UNIVERSIDADE FEDERAL DE SANTA CATARINA - ARARANGUÁ

CAROLINE FERNANDES FARIAS

TRABALHO DE CONCLUSÃO DE CURSO

ARARANGUÁ

2016

CAROLINE FERNANDES FARIAS

TRABALHO DE CONCLUSÃO DE CURSO DE GRADUAÇÃO EM ENGENHARIA DE ENERGIA

Trabalho de conclusão de curso na modalidade de artigo científico para a aprovação na disciplina de Trabalho de Conclusão de Curso do curso de Engenharia de Energia da Universidade Federal de Santa Catarina-Campus Araranguá

Aprovado em: 07 / 12 / 2016

Prof. Dr. Leonardo Elizeire Bremermann (Orientador)

Prof. Dr. César Cataldo Scharlau (Examinador)

Prof. Dr. Éverton Fabian Jasinski (Examinador)

Prof. Dr. Reginaldo Geremias (Supervisor)

DESIGN AND EVALUATION OF A FISH-FRIENDLY WATER TURBINE

Caroline Fernandes Farias*

ABSTRACT

Frequently hydroelectric plants are presented as benign to the environment, particularly small scale run-of-river schemes due to have been designed to maintain a natural flow regime. However, it has been highlighted for researches that even these schemes can be harmful to the environment whereas the majority of the damage caused to fisheries at hydraulics turbines is due to blade strike and injuries. In reason to improve the fish survival through the turbine, this study aims to design a low head, run-of-river, fish-friendly water turbine, which uses a free water vortex for extract the energy of the water in a micro hydroelectric and evaluate its performance using computational fluid dynamics.

Keywords: Micro Hydropower Stations. Run-of-river. Fish-friendly. Computational Fluid Dynamics.

1- Undergraduate student of Energy Engineering at the Federal University of Santa Catarina, Araranguá Campus, Rodovia Governador Jorge Lacerda, 3201, Jardim das Avenidas, Araranguá, Santa Catarina, Brasil, CEP 88900-000. E-mail: farias.caroline@hotmail.com

1 INTRODUCTION

Hydropower is one of the primary energy sources in the range of renewable energy. It aims to produce electricity by harnessing the existing hydraulic potential of a river. Frequently hydroelectric plants are presented as benign to the environment. Particularly, small scale run-of-river schemes, which have been designed to maintain a natural flow regime. This model simply diverts a proportion of the river flow through turbines and return the water downstream (International Energy Agency, 2012).

However, this topic is now controversial. Authors have evaluated the impacts that hydropower might cause to the aquatic environment. They highlight that even low-head, run-of-river schemes, could be harmful (Deng, et al., 2006, Halls and Kshatriya 2009, Larinier 2001, Odeh 1999).

Run-of-river schemes might cause changes in fish population structure, habitat alteration, loss of critical spawning, nursery habitat, biological diversity, modifications of water quality and hydrological regimes, barrier to fish migration and disruption of longitudinal connectivity threatening fish population. Nevertheless, the majority of the damage caused to the environment by hydraulics turbines is due to blade strike and injuries (Robson, Cowx and Harvey, 2011). Concerned about the fish survival through the turbine, new turbines have been designed aiming to make moderns hydropower plants more sustainable and environmentally friendly.

Thereat, the main aim of this project is design a low head run-of-river, fish-friendly water turbine. The turbine will operate in a free vortex, to extract the energy of the water. Where, the fluid will be channelled to a spiral tank, to create a free vortex and the propeller will be installed in the centre of the vortex. The vortex will avoid cavitation, which can be deadly to fish, and can accelerate the water towards the turbine to increase its performance.

The objectives of this study include, modelling and design a vertical shaft and fixed runner turbine. Respecting parameters, from the literature, to avoid fish mortality. Concluding the design, the best geometry for the aerofoil blades, details of the propeller geometry, will be presented. The theoretical assessment of the turbine performance at the vortex, and its behaviour in a real site, will be provided, using computer fluid dynamics**.**

This study began during the exchange period, where it was held at the University of Nottingham, sponsored by the Science without Borders, and concluded at the Federal University of Santa Catarina.

