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Methodology for the calculation of hydrokinetic turbines for tributary rivers of the Amazon in Bolivia

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Abstract: Hydrokinetic turbines are hydraulic machines that harness the kinetic energy of water currents through passage, which do not require civil works infrastructure for installation and are ideal for harnessing energy in small powers from 1 to 10 kW. They are suitable for supplying energy to up to three families for use in lighting and household appliances.

The design and manufacture of these turbines has shortcomings due to the lack of a detailed procedure, even more so in developing countries using appropriate technology for their application. This project develops a selection procedure for turbine blades according to the efficiency of lift and drag coefficients developed by Xfoil algorithm, then this selection proceeds to the power analysis that develops the turbine according to the BEM methodology, particularly gives emphasis to the procedure of calculating the power for different conditions of rotation depending on the angle of attack of the fluid in blade and also analyzes the blade pitch angle.

The present study clarifies the behavior of the hydrokinetic turbine for different rotations and river water velocities, which can take better advantage of the power, meaning that the developed program can plot a power curve of the hydrokinetic turbine in order to establish the optimal rotation, angle of attack, pitch angle and diameter of the turbine.

The program developed in Excel also allows exporting the blade geometry optimized for a power and water speed, exporting it through macros in Visual Basic for the design software SolidWorks the final geometry, in order to make the analysis of mechanical resistance and behavior with the fluid in ANSYS CFD software.

For this study, a review of approximately 60 theses was carried out and it was concluded that there is no clear procedure to determine the power according to the above variables.

The methodology used is absolutely theoretical analysis with the BEM methodology, but the behavior of the fluid inside the turbine was verified in ANSYS CFD software to complete and establish the pressures exerted by the water flow on the blades and in such a way to analyze the residence of the blades and to validate the water wake in order to rule out the turbulence that could cause vibrations in the rotor with Qblade software.

Key words: mechanical design; hydraulic energy; clean and sustainable energy; appropriate technology; change of energy matrix

1 Introduction

Renewable energies are an inexhaustible resource that can be used according to the available technology, but many times it is not possible to access these technologies due to the technological limitations to dominate nature. In the north of Bolivia there are mighty rivers such as the Mamoré, Abuna, Madre de Dios, Yata, etc. Due to their large flow rates, they require large-scale infrastructure to utilize them, just like the Jirau and San Antonio hydroelectric power plants downstream on the Brazilian side, which are installed on the Grand Madeira River where the hydroelectric power generation exceeds all the energy used by Bolivia (Energia Sustentável do Brasil).

But there are run-of-river turbines called hydrokinetic turbines that are suitable for high flow rivers and small waterfalls. These turbines take advantage of the speed of the water current and require simple infrastructures to be fixed to the river bank, which enables the turbines to be easily maneuvered in situations of water floods or abundant movement of shovels.

There are riverside populations in the sector of Riberalta, Guayaramerín, etc., that use gasoline and diesel generators for electricity supply and many of them do not have access. For this reason it is necessary to identify technologies that utilizes water flow to provide electricity to these populations. ITDG has conducted experience on the Peruvian side of northern Bolivia, which is very important for installing and using appropriate technology to manufacture hydraulic turbines (F Maldonado).

There is also a study in 2011 on the applicability of hydrokinetic turbines in Beni (P. Miranda, L. Marroyo), but today there are new initiatives for the installation of such turbines in order to reduce the cost of diesel used in these populations. As the international price of this fuel has risen due to the conflict between Russia and Ukraine, there is an increasing need to use hydropower and renewable energy to meet the needs of isolated populations.

The hydrokinetic turbines are devices that have similarity in calculation and operation to wind turbines and are easy to manufacture with appropriate technology, which arises in this opportunity through private and public initiatives to finance the manufacture of the same for installation in northern Bolivia, which are the tributaries of the Amazon. That is why it is necessary to develop appropriate calculation methods for a series of water velocities and turbine diameter in order to optimize the maximum use of power for each river and meet dispersed populations of 1 to 3 families that are typical in the Amazonian rivers.

2 Objectives

2.1 General

- Using calculation methods to select and determine the size of turbine blades.

2.2 Specific:

- Selection of airfoil for water flow based on performance curves available from NACA
- Optimization of the profile for maximum power and water velocity suitable for Bolivian Amazonian rivers
- Mechanical design verification
- Hydraulic Design Verification

3 Aerodynamic profile

An airfoil is defined as the cross section of a body that is placed in an air stream in order to produce a useful aerodynamic force as efficiently as possible. The cross sections of wings, propeller blades, windmill blades, compressor blades, jet engine turbine and hydrofoils are examples of airfoil surfaces. The basic geometry of an airfoil is shown in Figure 1.

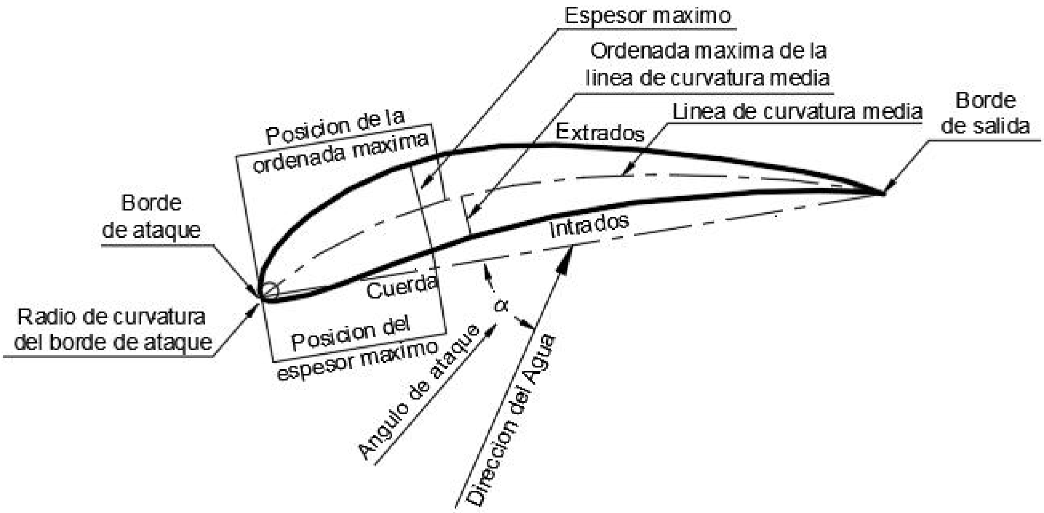


Figure 1. Airfoil geometry diagram

1. The mean line of curvature is an imaginary line that passes through the profile between the extrados and intrados, right through the middle of the extrados from the leading edge to the trailing edge.

2. The maximum thickness of the airfoil is where the greatest clearance between the top surface and the bottom surface is found. This parameter is important to leave enough space for the design of the wing structure.

