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Analysis of the dependence of the parameters in the power coefficient for a vertical axis hydrokinetic turbine

Ing. Jonathan Mendoza Acosta
dannymen1995@hotmail.es
https://orcid.org/0000-0002-3134-7918
Universidad Técnica Estatal de Quevedo
Quevedo - Ecuador

MSc. Kelvin Diego Moposita Ortega
kelvin.moposita.ortega@alumnos.upm.es
https://orcid.org/0000-0002-1032-8558
Universidad Técnica Estatal de Quevedo
Quevedo - Ecuador

ABSTRACT

This article sets the numerical simulation CFD, to analyze the geometric parameters on a vertical axis helical hydrokinetic turbine. This analysis is represented by volumes of control methods, to obtain the fluid dynamic behavior of water passing through the turbine. Turbine design, is considered with the selection of information studies by researchers, with reference to these data and study how to implicitly affect the power coefficient, varying different parameters of the hydrokinetic turbine; such as: increase the height, diameter of the rotor, which NACA profile type select, vary the chord length of the profile. Before obtaining a final parametric model, certain parameters previously stipulated by a Matlab script are dimensioned and subsequently bring the three-dimensional model to numerical simulation CFD.

Keywords: turbine hydrokinetic; matlab; CFD simulation.

Análisis de la dependencia de los parámetros en el coeficiente de potencia para una turbina hidrocinética de eje vertical

RESUMEN

Este artículo establece la simulación numérica CFD, para analizar los parámetros geométricos en una turbina hidrocinética helicoidal de eje vertical. Este análisis está representado por métodos de control de volúmenes, para obtener el comportamiento fluidodinámico del agua que pasa por la turbina. El diseño de la turbina, se considera con la selección de información de los estudios por parte de los investigadores, con referencia a estos datos y estudiar cómo afecta implícitamente el coeficiente de potencia, variando diferentes parámetros de la turbina hidrocinética; tales como: aumentar la altura, el diámetro del rotor, qué tipo de perfil NACA seleccionar, variar la longitud de cuerda del perfil. Antes de obtener un modelo paramétrico final, se dimensionan ciertos parámetros previamente estipulados por un script de Matlab y posteriormente se lleva el modelo tridimensional a simulación numérica CFD.

Palabras clave: turbina hidrocinética; matlab; Simulación CFD.

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1. INTRODUCTION

A turbine hydrokinetic is a mechanical means designed to produce energy, using only the kinetic energy provided by the current of the rivers or canals. Energy demand that can generate this type of turbine vertical axis helical hydrokinetic depends on the geometrical and physical conditions that holds the fluid. The advantage of a helical turbine are the dynamic fluid conditions that it can begin work, such speeds of 0.6 m/s onwards; compared to other turbines which require higher demand in the fluid velocity.

This type of turbines is studied through physical and numerical models to predict how they would run for various flow conditions. So to be able to parameterize a model, seeking a way to improve the efficiency and reliability of these turbines.

The analysis of the power coefficient is studied based on the main parameters of vertical shaft hydrokinetic turbines. To analyze how the flow acts on the turbine, the computational fluid dynamics will be associated with the CFD package - Ansys (Ansys, 2018), where the geometrical conditions of the turbine previously stipulated in a three-dimensional design (3D) intervene (SolidWorks, 2017; Shigley, 2008), and the physical conditions to which the model will be exposed.

Computational fluid dynamics (CFD) is an effective tool that allows to simulate fluid flows, calculate the forces that comprise the impact of the flow on the turbine; for this, applying turbulence methods, such as the Standard K-ε model, appropriate for numerical analysis when presenting this best result in the analysis.

The applicable objective of the present study is the comparison of the power coefficient between the different blade arrangements with the numerical simulations. First with the analysis in the Matlab script it is possible to dimension the height and diameter of the rotor; In addition to making a comparison between the profiles NACA 0018 - 0020 - 63-020 (Series, 2012), and select the profile that denote better yields according to the chord length of the blade, to take advantage of better efficiencies in low and high flow velocity conditions. In the numerical analysis of computational fluid dynamics (CFD), the design change in the number of blades and twist angle of the turbine is foreseen.

2. METHODS

STATE OF THE ART

A compilation of results is made, information from other researchers (Bachant, 2011; Bhutta & Nasir Hayat Ahmed, Mayo, 2012; Anmastache, 2015; Gorlov, 2010; Johnson, 2011; Tsai, 2014; Tuyen Quang Le, 2014), to establish the advances that have occurred on hydrokinetic turbines (Gustavo J. Marturet P, 2015; Khan M.J., 2015; Marturet, Gutiérrez, & Caraballo, 2017; Pongduang, 2015; Niblick, Cavagnaro, Hall, & Thomson, 2013). Through the review, what has been researched is detected, in this way the difference between what is researched and the results can be obtained in the new research proposals. In Table 1, a brief synthesis of the influential parameters is made in the determination of the power coefficient and how the values arise through the proposed formulas.

