANSYS tool, it aims to find the efficiency at the time of executing this simulation at full scale. Mainly the motivations of the work are based on new methods of obtaining energy for the conservation of the environment. This is how the idea of designing and simulating a new gravitational vortex turbine system, with geometries according to what has been found in the literature and in previous studies, is materialized. In this way we proceed to design and simulate a turbine device composed of a vortex impeller that can resist erosion and sediments and allows the development of a gravitational vortex with a considerable hydraulic power. Once the turbine geometry is defined, a modeling is made in ANSYS software, in order to know the behavior of the vortex, define the geometric configuration of it, which will also work under the concept of "drag".

Key words: energies; ANSYS; geometry; vortex chambers; impeller; rotation

1 Introduction

This study considers the hydrodynamic phenomena that occur in a modified version of a vertical axis vortex turbine in order to improve its performance. The modification proposed in this study is easy to perform, taking advantage of the water flow in rural areas. Numerical solutions by means of CFD (Computational Fluid Dynamics) have improved a lot in recent years thanks to more and more adequate calculation methods and specific algorithms. Hydropower problems involve important computational resources because the geometries considered are large, very complex and require the implementation of moving meshes with a high number of elements (Vargas, 2011). Hydropower forms one of the main sources for the acquisition of electricity worldwide, providing about 16% of the electricity in Latin America and the Caribbean and 20% of the hydropower potential worldwide (Calderon, 2019). However, about 1.2 % of people do not have electricity service in Ecuador according to INEC, especially in the rural sector (Escobar, 2017). The fact that they are in geographically isolated or difficult access areas where the coverage of the national electricity system is avoided due to this situation that some users have opted to use renewable energies such as small hydroelectric plants (PCHS). PCHS, due to their low greenhouse gas emissions, good performance and low costs, offer an alternative for the production of renewable menergies (Carpio, 2023). Among the PCHS, is the gravity vortex turbine (GVT), which works with the natural current of the river, operates at head conditions between 0.5 to 2m and flow rates of 0.1 to 2 m^3/s approximately, for generating capacities between 0.2 and 40 kW of electrical power (Pinta & Cofre Pinta, 2021). In addition to providing energy, it contributes to the reduction of pollution in rivers associated with the decomposition of organic matter, due to the oxygenation of the water generated by inducing an artificial vortex. However, it presents low efficiencies of around 38% (Guamushig, 2022), consequently the studies carried out around this turbine have the main objective of increasing the hydraulic efficiency. Both numerical and experimental studies have found that a relationship between the geometric parameters of the TVG tank directly affect the decrease or increase of the hydraulic efficiency, thus affecting the generation of electrical energy of the system. According to the literature, one of the most influential factors is the geometry of the tank.

Gravity vortex turbines are a type of hydroelectric turbine that uses the rotational flow of water created by a vortex to generate electricity. They are an innovative and promising technology that has the potential to contribute to the growing demand for renewable energy sources. In this article, we will explore the concept of gravity vortex turbines, their advantages and limitations, and their possible applications (Gardea & Villegas, 2001).

Gravity vortex turbines use the principles of hydrodynamics and vortex dynamics to generate electricity. They consist of a cylindrical structure, with an opening at the bottom that allows water to flow. The water spirals around the central axis of the cylinder, creating a vortex. The derotational flow of water is harnessed by a series of blades or vanes that are placed in the path of the vortex. As the blades rotate, they drive a generator that produces electricity (Gardea & Villegas, 2001).

One of the advantages of gravity vortex turbines is that they can operate with a low head (the vertical distance between the inlet and outlet of the water) and a low flow rate. This makes them suitable for use in areas with low water pressure or low flow, such as small rivers or streams. In addition, they have a relatively simple design and can be easily installed and maintained. Gravity vortex turbines have several advantages over traditional hydroelectric turbines. One of the main advantages is that they can generate electricity from low head and low flow sources. This makes them ideal for use in areas where traditional hydroelectric turbines are not viable, such as small rivers or streams. They also have a low environmental impact and do not require the construction of large dams or reservoirs.