3. Point of maximum thickness: It is the point on the chord, whose distance between top and bottom measured perpendicular to the chord, is maximum. The maximum thickness is an important characteristic, usually expressed as a percentage of the chord. The value varies from 3% in the slenderest ropes to 18% in very thick ropes.

4. Leading edge: It is the front part of the airfoil. It is called "leading edge" because it is the first part that comes into contact with the airflow, causing it to bifurcate towards the intrados and extrados. (B.A.)

5. Trailing edge: Also called "trailing edge". It corresponds to the point where the airflow generated from the inside and outside gathers and leaves the contour. Although in most charts it is treated as sharp, it is not always the case, having in some cases a square termination (B.S).

6. Intrados: It is the inner part of a structure. In a surface profile it corresponds to the lower part of the same.

7. Extrados: This is the upper part of the profile, usually where lower pressure than the atmosphere is generated to allow for flight.

8. Chord: straight line connecting the leading edge to the trailing edge. It is one of the main dimensions of the profile.

9. Leading edge radius: defines the shape of the leading edge as a circle tangent to the extrados and intrados, and the center is located on the tangent line at the origin to the mean curvature line. Its magnitude defines the sharpness of the A.B., which has an effect on the stall.

10. Maximum curvature: It is the maximum distance between the average curvature line and the contour line. This value and its position along the chord help to define the shape of the mean curvature line. The value of the maximum ordinate and its position are usually given as a percentage of the chord.

11. Angle of attack: the angle of attack formed by the direction of the incident current with respect to the chord of the profile (Figure 1).

4 Airfoil classification

An airfoil means a two-dimensional cross-sectional shape of a wing whose purpose is to generate lift or minimize drag when exposed to a moving fluid. The word is an Americanization of the British term aerofoil which itself is derived from the two Greek words Eros ("of the air") and Phyllon ("blade") or "airfoil". Given its use in various fields of airfoils it can be mentioned in the same way in the field of hydraulics called hydrofoils.

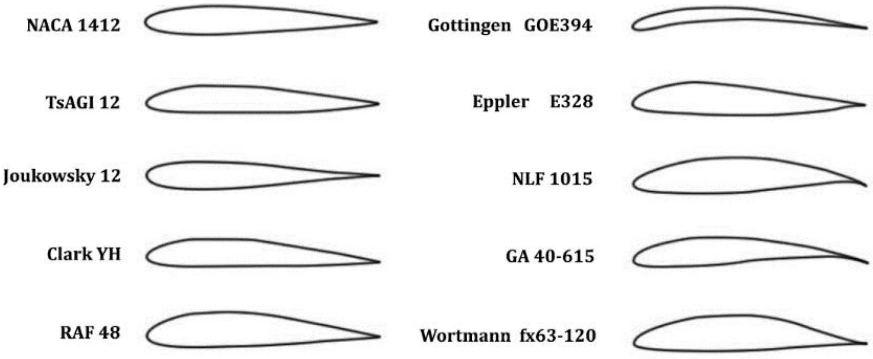


Figure 2. Airfoil geometry diagram

In order to standardize the nomenclature of the contours and clearly identify them, the different series were developed. However, each family identifies its profiles in a particular way with a numerical code in which each digit specifies a characteristic of the profile following design rules specific to each series. Among the different profile families we can highlight the NACA, TsAGI, Joukowsky, Clark Y, RAF, Gottingen, Eppler, NLF, GA, Wortmann, Selig, etc. series.

NACA series are the most widely used today, not limited only to wing design and aviation. The TsAGI series are the Russian counterpart of the NACA sections, and are therefore widely used in the Russian aircraft industry. Joukowsky sections were the first to be defined theoretically, however, they are not currently used. Clark Y (USA) and RAF (UK) sections, the first attempts to define a family of sections, are currently used for propellers. On the other hand, the Gottingen, Eppler and Wortmann series are German sections; The first family is for general use, while the second and third are specialized for gliders. Finally, the NLF and GA sections are the latest designs developed by NASA, the former being applied in gliders and the latter in light aircraft. (A Robles).

4.1 The four-digit NACA wing sections define the airfoil by:

- A digit describing the maximum sag as a percentage of the chord.
- A digit describing the maximum pitch distance from the leading edge of the aerodynamic surface in tens of percent of the chord.
- Two digits describing the maximum thickness of the airfoil surface as a percentage of the chord.

Table 1. Classification of aerodynamic profiles

Family	Advantages	Disadvantages	Applications
Series 4	- Good loss characteristics - Center of pressures approximately constant	- Low CL - High resistance - High pitching moment	- General aviation - Stabilizers - Supersonic jets - Helicopter blades - Racks - Missile fins and rockets

Series 5	- Higher CL - Low pitching moment -Little affected by roughness	- Poor stall characteristics - High resistance	- General aviation - Aircraft powered by piston engines - Business jets
Series 16	- Avoids suction peaks - Low resistance at high speeds	- Low lift	- Aircraft propellers - Ship propellers
Series 6	- High CL - Very little resistance within its operating range - Optimized for high velocities with large laminar flow regions	- High resistance outside the operating range - High pitching moment -Poor stall characteristics - Sensitive to roughness	- Piston engine-powered bombers - Business jets -Supersonic jets - Training jets
Series 7	- Very little resistance within its operating range - Low pitching moment	- Reduced CL - High resistance outside the operating range - Poor stall characteristics - Very sensitive to roughness	- Rarely used
Series 8	- Unknown	- Unknown	-Very rarely used

Source: A. Robles, Diseño de perfiles aerodinámicos mediante metodología inversa, Tesis Universidad de Sevilla 2115

5 Lift and drag

Lift on a body is the force on the body in a direction perpendicular to the direction of flow. The lift force will only be present if the fluid incorporates a circulatory flow around the body such as that around a rotating cylinder.

The velocity over the body increases and, therefore, the static pressure is reduced. The downward velocity slows down, giving an increase in static pressure. Then, there is a normal upward force called lift force.

Drag on a body in an approaching flow is defined as the force on the body in a direction parallel to the flow. For an airfoil to operate efficiently in a wind turbine, water turbine, aircraft propellers, aircraft wing, etc., the lift force must be high and the drag force must be low. For small angles of attack, the lift force is high and the drag force is low. If the angles of attack (α) increase beyond a certain value, the lift force decreases and the drag forces increase. So, the angle of attack plays a vital role. In applications where we want a fluid stream to "push" with the highest possible force on a solid, this solid will be designed to have the right shape and angle of attack to achieve the highest possible lift and lowest possible drag as shown in Figure 2.