The dissertation includes a literature review at section 2, section 3 presents the methodology, followed by the proposed project at section 4, results and discussion at section 5. Finally, conclusion, references and appendices are presented.

2 LITERATURE REVIEW

In this section the literature review will be presented, which covers the recent studies around the subject. The quantitative parameters that can characterize a fish-friendly turbine will also be defined.

2.1 Hydroelectric Power Plants

Water as mechanical energy source has been used for millennia of years around the world. However, only in the 19 century when water mills were coupled to electric generators, water started to be used as source of electric power. Suddenly, hydroelectric power plants (HPPs) became popular since twentieth century, for provide energy from nearby plants to load centres (International Energy Agency, 2012).

Nowadays, hydroelectric power plants can be divided into five groups which depends how much power they can generate. The micro HPP is to denominate, schemes with power bellow 75kW, mini HPP to power between 75 and 1.000 kW, small is to 1000 and 10.000 kW, medium is between 10.000 and 150.000 kW and large schemes are bigger than 150.000 kW.

Additionally, Run-of-River hydropower schemes are characterized by maintain the natural flow, avoiding the construction of a dam. Generally, they are installed near to the surface of the river. These plants generate power from the water flow and can be an option to reduce the environmental impact caused by dams and its construction (Faria, 2012).

Currently in Brazil the hydroelectric Power Plant of Belo Monte (PA), San Antonio (RO) and Jirau (RO) are some examples of run-of-river schemes. Belo Monte power plant installed on the River Xingu (PA), it has 18 turbines Francis and 6 bulb turbines in the complementary power house. This plant has only a small pool of water during the floods. During the dry season, it does not stock water in order to not compromise the volumetric flow downstream of the river. These measures aim to maintain a minimum flow in the river during the year, reducing environmental impact with a smaller flooded area and not interfere in fishing activities in the region. Belo Monte has a ratio between flooded area and power generated, equals to 0.04 Km^2/MW (Eletrobras, 2015).

Jirau HPP, installed on the Madeira River (RO), can generate 3,750 MW at full capacity. This scheme has 50 turbines bulb and is the world's largest bulb turbine power plant. It has a ratio of flooded area and power generated equals to 0.07 Km^2/MW. Also, under construction on the Madeira River (RO), the Santo Antônio power plant has 50 turbines Kaplan. The plant has the smallest ratio between flooded area and power generated, throughout the Amazon, which is equals to 0.03 km^2/MW. As a matter of comparison, Itaipu, the largest hydroelectric power generation company in the world, has a capacity of 14,000 MW using 20 Kaplan turbines. However, the flooded area corresponds to 1.35 million square kilometres, generating a coefficient of 0.1 km^2/MW (Eletrobras, 2015).

These coefficients, highlight that run-of-river schemes are more environmentally-friendly than traditional hydropower plants, regarding the flooded area.

2.2 Environmental Issues

Hydroelectricity presents several advantages over most other sources of electrical power. It promotes energy security and the reductions in prices paid by the final consumer due to an excellent rate of cost and efficiency. However, environmental issues have been identified in the development of hydropower, including water quality, migratory species and biodiversity impacts (Eletrobras, 2015).

Run-of-river hydropower schemes are considered to be more environmentally and socially friendly than traditional hydropower schemes, due to its impacts be much less severe. These impacts are mostly restricted to the aquatic environment and often limited to fisheries (Robson, Cowx and Harvey, 2011). Generally, run-of-river schemes does not change the natural flux of the river. This aspect allows to preserve and to sustain the development of migratory species at the river. However, the river system is altered causing flow-depleted stretches between intake and outfall. Migratory species such as salmons, eels, lampreys and trout must have free passage throughout the river, what can be interrupted by impoundments structures. These barriers create different conditions in which the native biota is not used to. Some fishes are very sensitive to changes in their natural habitat causing disappearance and decay of these species population (Robson, Cowx and Harvey, 2011).