Another advantage of gravity vortex turbines is that they are relatively inexpensive to build and maintain. They have a simple design and can be easily installed, making them an attractive option for communities or businesses wishing to generate their own electricity. While gravity vortex turbines have several advantages, they also have some limitations. One of the main limitations is that they are not as efficient as traditional hydroelectric turbines. This is because they rely on the rotational flow of water, which is less powerful than the linear flow of water used by traditional hydroelectric turbines. As a result, gravity vortex turbines are best suited for small-scale applications (Ayala & Benavides, 2016).

Another limitation of gravity vortex turbines is that they are sensitive to changes in water flow and velocity. If the flow rate or velocity drops too low, the vortex will break and the turbine will stop generating electricity. They are also susceptible to damage from debris or sediment in the water.

Gravity vortex turbines have several potential applications, particularly in remote or off-grid locations. They can be used to generate electricity for small communities, farms or businesses that are not connected to the grid. In addition, they can be used to power remote monitoring stations, water treatment plants or other infrastructure.

Gravity vortex turbines can also be used in conjunction with other renewable energy sources, such as solar or wind power, to provide a reliable and constant source of electricity. By combining different renewable energy sources, it is possible to create a hybrid energy system that is more resilient and sustainable (Aho & Buckspan, 2012).

2 Methodology

For the development of the study, the methodology is proposed in two phases, each consisting of four stages, as described in Figure 1.

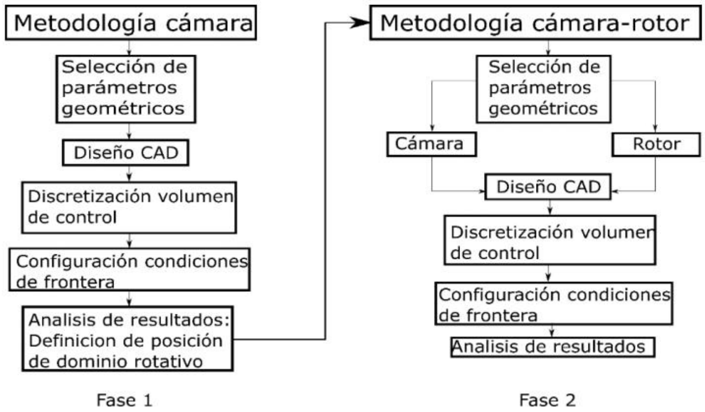

Figure 1. Flow diagram of the applied methodology

(1) Camera design

Following the methodology proposed in phase 1, the geometry of the chamber is designed according to (Elbatran, Yaakob, & Shabara, 2015) in the SpaceClaim module of the commercial program ANSYS® V19.1. The outlet diameter is configured with a ratio of the tank diameter of 14%, 16% and 18% (case A, B and C respectively), and also adding a reduction of area to the channel before reaching the tank (Seto & Dhakal, 2014). Figure 2(a) shows the dimensions of the tank and the inlet conduit for each proposed situation. Figure 2(b) shows the height of the flume and the dimensions of the conical tank. In all cases, the tank height was kept constant.

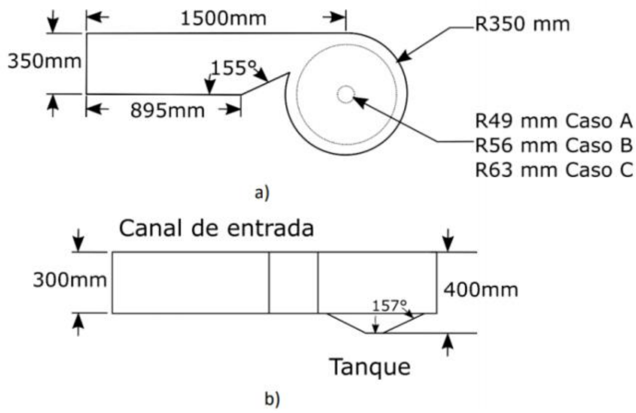

Figure 2. Chamber dimensions for each proposed model

(2) Calculations vortex behavior

The vortex rotates without the need of an external force.