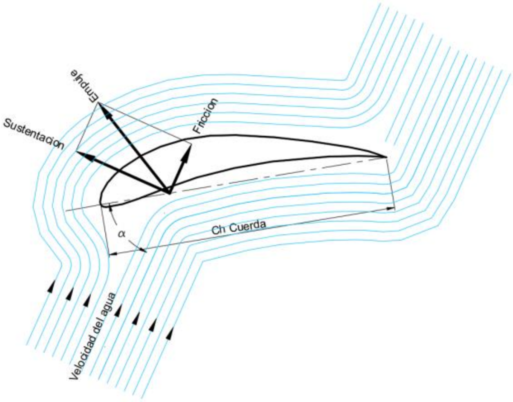


Figure 3. Fluid flow around the profile Source: Own elaboration

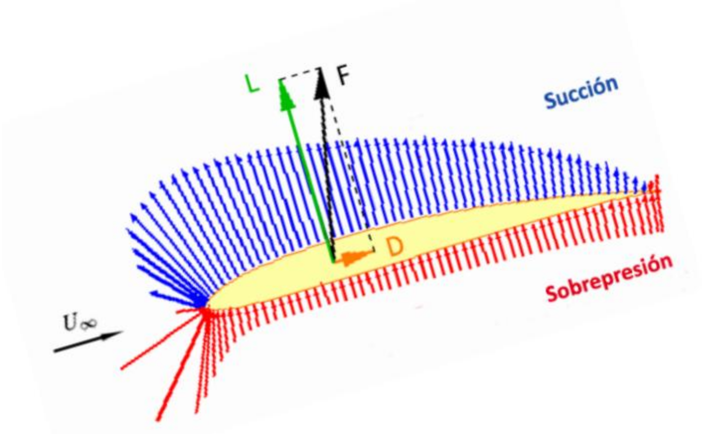


Figure 4. Distribution of overpressure in the wing
Source: A. Robles, Diseño de perfiles aerodinámicos mediante metodología inversa,
Tesis Universidad de Sevilla 2115

6 Method for the calculation of hydrokinetic turbines

Currently, the theories developed are based on the design of horizontal axis wind turbines, which are positioned in the renewable technology market as one of the main ways of extracting energy from natural resources such as wind. These theories provide information according to their limitations (Table 4.7), motivating the creation of new theories.

Table 2. Wind turbine and hydrokinetic calculation methodologies

Theory	Actuator Disc	Angular Momentum	Element Blade	Moment of the Blade Element
Information required	Diameter	TSR diameter	Diameter TSR Profile aerodynamic	Basic geometry TSR Profile data (CL, CD, CM, α)
Information provided	Basic estimation of power and thrust.	Basic estimation of power, thrust and torque.	Basic aerodynamic forces	Radial distribution of aerodynamic rotor forces

Source: N. Volpe, F. Zeitler, Optimized Hydrokinetic Turbine Design. Augmented with Diffuser, Thesis, Universidad Tecnológica Nacional FRSF, 2020.

An example of these theories is the Actuating Disc Theory, which allows the basic estimation of the rotor power and traction, knowing only the rotor area. Similarly, the Rotor Disc Theory is presented, which, in addition to the specifications provided by the Actuating Disc Theory, allows estimating the torque generated on the shaft based on the diameter and TSR of the rotor. However, both theories are limited by the omission of aerodynamics in the rotor.

As a consequence of these gaps in the information provided by the theories, the Blade Element Momentum (BEM) Theory arises, which considers the radial distribution of aerodynamic forces in the rotor, requiring its basic geometry, the TSR and certain airfoil data (M Egúsquiza).

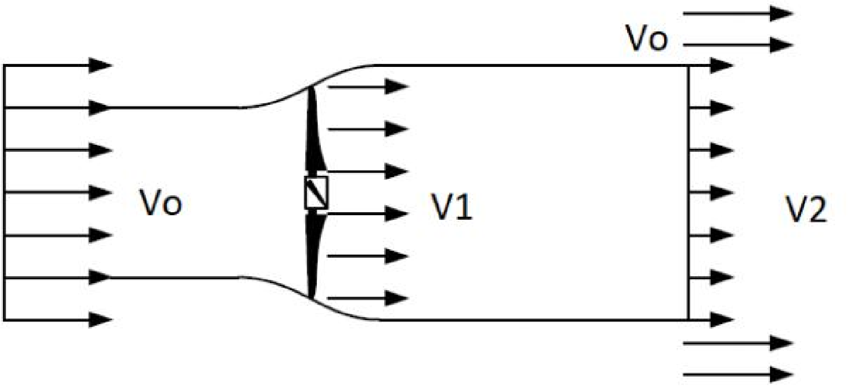


Figure 5. Model of water flow in the hydrokinetic turbine

Source: N. Volpe, F. Zeitler, Design of an Optimized Hydrokinetic Turbine with Diffuser Augmented with Diffuser, Thesis, Universidad Tecnológica Nacional FRSF, 2020.

6.1 Blade element theory

This theory analyzes the forces on a blade section with respect to its geometry. The blades, being in constant rotation, present different properties along their structure, such as the reactions generated in the airfoil.

The following considerations are taken into account for this theory:

- The blade is divided into N sections
- No hydrodynamic interaction between elements
- The forces on the blade are determined solely by the lift and drag characteristic of the airfoil.

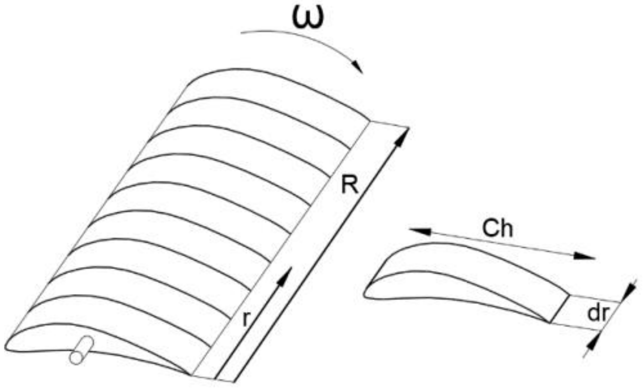


Figure 6. Blade element model

Source: Gizachew Dereje,* and Belete Sirahbizu, Design and Analysis of 2MW.

Horizontal Axis Wind Turbine Blade IJISET, 2019

Where:

Ch: blade chord (m); *dr*: blade segment under study (m);

r: localized radius for the blade segment (m); R: blade radius (m).

The forces acting on the blade will be parallel or perpendicular to the relative fluid velocity, which is defined in the Angular Momentum Model.