Brazil has the greatest diversity of migratory fish species, approximately 3,000 species, a quarter of the world total. However, the survival of these and other species and the fishing activity has been endangered, due to the construction of hydropower stations in the course of their migratory routes. A study in Itaipu on the Parana River, in 1989, proved that 6 species of fish have become extinct after the construction of the plant (Agostinho, Júlio and Borghetti, 1992). According to the Brazilian federal law of environmental crimes (Law 9,605 of 02/13/98) fish kill is regarded as damage to wildlife and environmental crime. It justifies the need to mitigate the environmental impacts on fish populations caused by HPPs throughout the national territory (Abel, 2010).

2.3 Turbine models

Turbines are used to convert hydraulic energy into rotational kinetic energy. The main types of turbines can be divided into impulse turbines and reaction turbines. The predominant type of impulse machine is the Pelton model, which is suitable into a range of heights of 150-2,000 m. (Massey, 1998).

Reaction turbines are characterized by use pressure and kinetic energy of the water. The working fluid goes into a spiral casing surrounding the rotor, completely filing the passages in the runner. These turbines are also composed by volute and stationary guide vanes installed around the periphery of the runner, that directs the fluid to the runner. These turbines can be also into two main types: radial or mixed flow and axial flow (Massey, 1998).

Francis turbines are used more often in radial flow. Kaplan turbines with blades adjustable rotor, is the main type of machines used in axial flow. Other models which can be used with axial flow are tubular, bulb and Straflo turbines. The basic design of Kaplan and Francis turbine is shown on Figure 2.1 (Massey, 1998).

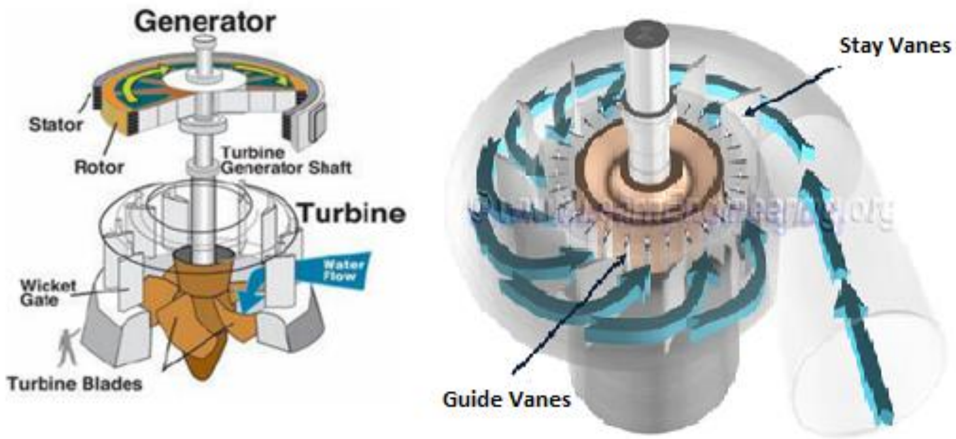


Figure 2.1: Kaplan and Francis Turbine. Source: Deng, et al., 2006

In reason to protect the fisheries and avoid disappearance and decay of fish population, the United Kingdom, considers that, the greatest issue for these fishes at hydroelectric facilities are injuries and mortality of eggs, larvae, juveniles and adult fish that pass through the turbine (Deng et al., 2007).

The Environment Agency published in 2013 the ‘Guidance for run-of-river hydropower’. It is summarized that fish-friendly turbines must increase the runner radius, in reason to reduce the impact pressure on fish, maximise the size of the flow passages, use fewer blades to minimise the number of leading edges, avoid cavitation, reduce shear stress and allow minimum pressures within the turbine to fall to no less than 0.6 bar (Environment Agency, 2013).

Fish are vulnerable to injury when pass through the turbine, due to pressure changes, shear stress, turbulence, strike, cavitation and grinding. However, the majority damage caused in fisheries come from the direct contact between the fish and leading edge of a turbine blade, characterized by blade strike (Deng, et al., 2006).