Table 1.

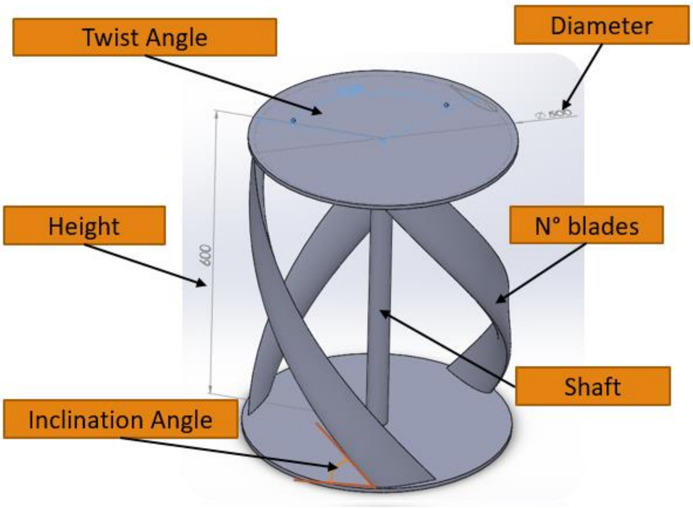
Information collected on geometric conditions of the turbine and flow physics.

Components	Parameter	Quantity	Unity	Formula used
Fluid properties	Fluid density	998	Kg / m3	-
	Kinematic viscosity	1.1 x 106	m2 / s	-
	Fluid velocity	1 - 5	m / s	-
Turbine	Number of blades	3	-	-
	Type airfoil	NACA 0018		-
	Solidity ratio	0.34	-	$\sigma = \frac{n * C}{\pi * D}$
	Aspect Ratio	1.33	-	$RA = \frac{H}{D}$
	Diameter	0.45	m	-
	Radio	0.225	m	$R = \frac{D}{2}$
	Height	0.60	m	-
	Swept area	0.27	m2	$A_{cap} = D * H$
	Chord length of the blade	0.16	m	$C = \frac{\sigma * \pi * D}{n}$
	Inclination angle	51.85	°	$\delta = tan^{-1}\left(\frac{n * H}{\pi * D}\right)$
	Angle of twist	120	°	-

The parameters described in table 1, are shown in figure 1 based on the information obtained for a previous model of hydrokinetic turbine with helical vertical axis.

Figure 1.

Implicit parameters in a helical hydrokinetic turbine.



ANALYTICAL METHOD

Analyzing the different types of hydrokinetic turbines and opting for the application of helical vertical axis turbines, the characteristics of their structure make their design functional at low water level height, with availability of the low power energy resource, being the case in the areas of influence of our region.

In addition, perform an analysis by means of the Matlab script (Niblick A. L., 2012), under the condition of changes in its geometric parameters, it allows to decompose a whole in its parts to study each of its elements, as well as they are related to each other. In this way, it is analyzed what effects they cause in the operation or efficiency of the turbine. To understand what is the power coefficient (Cp.), which is the relationship between the power-turbine and the power delivered by the fluid, as seen in equation 1.

$$Cp = \frac{Pot_{Turbine}}{Pot_{Fluid}} \rightarrow Cp = \frac{T * \omega}{\frac{1}{2} * \rho * A * v^3} \qquad \textbf{EC. 1}$$

Where the numerator of equation 1, has values of: Torque (T) by the angular velocity (ω) that the turbine will obtain. For the denominator values: water density (ρ), cross-sectional area (A) of the rotor, by the speed of the fluid raised to the cube (v^3). The tip speed ratio of the blade (λ) is indicated in equation 2, and represents the speed rotation of the turbine in the blade with respect to the flow velocity in the free current (v).

$$\boldsymbol{\lambda = \frac{\omega * R}{v}} \qquad \textbf{EC. 2}$$

All aerodynamic profile, which moves through a viscous fluid is subjected to lift forces (F_L), also to forces opposed to the movement of the object, which would be the drag forces (F_D). The forces are expressed as a function of the lift coefficients (C_L) and drag (C_D), respectively for each force generated in the blade of a hydrokinetic turbine. Equations 3 - 4, allow to calculate the lift and drag forces present in the blade, as it interacts with the fluid.

$$\boldsymbol{F_L = \frac{1}{2} * \rho * v^2 * C_L} \qquad \textbf{EC. 3}$$

$$\boldsymbol{F_D = \frac{1}{2} * \rho * v^2 * C_D} \qquad \textbf{EC. 4}$$

The forces are produced from the values: water density (ρ), speed of the fluid squared (v^2), by the coefficients of lift (C_L) y drag (C_D), respectively for each force. The equations described are implicit in the Matlab script for the tabulation of results and obtain the performance of the turbine, according to a NACA profile studied.