The equation shows the behavior of the vortex.

$$-\frac{d}{dr}(p + y \times z) = -\rho\frac{V}{2r} \tag{1}$$

p = pressure on the surface of the fluid

y = product of density multiplied by gravitational acceleration

z = height

ρ = fluid density

v = fluid velocity

r = distance to the axis of rotation

(3) Behavior of vortex height and radius

From the equation, mathematical models describing the behavior between height and radius are reflected.

$$z(r) = z_\infty - \frac{B^2}{2gr^2} \quad (2)$$

$$z(r) = -\frac{{W_o}^2}{2g} r^2 \quad (3)$$

$z\infty$ = height at maximum vortex height; height at greatest distance from axis of rotation

B = model constant

w_0 = initial angular velocity of the vortex

g = acceleration of gravity

r = distance to the axis of rotation

$w = w_0$

(4) Feeding channel

Velocities are shown to be high, which could not be negligible, so the assumption of total is not considered valid either. This is reflected in a free vortex, as shown by the open channel report of the hydraulic flow.

$$Fr = \frac{V}{\sqrt{gy}} \quad (4)$$

Fr = Froude number (dimensionless)

v = velocity (m/s)

g = gravity (m/s^2)

y = hydraulic tie rod (m)

(5) Flow area

The value of the velocity is intended to have a supercritical flow so that the energy is higher and the stretching is lower. A flow rate of 2 m/s and velocity up to 2.7 m/s will be maintained.

$$A = Q/v \quad (5)$$

v = velocity (m/s)

Q = volumetric flow (m^3/s)

A = area (m^2)

(6) Hydraulic tie rod

It is the vertical distance from the lowest point of the channel section to the free water surface.

$$y = \sqrt{A/2} \quad (6)$$

y= hydraulic tie rod (m)

(7) Width of the channel base

For regular and simple channel sections, the geometric elements can be expressed mathematically in terms of the flow depth and other dimensions of the section.

$$b = A/y \tag{7}$$

b = width of channel base (m)

(8) Transmission length

A mechanism for transmitting power between two or more elements within a machine.

$$Lt = \frac{b - be}{2(tan(12.5))} \tag{8}$$

Lt = transition length (m)

be = width of the base of the inlet to the vortex chamber

(9) Vortex chamber

A flat chamber floor minimizes organic matter capture and hydraulically directs sand into the lower reservoir, converting the upper chamber into a forced vortex unit.

$$D_t = 0.27 * H_b \tag{9}$$

H_b = vortex chamber height

D_t = vortex chamber diameter

(10) Discharge orifices

The jet that flows freely through an orifice is called the liquid jet and its spiral trajectory is called the spiral trajectory.

$$Do = 0.16 * Dt \tag{10}$$

DO = discharge orifice diameter (m)

(11) The entrance to the vortex chamber

These structures connect an inlet duct to an outlet duct through a single chamber.

$$be = 0.52 * Do \tag{11}$$

be = width of the base of the vortex chamber inlet (m)

(12) Vortex chamber height and diameter

In order to find the most appropriate dimensions for the height and diameter of the discharge, the study was based on the work on different structures.

$$Dc = 0.45 * Dt \tag{12}$$

$$Hc = 0.36 * Hb \tag{13}$$

Dc = diameter of discharge cone (m)

Hc = discharge cone height (m)

(13) Model scaling

It takes shape in the final section, where the characteristics of the field prototype, the forces to be reproduced in the model, the selected scaling alternative, the calculation of the model properties and finally a validation of the scaling in the

ANSY simulator are defined.

$$\frac{Frp}{Frm} = \frac{\left(\frac{v^2}{yg}\right)p}{\left(\frac{v^2}{yg}\right)m} = 1 \tag{14}$$

3 Results and discussion

We proceed to work on the X-plane by making a 2D model with the measurements of the drive shaft.