From Figure 4, 5 and 6 the following is determined:

$$tan\varphi=\frac{V1(1-a)}{\omega r(1+a')}=\frac{1-a}{(1+a')\lambda r}$$

$$a=\frac{V_1-V_2}{V_1}$$

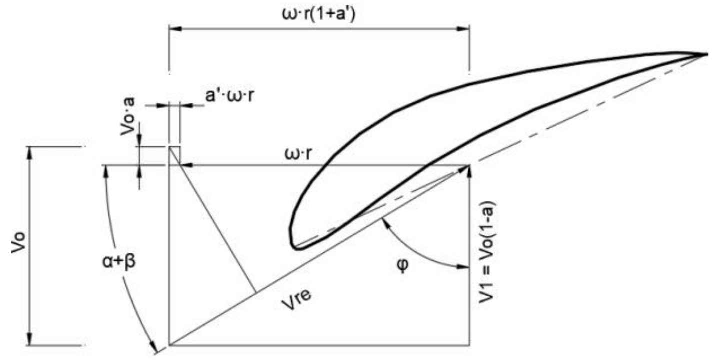


Figure 7. Velocities as a function of induction factors a and a' Source: Own elaboration

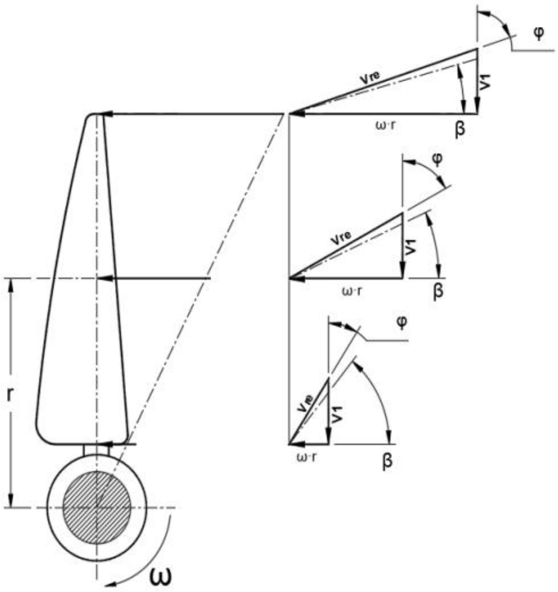


Figure 8: Velocity triangles for different blade radial positions with radius r

Source: N. Volpe, F. Zeitler, Diseño de Turbina Hidrocinética Optimizada Aumentada con Difusor, Tesis, Universidad Tecnológica Nacional FRSF, 2020

Where:

φ: angle of incidence (°); r: localized radius for the blade segment (m);

ω: angular velocity of the rotor (rad/s); λr:localized specific velocity (dimensionless);

a: axial induction factor (dimensionless); a′: angular induction factor (dimensionless);

V_0 : fluid velocity before entering the turbine (m/s); V_1: fluid velocity impacting the blade (m/s)

V_{re}: relative velocity of the fluid in the blade (m/s); Chc:perpendicular component of the chord (m)

For each blade section we have this way:

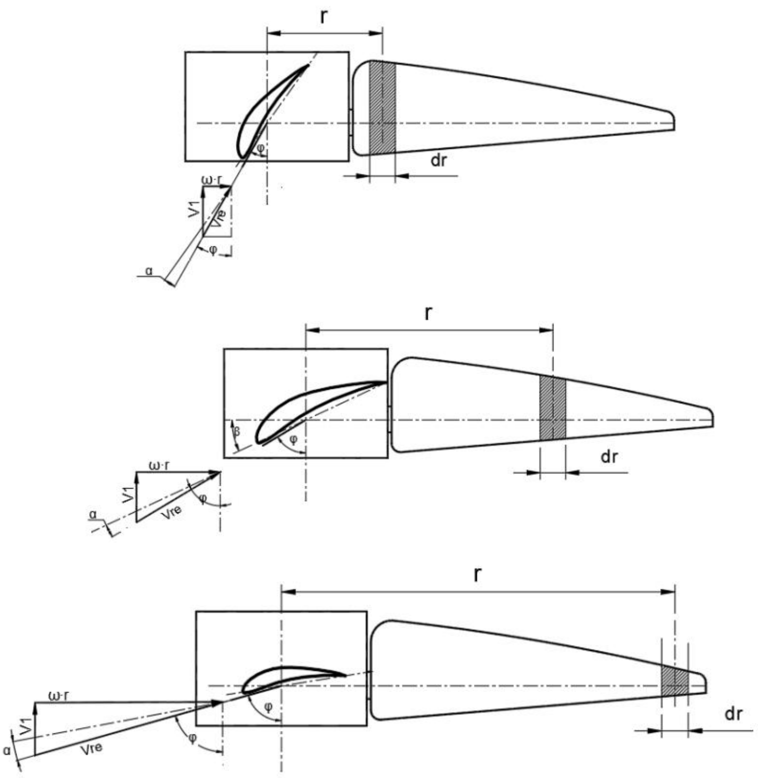


Figure 9. Velocity triangles for different blade radial positions with radius r

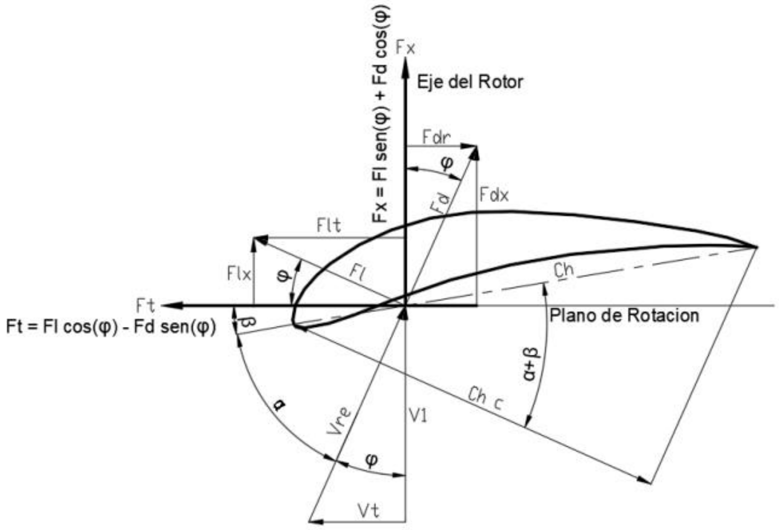
The area of each blade section is determined by the chord length *Ch* and the element length *dr* (Figure 9):

$$A=C_h\,dr$$

Where:

A:blade section area (m^2); C_h: rope length (m); *dr:* length of the annular element (m).