Table 2, shows a comparison between the profiles NACA 0018, 0020 and 63-020, where it is carried out simultaneous, same conditions for the fluid velocity and chord length of the profile. Maintaining constant diameter (0.5 m) and height (0.6 m) of the turbine. Analyzing the variables (Torque, power of the turbine and Cp.), located in the table, obtaining different results for each profile studied, in such a way, selecting the parameters that show a better performance, as is the case of the NACA 0020 profile.

Table 2. *Results of each NACA profile.*

Results	NACA 0018	NACA 0020	NACA 63-020
Velocity of flow	1.05 m/s	1.05 m/s	1.05 m/s
Chord length	0.12 m	0.12 m	0.12 m
Torque	10.15 N.m	12.95 N.m	7.75 N.m
Turbine power	72.44 W	92.47 W	55.34 W
Cp.	0.41	0.53	0.31

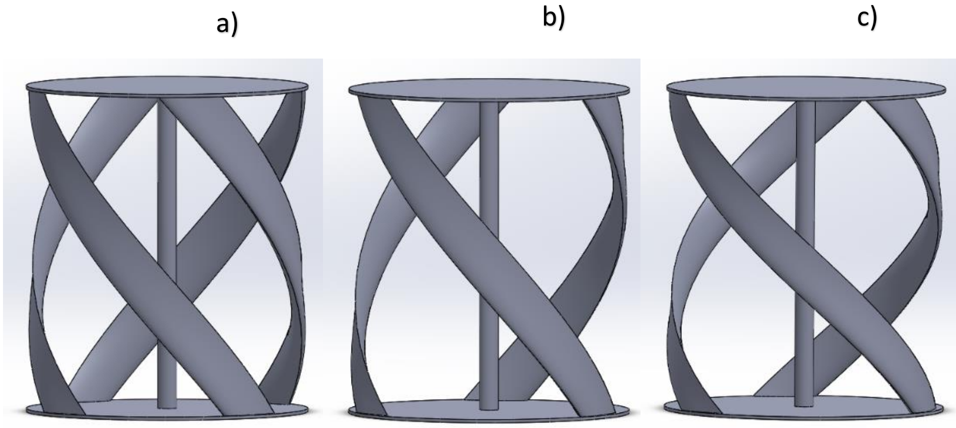
SIMULATION

With the analysis of the parameters in Table 2, the analyzed data (chord length, NACA profile, height, diameter) is linked to the model parametric (3D) of the hydrokinetic turbine with helical vertical axis. Then, by experimenting to change now only the number and angle of twist of the blades in the parametric design which are geometric variables that are implicit, in such a way, sketching three different models to verify if these affect in any way in the power coefficient.

Then, relating the computational fluid dynamics (CFD) with the elaborated models to obtain the analysis at low and high velocity of the flow for each proposed model; and as the last point based on numerical simulations obtain the best power coefficient.

Figure 2, shows the sketched models in their different configurations for the blades: a) four blades - 120 °, b) three blades - 120 °, c) three blades - 150 °. Maintaining constant its other parameters such as height (0.6 m), diameter (0.5 m), blade chord (0.12 m) and profile NACA 0020.

Figure 2. *Configurations for the blades: a) four blades - 120 °, b) three blades - 120 °, c) three blades - 150 °.*



Figures 3 and 4 denote the dimensions of the computational domain that are established according to the diameter (D) and height (H) presents by the turbine; for the volume of control it is recommended that it be at least twice the diameter of the turbine upstream and four times its diameter downstream, to avoid particularities in the results. A fluid section of 6D wide by 3.5H high and 12D long is modeled, these dimensions have been based on: (Mott, 2006; White, 2013; Marturet, Gutiérrez, & y Caraballo, 2016), realizing this sizing with origin of coordinates in the center of the helical hydrokinetic turbine.