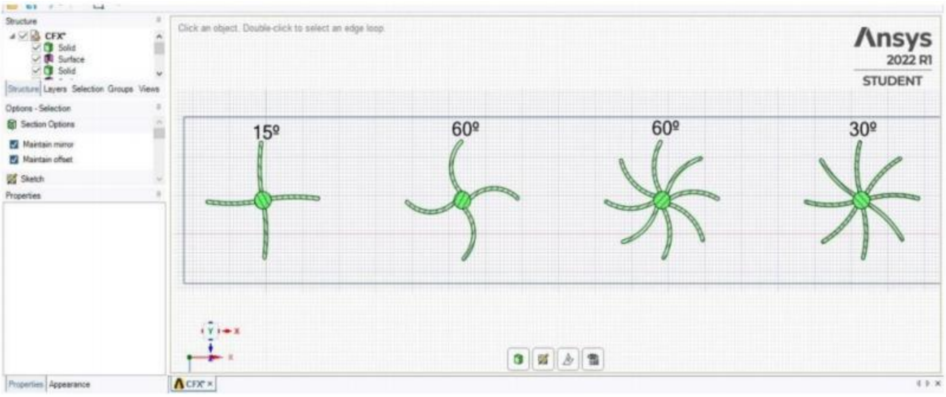

Figure 3. 2D modeling with PTO shaft measurements

The measurements according to the drive shaft are determined and the turbines are designed, checking each one of them at a different angle.

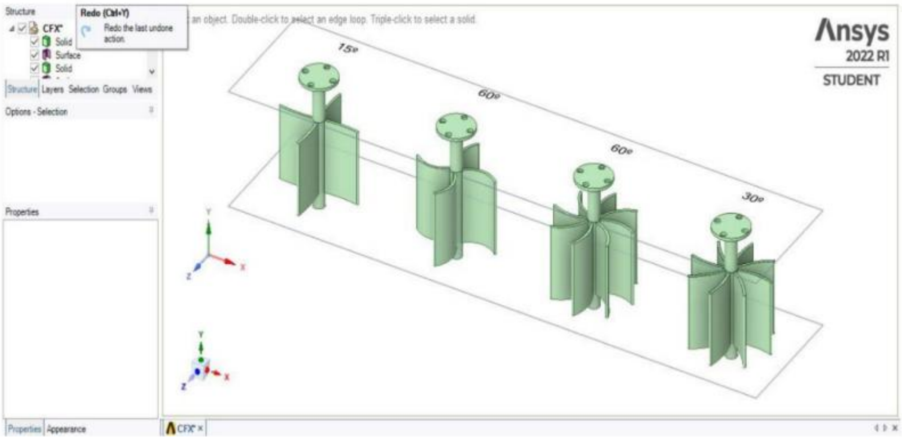

Figure 4. Turbine design

3.1 4-blade turbine with 15° angle

We proceed with the analysis of the 4-blade turbine of 15° angle where we can determine the effort obtained by the design. We can verify the results shown in the graph and the calculations determined by the software in order to verify the efficiency of the 4-blade turbine of 15° angle.