Therefore, the forces acting on the vane are obtained from



$$F_l = C_L \frac{1}{2} \rho V_{re}^2 C_h \, dr$$

$$F_d = C_D \frac{1}{2} \rho V_{re}^2 C_h \, dr$$

$$F_x = F_l \, sen\varphi + F_d \cos\varphi$$

$$F_t = F_l \cos\varphi - F_d \, sen\varphi$$

Figure 10. Triangle of forces for the profile located at a certain radius r

Where:

F_l: lift force on an annular element (N); F_d: drag force on an annular element (N);

F_x: normal force on an annular element (N);

F_t: tangential thrust force on an annular element (N); C: lift coefficient (dimensionless);

C: drag coefficient (dimensionless);

: fluid density (kg/m^3);

Thus, the total torque exerted on the shaft will depend on the number of vanes and the thrust force at a given radius:

$dQ = Br\ Ft$

$dF_x = B\ F_x$

Where:

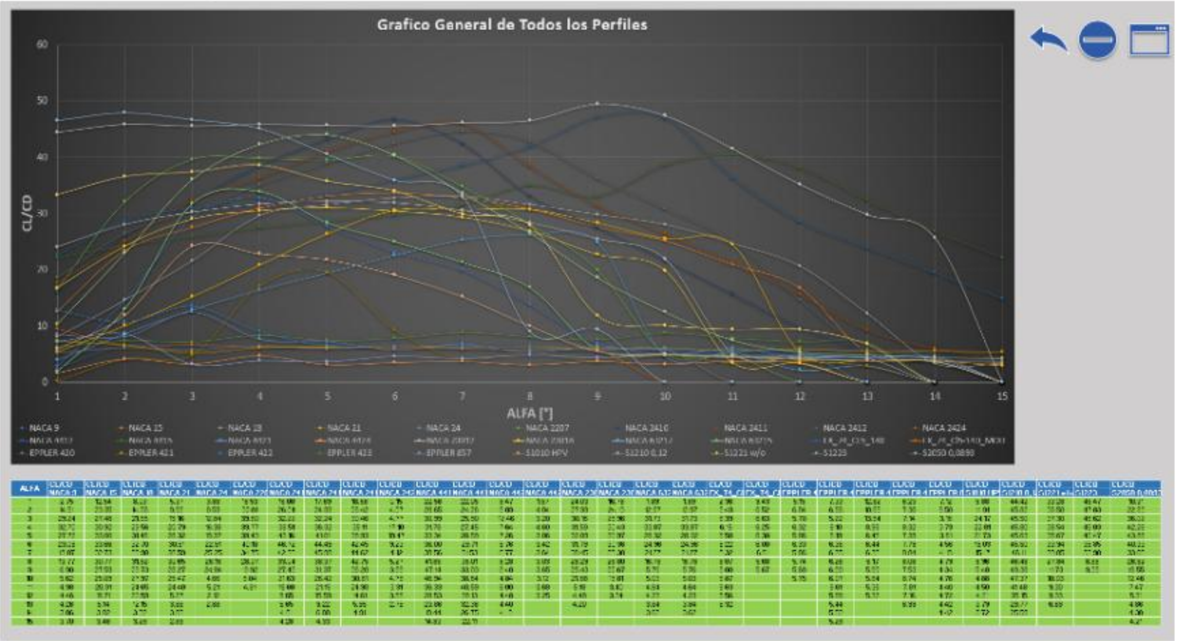
dQ: torque exerted on a ring element (N); dFx: normal force exerted on an annular element (N)

B: number of blades on the rotor (dimensionless);

In this way it is possible to express the behavior of a blade with the fluid velocity parameters.

7 Modeling and simulation

The selected blade profile has been filtered by the applicability for hydraulic use, generating 30 profiles recommended by different theses and scientific articles and which have been used in hydrokinetic turbines.



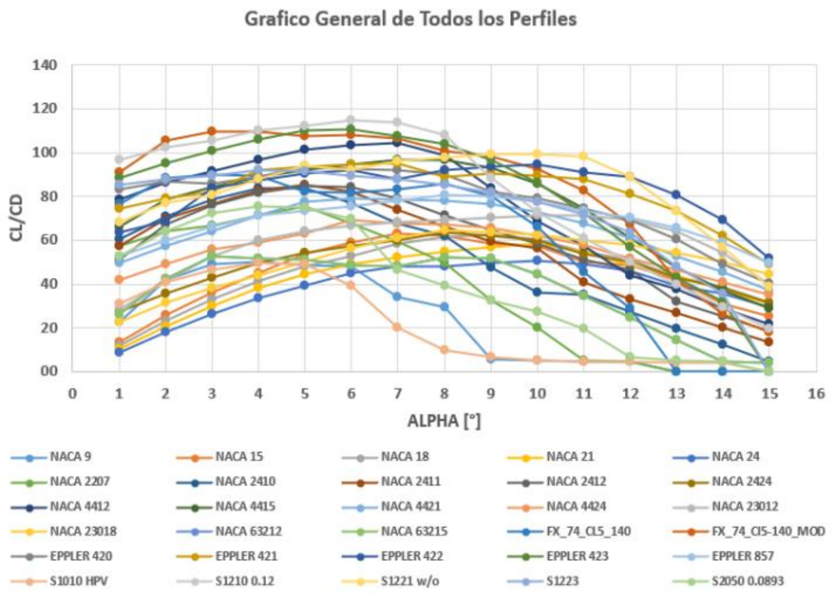


Figure 11. Comparative table of lift and drag coefficients for recommended hydrofoil profiles

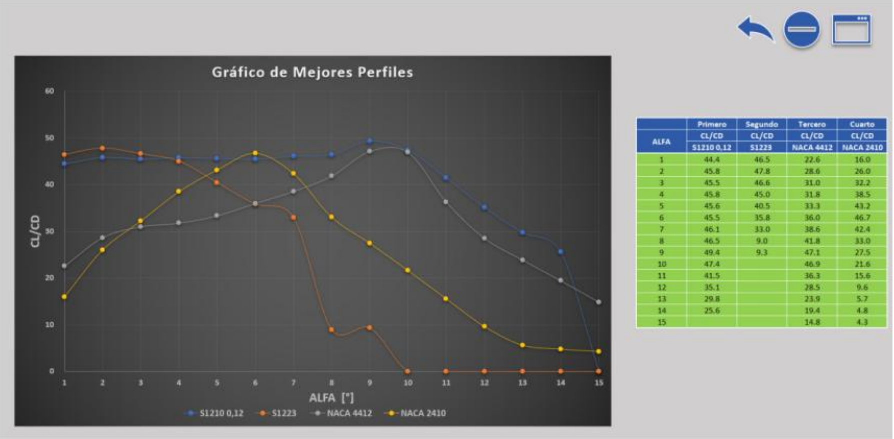
Source: P. Maldonado, Validación Turbina Hidrocinética, P. Maldonado, Ende Guaracachi