Figure 3. *Side view of the domain dimension.*

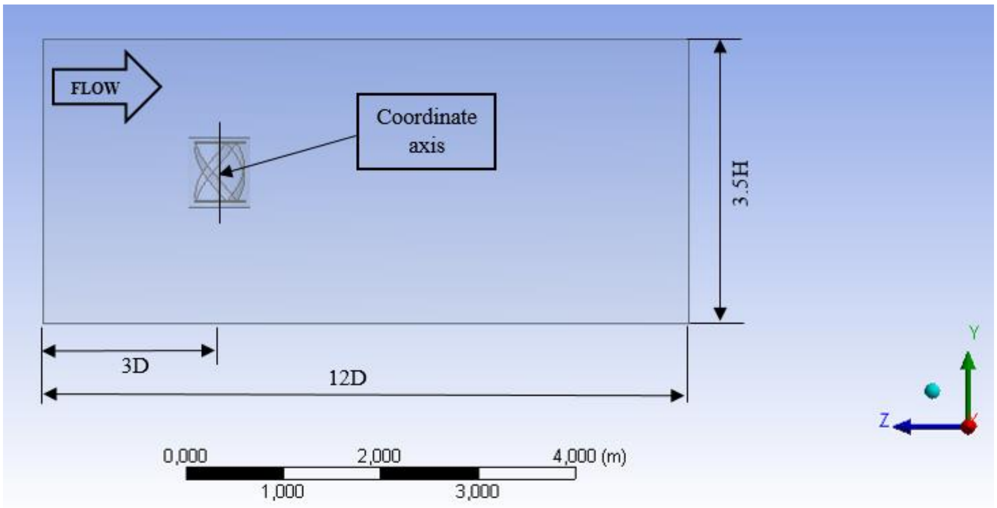
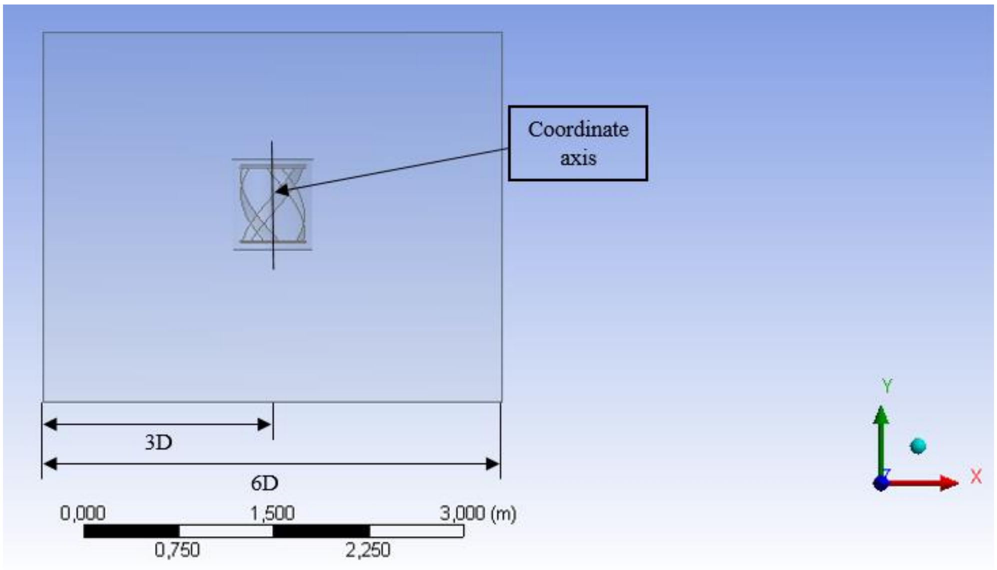
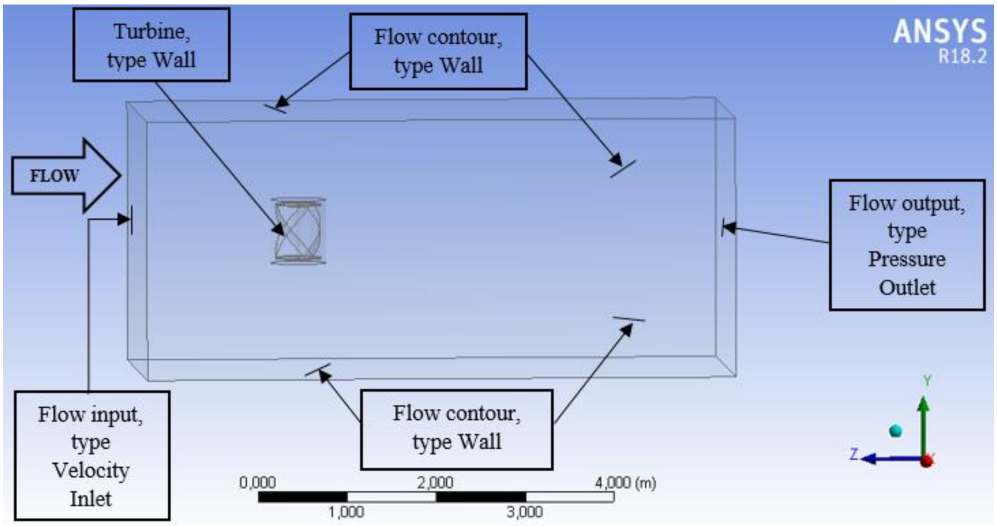


Figure 4. *Front view of the domain dimension.*



The boundaries of the computational domain, in its boundary conditions for the vertical axis hydrokinetic turbine, are configured as indicated in Figure 5, for the three models proposed. The wall type configuration is established (Wall) for the side faces, top and bottom of the rectangular geometry domain that limits the contact area through which the fluid will flow, and in the same way for the turbine because it is where the fluid will be circulating in contact with the rotor, in addition, the front face is assigned type (Velocity Inlet) of the water flow in a maximum - minimum range; and finally the back face of type (Pressure Outlet). Also, the condition of contour in the blades is considered stationary (Stationary Wall) and wall type.