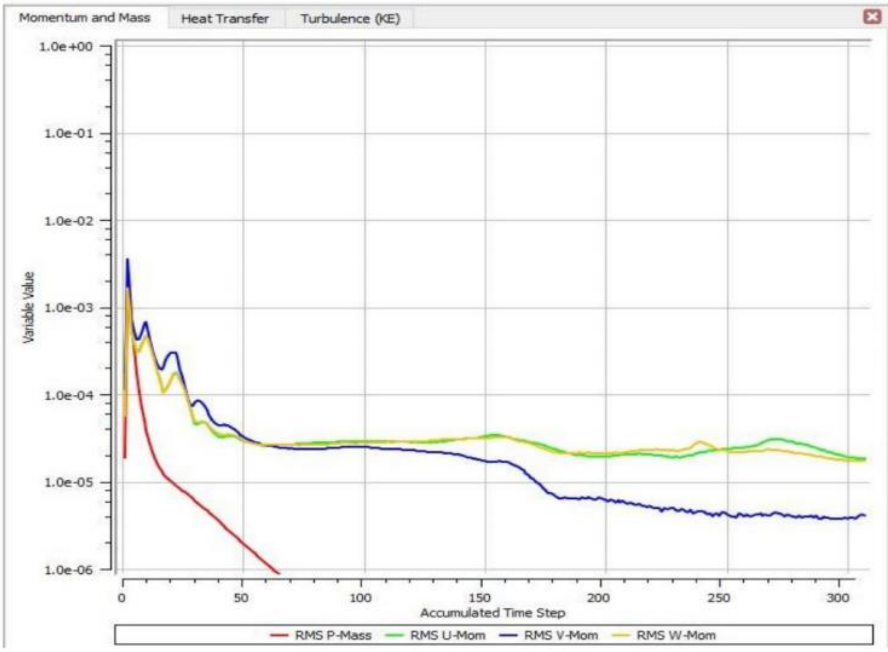

Figure 5. 15° Turbine statistics

3.2 4-blade turbine with 60° angle

The analysis of the 4-bladed turbine of 60° of angle is made where it is possible to determine the effort that is obtained when carrying out the design. It can verify the results displayed in the graph and the calculations determined by the software, thereby verifying the efficiency of the 4-bladed turbine of 60° angle.

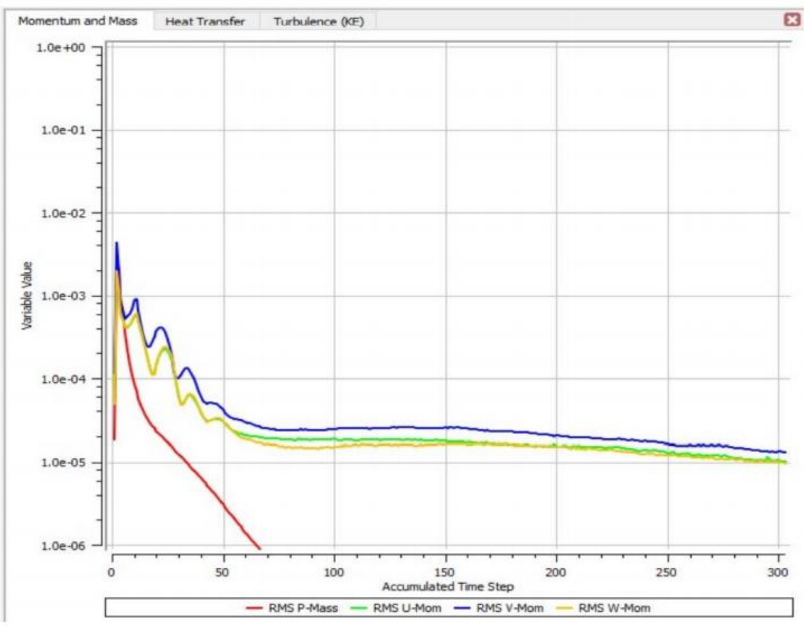

Figure 6. 4-blade turbine of 60° angle

3.3 8-blade impeller with 60° angle

We proceed with the analysis of the 8-blade turbine of 60° angle where it is possible to determine the effort that is obtained when carrying out the design. The results shown in the graph and the calculations determined by the software can be verified and in this way the efficiency of the 8-blade turbine of 60° angle can be verified.