Table 3. Water velocities in Bolivian Amazonian rivers

No.	Station	Average speed (m/s)	Average depth (m)
1	Fortaleza de Abuna Abajo	0.1 - 1.5	1.0 - 7.0
2	Fortaleza de Abuna Capitanía	0.1 - 0.6	2.0 - 5.0
3	Villa Bella	0.2 - 1.5	2.0 - 6.0
4	Nueva Esperanza	0.1 - 3.0	1.0 - 7.0
5	Manoa	0.1 - 0.8	2.0 - 5.0
6	Yata	0.1 - 0.65	1.5 - 5.5
7	Arcade Israel	0.1 - 2.5	1.5 - 4.5
8	Tambaqui	0.05 - 0.2	0.4 - 2.0
9	Río Negro	0.05 - 0.8	1.0 - 6.0
10	Guayaramerín	0.1 - 0.8	2.0 - 6.0
11	Cachuela Esperanza	0.1 - 1.5	1.0 - 5.0

Source: Ende Guaracachi S.A

In the previous graph it is possible to observe the behavior of each profile with its corresponding drag and displacement curve as a function of the angle of attack α, for this calculation a computational application has been developed to filter the best profiles that could be used for water velocities in the northern Amazonian region of Bolivia that fluctuate between 0. 5 to 3.5m/s (ENDE 2022), the data source of drag Cd coefficients and Cl coefficient of desubstantiation were imported from the XFOIL application and also available on the NACA website.



ALFA	Primero	Segundo	Tercero	Cuarto
	CL/CD	CL/CD	CL/CD	CL/CD
	S1210 0,12	S1223	NACA 4412	NACA 2410
1	44.4	46.5	22.6	16.0
2	45.8	47.8	28.6	26.0
3	45.5	46.6	31.0	32.2
4	45.8	45.0	31.8	38.5
5	45.6	40.5	33.3	43.2
6	45.5	35.8	36.0	46.7
7	46.1	33.0	38.6	42.4
8	46.5	9.0	41.8	33.0
9	49.4	9.3	47.1	27.5
10	47.4		46.9	21.6
11	41.5		36.3	15.6
12	35.1		28.5	9.6
13	29.8		23.9	5.7
14	25.6		19.4	4.8
15			14.8	4.3

Figure 12. Recommended profiles for a specific water velocity Source: P. Maldonado, Validación Turbina Hidrocinética, P. Maldonado, Ende Guaracachi

For each location with population on the river bank identified with water velocity between 1 to 2m/s, 4 wing profiles are filtered, in this way it is possible to identify for each water velocity a profile among 4 classified.

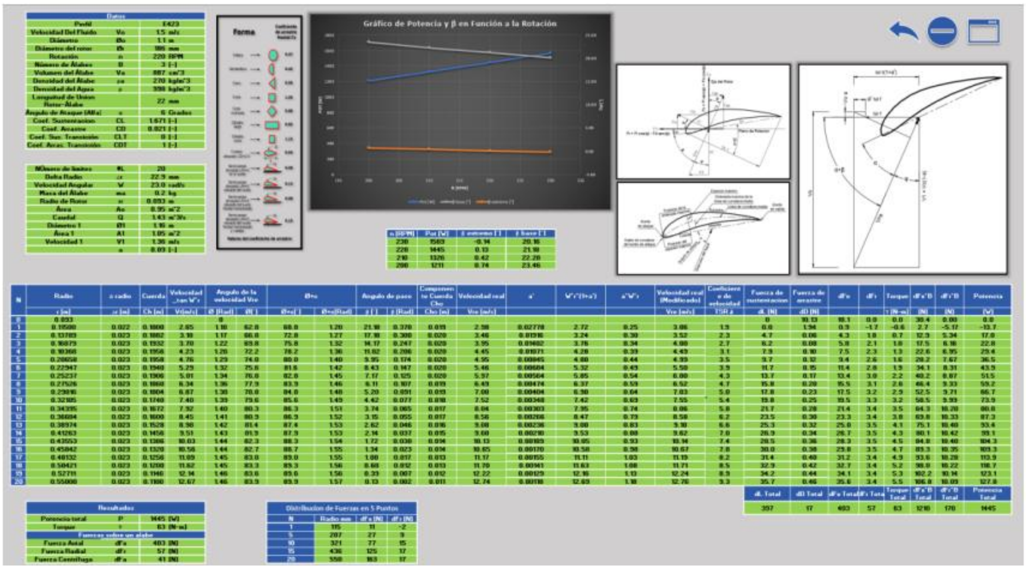


Figure 13. Optimization of power and blade pitch angle for maximum power and rotation

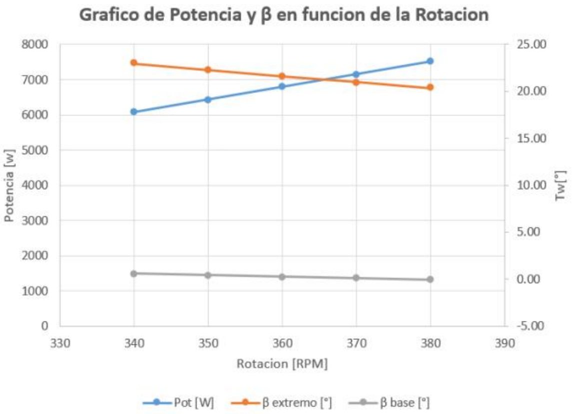


Figure 14. Optimal power curve and blade pitch angle

Source: P. Maldonado, Validación Turbina Hidrocinética, P. Maldonado, Ende Guaracachi

Through the latter figure, it shows the results of selecting the optimal profile for water velocity, turbine diameter, turbine rotational force, and recommended blade geometry with the suggested twist angle β for manufacturing.

This application can generate the optimal blade geometry and then verify the wake of the fluid, which must be in the range of non-turbulent, using QBlade software to export data from the Excel application.

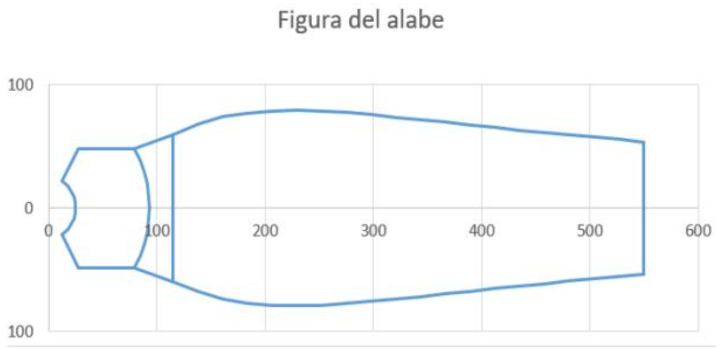


Figure 15. Geometry of the recommended vane

Source: P. Maldonado, Validación Turbina Hidrocinética, P. Maldonado, Ende Guaracachi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Microsoft Excel