Figure 5. *Configuration of the boundary conditions.*



3. RESULTS

SCRIP MATLAB

With the results of table 3, some configurations for the turbine sizing are discriminated, the profile NACA 0018 reflects low performance in the coefficient of lift that produces lower performance, in addition, a 6-digit profile (NACA 63-020) is discarded when generating high drag.

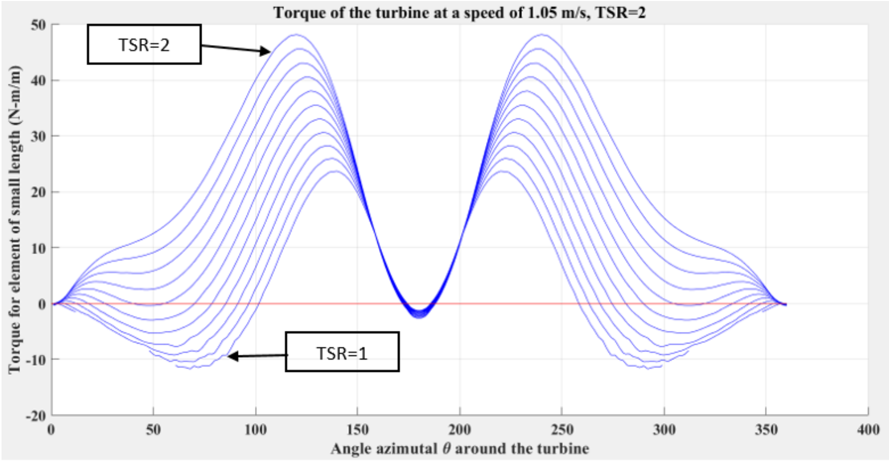
Table 3. *Description of configurations used in the modeling Script.*

Description - Parameters				Results			
Velocity [m/s]	**Chord length [m]**	**Diameter [m]**	**Height [m]**	**Torque [N.m]**	**Fluid power [Watt]**	**Turbine power [Watt]**	**Cp.**
Profile – NACA 0018				**Results**			
1.05	0.10	0.5	0.6	-	-	-	-
1.4	0.12	0.5	0.6	19	411.6	170	0.41
1.9	0.15	0.5	0.6	36.7	1028	446.3	0.43
2.5	0.18	0.5	0.6	-	-	-	-
1.05	0.12	0.5	0.6	10.15	173.64	72.44	0.41
2.5	0.12	0.5	0.6	38.78	2343	659.2	0.28
Profile – NACA 0020				**Results**			
1.05	0.10	0.5	0.6	10.47	173.64	74.75	0.43
1.4	0.12	0.5	0.6	23.98	411.6	214.8	0.52
1.9	0.15	0.5	0.6	47	1028	615.8	0.58
2.5	0.18	0.5	0.6	-	-	-	-
1.05	0.12	0.5	0.6	12.95	173.64	92.47	0.53
2.5	0.12	0.5	0.6	51.34	2343	872.8	0.37

In the previous table, it is analyzed that the chord length of the blade depends on the speed of the fluid, having a high incidence in the development of the power coefficient (Cp.). Taking as a measure 0.12 m the length of the chord to take better advantage of the water resource at low and high flow velocities. In addition, the NACA 0020 profile gives better benefits by having better power coefficients compared to the NACA 0018 for the same conditions.

The following graphs show the modeling results of table 3, with the parameters of the turbine with profile NACA 0020 and length of the chord (0.12 m). Figure 6 describes how the torque develops without showing alterations or discontinuities along the turn of the turbine for tip speed ratio of 1.2 to 2. The tip speed (TSR = 1-1.1) shows discontinuities in the torque, which would cause yield losses in these points.

Figure 6. *Torque per element developed around the turbine (1.05 m/s).*



In figure 7, it shows the behavior of the lift coefficient (C_L) and drag (C_D), which are fully developed around the turbine turn. This result is carried out for fluid velocity of 1.05 m/s.