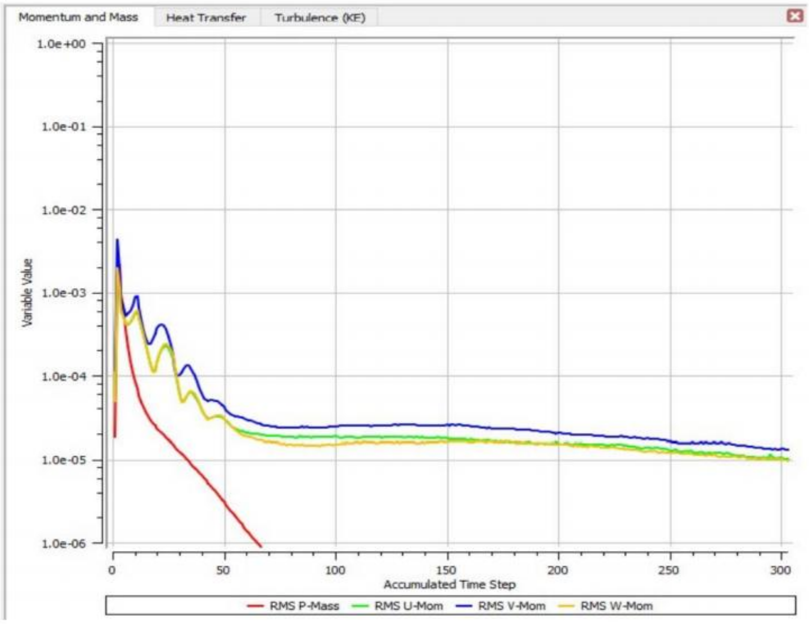

Figure 6. 8-bladed turbine with 60° angle

3.4 8-blade turbine with 30° angle

The analysis of the turbine with 8 blades of 30° angle is made where it is possible to determine the effort that is obtained when carrying out the design. The results shown in the graph and the calculations determined by the software can be verified and in this way the efficiency of the 8-bladed turbine of 30° angle can be verified.

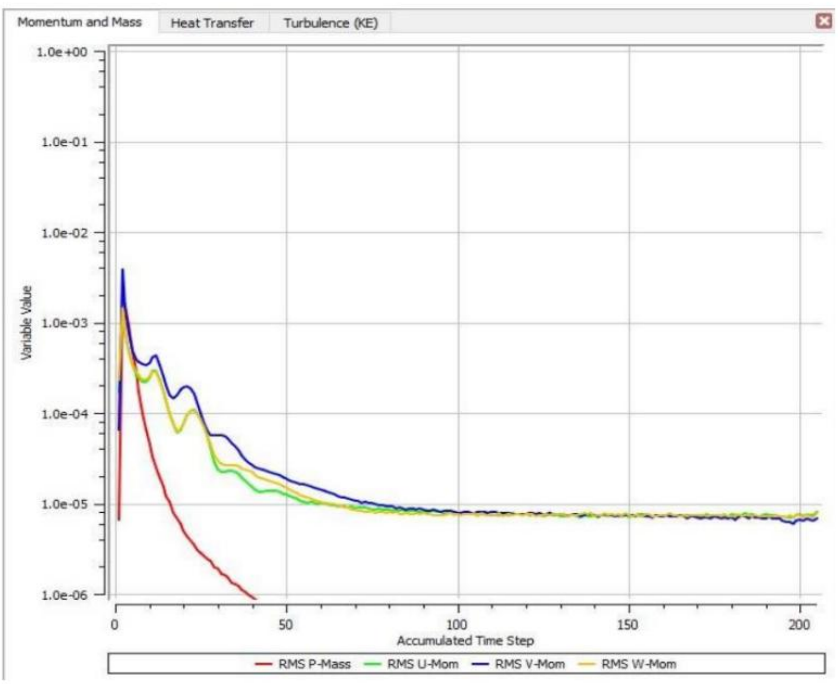

Figure 7. 8-blade turbine with 30° angle

4 Conclusions and recommendations

- Comparing the various turbine designs one by one, it is found that the 4-blade turbine with angles of 15° and 60° cannot adequately capture the kinetic energy generated by the vortex created in the simulation, so the 8-blade turbine with an angle of 30° is the most suitable because it is versatile for the simulation data and because it makes better use of the kinetic energy generated by the eddy current simulations.