Perfil para SolidWorks creado con exito

Figure 16. Exporting Warping Data to QBlade Software Source: P. Maldonado, Validación Turbina Hidrocinética, P. Maldonado, Ende Guaracachi

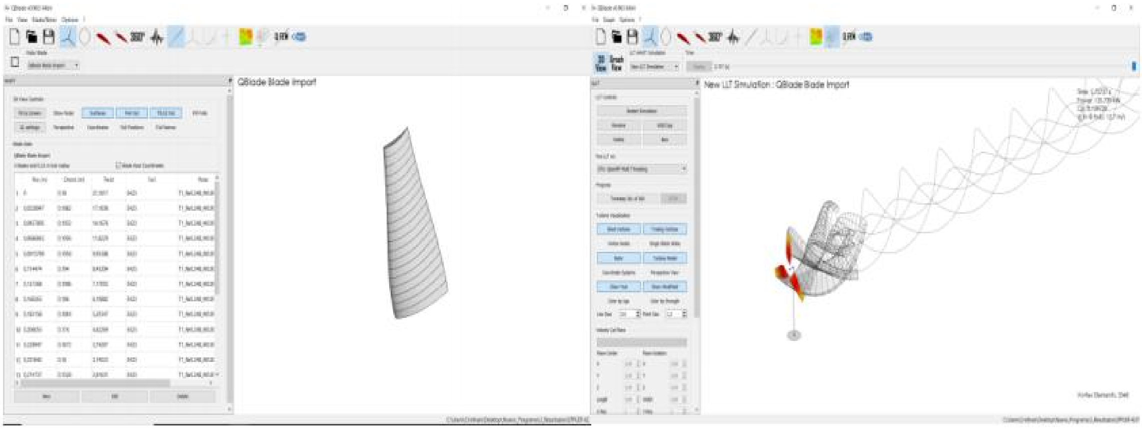

Figure 17. Simulation of blades in Qblade software Source: P. Maldonado, Validación Turbina Hidrocinética, P. Maldonado, Ende Guaracachi

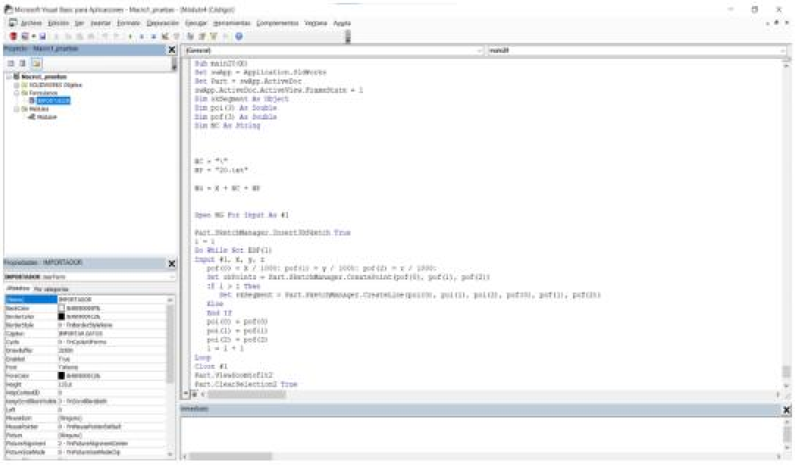

Figure 18: Excel and SolidWorks macros for exporting 3D drawings Source: P. Maldonado, Validación Turbina Hidrocinética, P. Maldonado, Ende Guaracachi

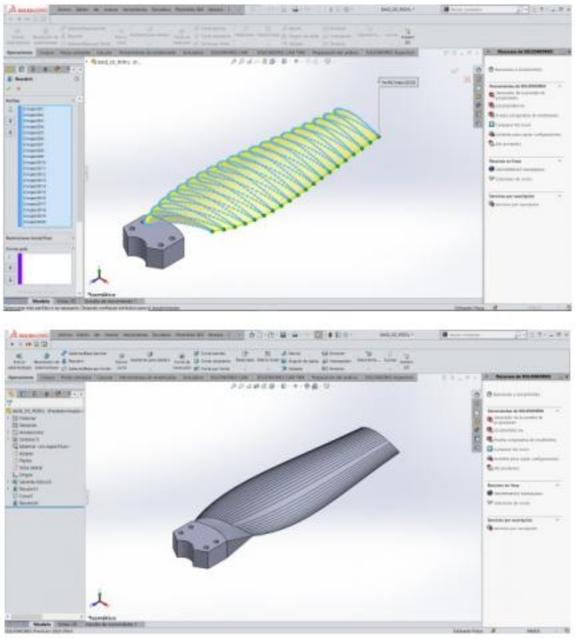

Figure 19. Blade design in SolidWorks software Source: P. Maldonado, Validación Turbina Hidrocinética, P. Maldonado, Ende Guaracachi

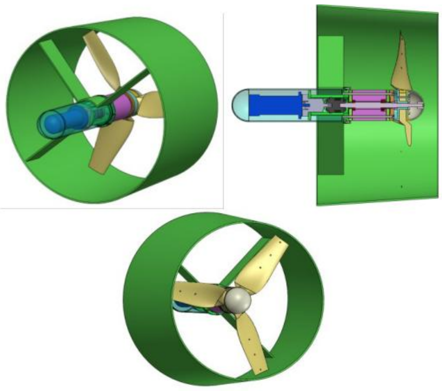

Figure 20. Blade design in SolidWorks software Source: Maldonado, Validación Turbina Hidrocinética, P. Maldonado, Ende Guaracachi