Figure 7. *Coefficients of lift (C_L) y drag (C_D) to (1.05 m/s).*

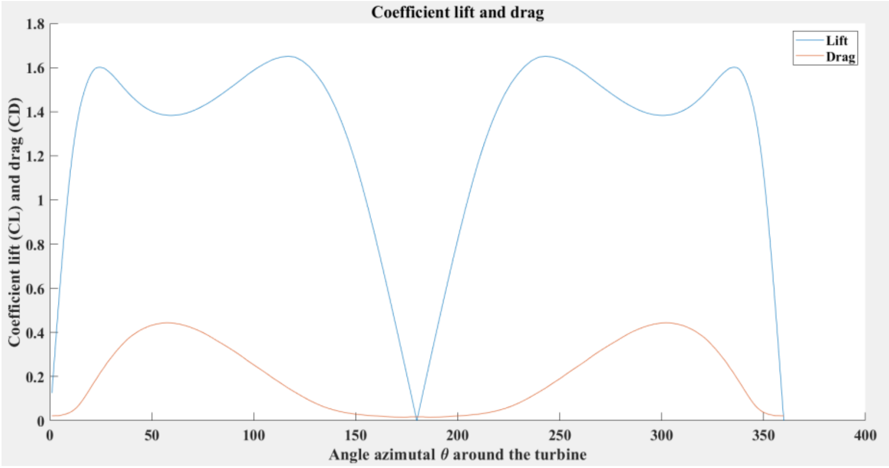
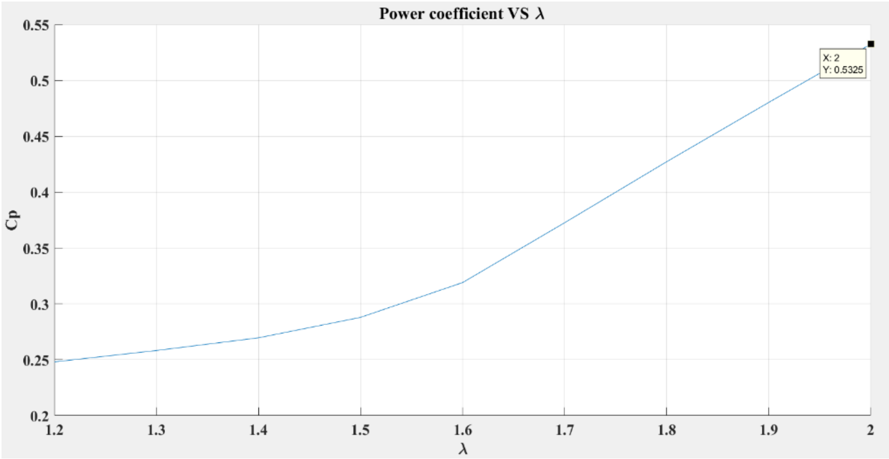


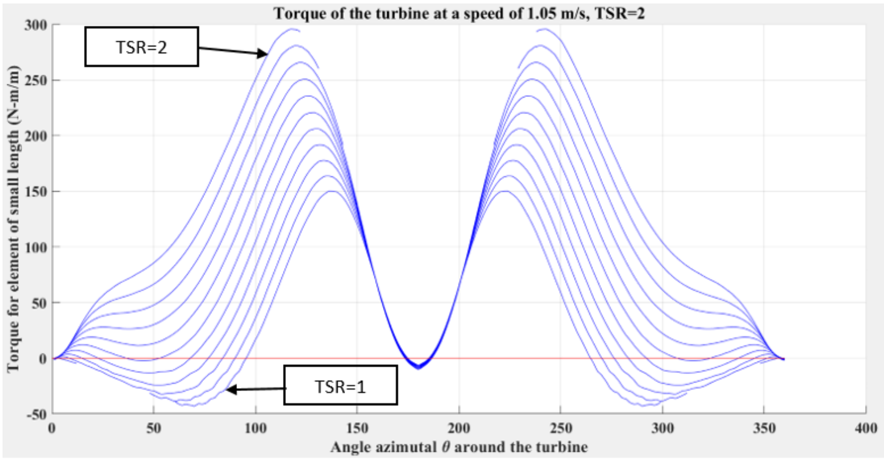
Figure 8, shows the power coefficient (Cp. = 0.53 = 53%) for the highest tip speed ratio (TSR = 2) that developed at that flow velocity.

Figure 8. *Power coefficient (1.05 m/s).*



In conditions of flow velocity to 2.5 m/s, the following graphs are shown, in order to evaluate the water resource and the low speeds. Figure 9, describes the torque that shows discontinuities for the tip speed ratio (TSR), (λ = 1 to 1.1 and λ = 1.7 to 2).

Figure 9. *Torque per element developed around the turbine (2.5 m/s).*



In figure 10, we also observe the discontinuity in the lift and drag coefficients, this is due to the speed of 2.5 m / s it does not allow to generate the lift and drag coefficients, tending these to zero until the turn starts to generate.