- It was found that the larger the outlet diameter, the stronger the gravitational vortex formation, and the good vortex formation prevents the formation of recirculating liquid causing hydraulic losses.
- Demonstrate the use of technological tools that allow us to keep in mind the materials in which they were used to realize an adequate structure in real life.
- It is suggested to vary the angular velocity to see what kind of correlation this produces, but experimental assembly is also recommended, so that the results obtained in this study can be compared and confirmed.
- The initial approach is important because it allows to adapt the simulation to the communities and their requirements. This allows to minimize future costs of extreme modifications.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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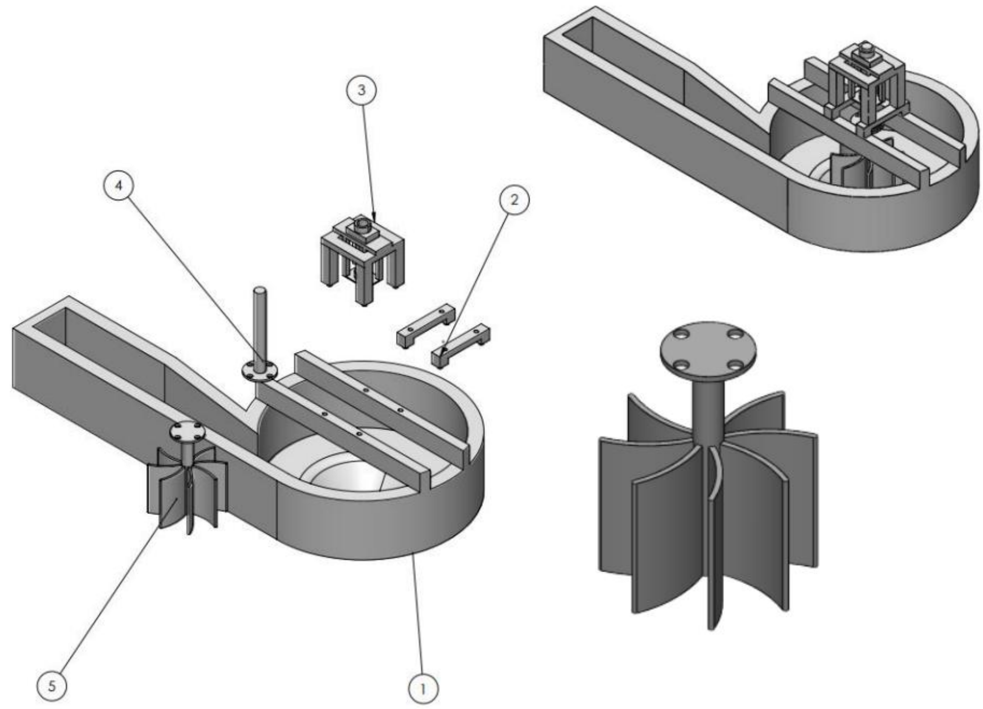
Annexes



Nº DE ELEMENTO	Nº DE PIEZA	MATERIAL	CANTIDAD
1	ESTRUCTURA	CONCRETO	1
2	SOPORTE_BASE_ÁRBOL	ACERO INOXIDABLE	2
3	BASE	ACERO INOXIDABLE	1
4	ÁRBOL_TRANSMISIÓN	ACERO INOXIDABLE	1
5	TURBINA	ALUMINIO 1060	1