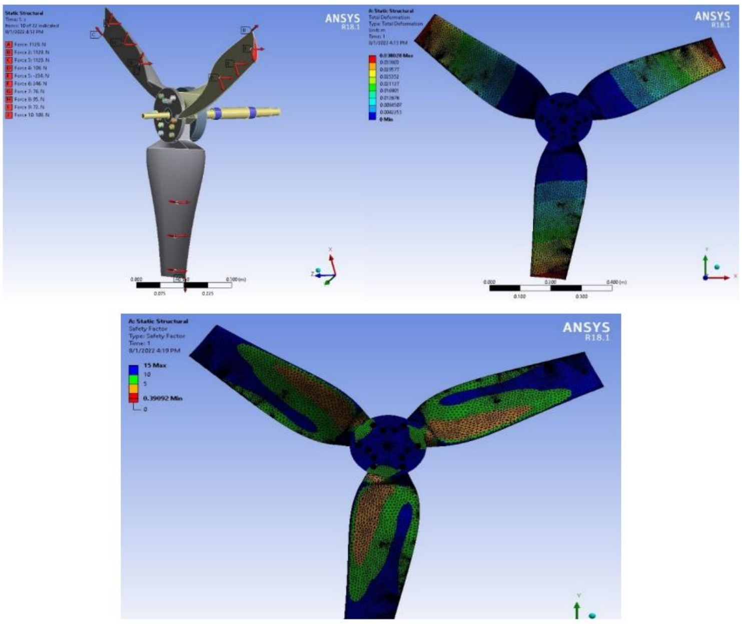

Figure 21. Mechanical simulation of the blade in ANSYS software

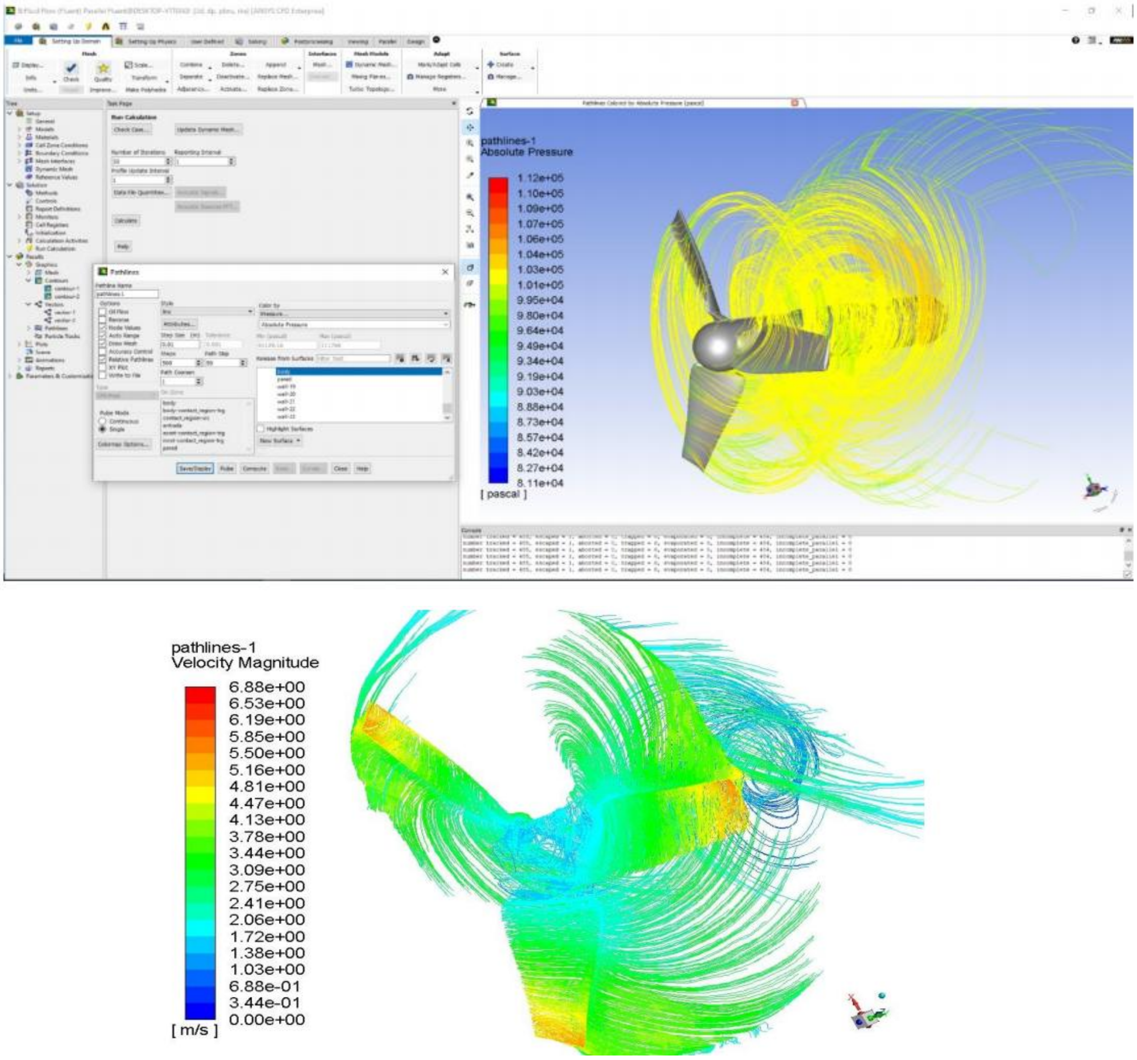

Figure 22. CFD simulation of the blade in ANSYS software Source: P. Maldonado, Validación Turbina Hidrocinética, P. Maldonado, Ende Guaracachi

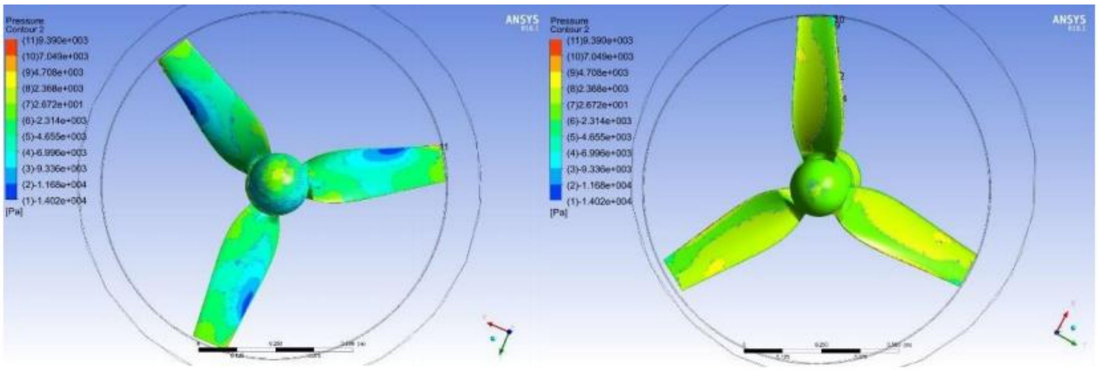

Figure 23. CFD simulation of the blade in ANSYS software, pressures and velocities Source: Validación Turbina Hidrocinética, P. Maldonado, Ende 2022

Figure 24. 3D printed manufacturing blade model, scale 1:1 Source: Own elaboration

8 Conclusion

A functional application is developed in Excel to optimize the design of a hydrokinetic turbine suitable for characteristic rivers in northern Bolivia that are tributaries of the Amazon.

There is a shortage of energy access in this jungle area with an abundant population and these areas can obtain clean daily energy faster for daily use and improvement in health, education and communication, and achieve sustainable development and construction through appropriate technology.

The computational applications for data export are made in Visual Basic application macros from SolidWorks, Excel, QBlade, Xfoil, which can be available for educational use and training by the author.

The use of the applications can help a lot for the manufacture of turbines with appropriate technology in Bolivia.

Conflicts of interest

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

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