Figure 10. *Coefficients of lift (C_L) y drags (C_D) to (2.5 m/s).*

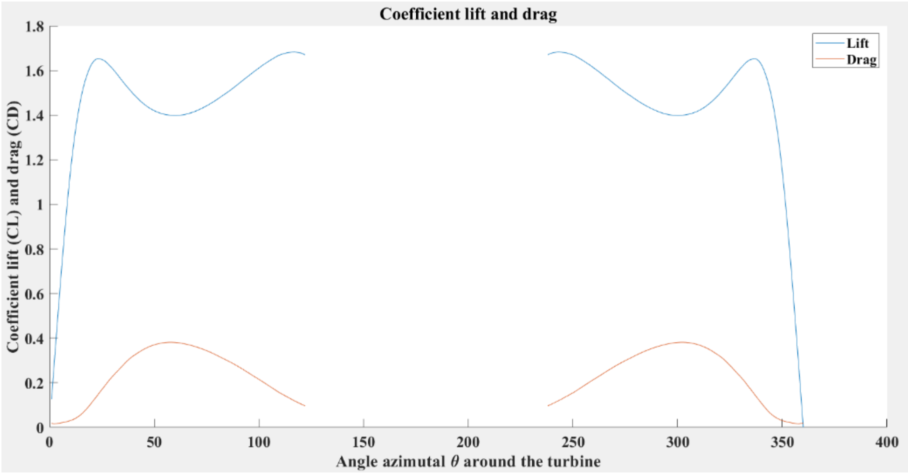
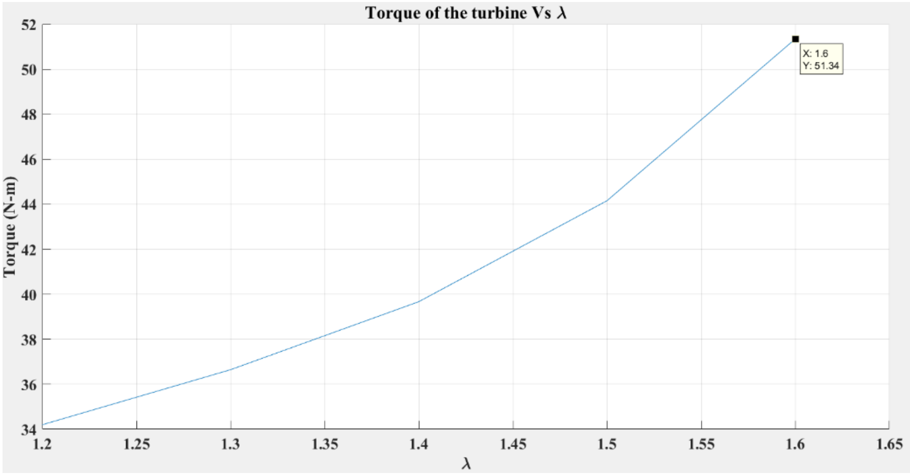


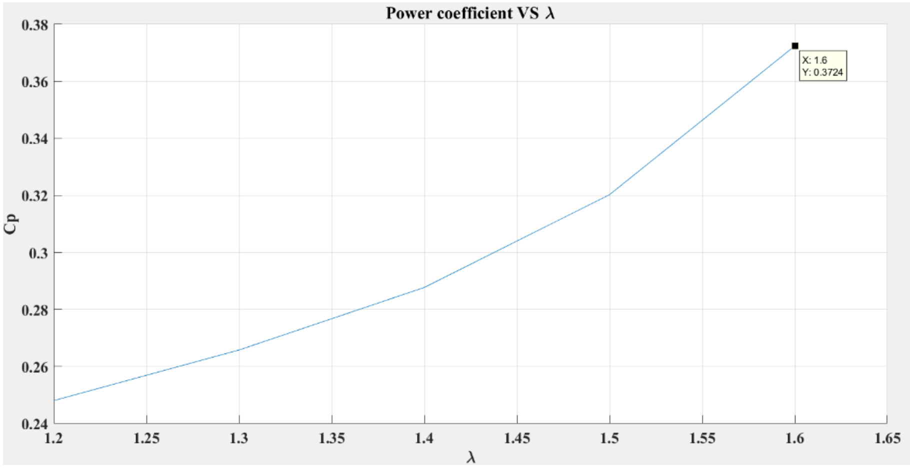
Figure 11, shows the total torque of the turbine for a tip speed range in the blade. For a TSR = 1.6 a torque equal to 51.34 N-m is generated.

Figure 11. *Total torque of the turbine (2.5 m/s).*



With the parameters established in the turbine and the maximum condition of the fluid, a power coefficient equal to (0.37 = 37%) is obtained for a lambda value of 1.6, described in figure 12. Although the coefficients are not fully developed due to the chord length of the blade, it is possible to take advantage of a performance between a range of tip speeds of the blade (λ).

Figure 12. *Power coefficient (Cp.) (2.5 m/s).*



ANSYS FLUENT – CFD

For the determination of the power coefficient some simulations were carried out, where some different configurations were experienced in the blades to define which variable has the greatest impact, be it your number of blades, twist angle or both; parameters stipulated previously in figure 2. Keeping the other parameters equal as: diameter (0.5m), height (0.6m), length of rope (0.12m), profile NACA 0020. With the help of the complement (Function Calculator - Ansys) the different forces were obtained for each coordinate axis (X, Y, Z); and with the conditions established in the simulations, results of torque, turbine power and Cp. were obtained. stipulated in table 4.