Larinier (2001), shows that the rate of downstream passage mortality of juvenile salmons through Francis turbines is from 5 to 90% and through Kaplan turbines is from 5 to 20%, depending of the wheel, conditions of operation, head, and fish size. The author pointed that the reason why Francis turbine has mortality average bigger than Kaplan turbine is due to Francis works in higher head (Larinier, 2001). Other research carried by Halls and Kshatriya (2009), states a close correlation between the length of fish and the probability of death caused by blade strike, as shown on Figure 2.2. The expectation is no survival for fishes bigger than one meter that pass through the turbine.

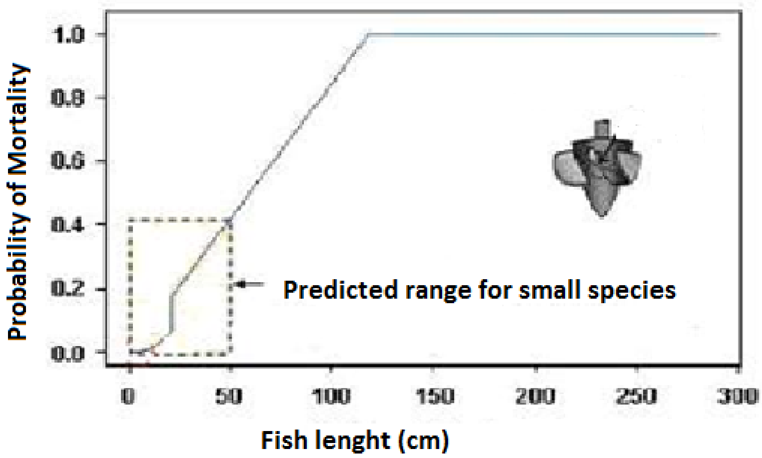


Figure 2.2: Probability of death caused by blade strike. Source: Halls and Kshatriya, 2009

Larinier (2001), also accentuates the importance of turbine design, characteristics such as the type of head, number of blades and rotational speed can be crucial in fish survival. However, the author does not provide numerical data to inform to what extent a turbine becomes dangerous to fish.

The lesion and mortality mechanisms depend where the fish will pass through the turbine. If such an area is surrounding the blade, the fish will suffer injury due to blade strike. The lesion, also depends of the size of the fish, number of blades and their spacing, turbine speed, flow velocity and discharge. However, quantifying exact sources of fish injury and mortality through the turbine is challenging due to the lack of controlled experiments (Odeh, 1999).

The design criteria that Odeh (1999), finds for turbines be considered environmentally friendly are: head between 23 and 30 meters; a volumetric flow of 28.3 m^3/s; peripheral runner speed less than 12.2 m/s; rate of change of pressure must be less than 80 psia/s (the author assumes that fish injury occurs at 160 psia/s); the clearance between runner and fixed turbine housing components of 2 mm or less and also the limit value of the shear stress indicator identified as 450 ft/s/ft. Values above of all these rates are believed to cause mortality. The author proposes that peripheral runner velocity lower than 6 m/s can eliminate the strike injury and 12.2 m/s can be expected the minimum strike injury. The final design proposes by Odeh (1999) is shown on Figure 2.3, it is a vertical shaft runner with two blades, 5.3 meters diameter, works with 25 m head and peripheral runner speed of 19 m/s, value bigger than what is proposed in reason to increase the efficiency.

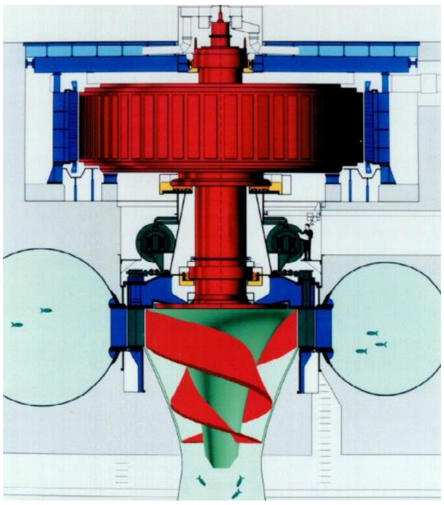


Figure 2.3: New Turbine Design. Source: Odeh (1999)