Table 4. *Power coefficient according to the configuration of the blade.*

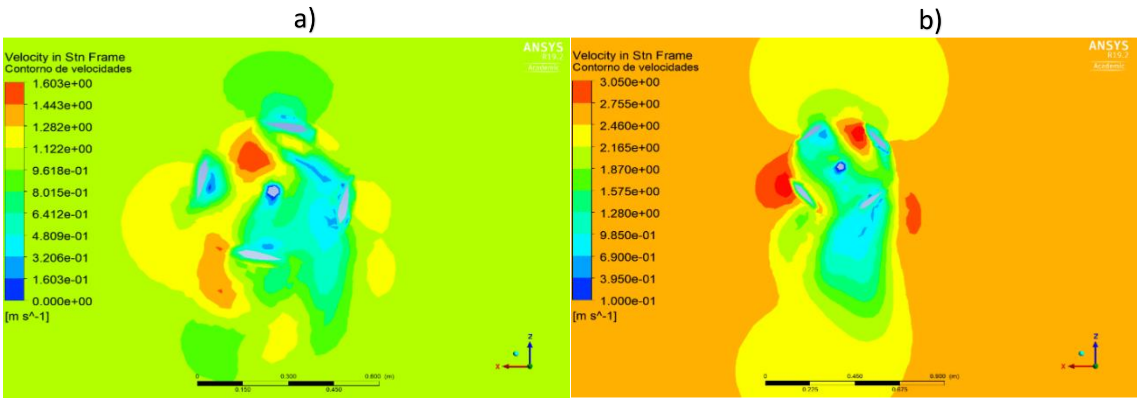
	Description			Results			
N° Simulation	**Velocity [m/s]**	**N° Blades [-]**	**Angle twist [°]**	**Torque [N.m]**	**Fluid power [Watt]**	**Turbine power [Watt]**	**Cp.**
1	1.05	4	120	34.44	174	86.1	0.49
2	2.5	4	120	244.14	2343.75	1220.73	0.52
3	1.05	3	120	22.21	174	55.52	0.32
4	2.5	3	120	138.22	2343.75	691.1	0.29
5	1.05	3	150	26.81	174	67.03	0.38
6	2.5	3	150	196.40	2343.75	981.97	0.42

In table 4, it can be highlighted that the rotor formed by four blades has a higher performance in extracting power from the fluid compared to that of three blades for the same angle of twist, denoting power coefficients (0.49 = 49% and 0.52 = 52%) for a minimum and maximum speed, respectively. While in the turbine with three blades at 120 ° of twist, power coefficients are presented (0.32 = 32% and 0.29 = 29%), respectively in flow velocities of 1.05 m/s and 2.5 m/s.

Another way to get better performance is a 150 ° twist angle that boasts power coefficients (0.38 = 38%, 0.42 = 42%) for low and high speeds, respectively.

Then, we highlight the simulations 1 and 2, which resulted in better power coefficients than in the rest of the simulations; figures 13 a) and b) show the velocity contours that occur at 1.05 m/s and 2.5 m/s, respectively.

Figure 13. *Contour speeds a) Simulation 1- 1.05 m/s, b) Simulation 2 - 2.5 m/s.*



4. DISCUSSION Y CONCLUSIONS

With the processed data of the variables in table 3, by means of a Matlab script, taking a procedure different from the data, not only through reading but also with the backing of this computational software that allowed to check, compare and constitute the inherent variables in the power coefficient of a form numerical. It was possible to delimit the most influential parameters for a vertical axis hydrokinetic turbine, in this way design the model, with type of NACA profile, chord length, diameter and height in the rotor; with the stipulated physical conditions.

In the numerical simulation (CFD), the results are described in table 4, where it was possible to study the conditions in the number and angle of twist for the blades; variables that were not studied in the Matlab script. This analysis allowed to see the fluid-dynamic behavior for the three elaborated models, highlighting among them better results, a turbine with four blades at 120 ° twist, with diameter (D = 0.5 m) and height (H = 0.6 m).

All this process leads to establish a configuration that shows a better performance, before the other proposed models, and select a final design. In first instance, doing out a process of modeling in Matlab that allowed to determine certain parameters and to diminish the use of the computational resource, when not executing a great number of three-dimensional simulations. Later, in the software of CFD - Ansys, obtaining the results thrown by the three-dimensional numerical simulation, to diagnose the best configuration of the turbine.

Table 5, on the left side, shows the parameters that could be analyzed in the Matlab script, determining yields, with such geometric and physical conditions. For the right side of the table, the study of the missing variables that are implicit in the power coefficient is completed. In this way the parameters are described to obtain a better performance, as shown in table 5, in the CFD simulation part.

Table 5. *Comparison of the variables for the hydrokinetic turbine.*

Script Matlab Modeling		**Simulation CFD**	
N° of blades	-	N° of blades	4
NACA profile	0020	NACA profile	0020
Twist Angle	-°	Twist Angle	120°
Inclination Angle	-°	Inclination Angle	56.86°
Chord length of blade	0.12 m	Chord length of blade	0.12 m
Diameter	0.5 m	Diameter	0.5 m
Height	0.6 m	Height	0.6 m
Velocities	1.05 – 2.5 m/s	Velocities	1.05 – 2.5 m/s

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