Ploskey and Carlson (2004), use a mathematical model to predict blade strike in Kaplan turbines. This model takes in consideration geometry of the turbine blades, discharge, fish length, orientation and distribution along the runner. Their predictions shown that the probability of blade-strike increase with decreasing discharge. However, it was not significantly correlated with empirical estimates of injury or mortality. The orientation, which the fish goes through the turbine can explain why this disagreement happened. The probability of injury is bigger if the fish gets into the turbine with an angle of 90º than with 30º, in relation to the leading edge of the blade. The aspect that the fish is presented to the leading edge, can be an important factor to fill the lack of biological information about the fish survival (Ploskey and Carlson, 2004).

In reason to avoid fish mortality, new technologies have been developed over the years. As a first example, the Archimedean screw turbine, which operates with a slow rotational speed, extremely low shear forces and no pressure changes. However, this schemes are considered uneconomic and has disadvantages because of their large size (Robson, Cowx and Harvey, 2011). The Archimedean screw turbine can be seen on Figure 2.4.

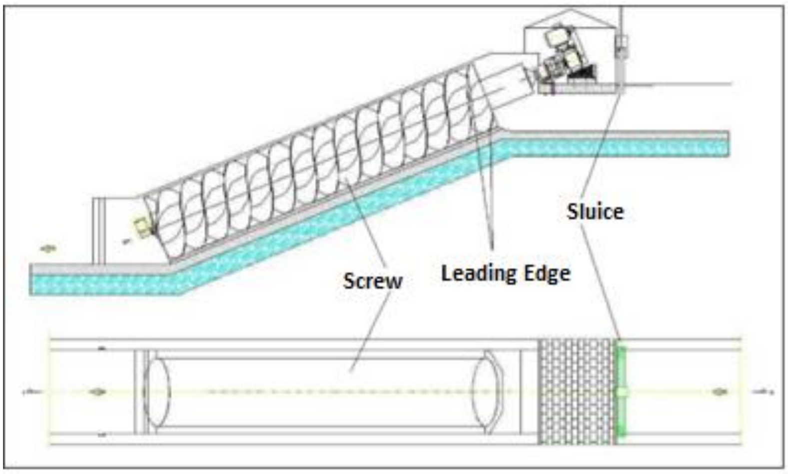


Figure 2.4: Archimedean Screw. Source: (Kibel and Coe, 2011)

It is recommended to Archimedean Screws, use 3 to 5 blades and tip speed should not exceeds 3.5 m/s. Speeds above 4 m/s would cause injury to fishes larger than 2 kg and to fishes below 4 kg at speeds of up to 3.5 m/s. The biggest probability of blade strike occurs with 3 blades, at rotational speed between 35 and 45 rpm (Kibel and Coe, 2011).

Aiming to decrease the damage in fish populations in United Kingdom, the Environment Agency (2013) had stated that Archimedean screws must have the maximum tip velocity below 5 m/s and/or diameter exceeding 5 m.

A further example of new technology is the gravitational vortex power plant, which will be covered in the next section. Nevertheless, regardless size or technology, the hydropower projects must be designed and operated to decrease and compensate impacts on the environment and local populations.

2.4 Gravitation Water Vortex Power Plant

The Gravitational Water Vortex Power Planst (GWVPP) have been recently studied and improved to reduce the environmental damage in small hydropower stations.

This new technology is characterized by use the energy from a large water vortex that is created artificially by a small head difference on a river (Mulligan and Hull, 2010).

In reason to create a vortex, the river water is channeled to a straight inlet to a circulation tank. Sequentially, at the bottom of basin the water through by a pipe at the outlet, returning to the river (Dhakal et al., 2014). The turbine must be located at the centre of the vortex to run due to the rotational kinetic energy (Yaakob, et al., 2014). The basic design is shown on Figure 2.5.

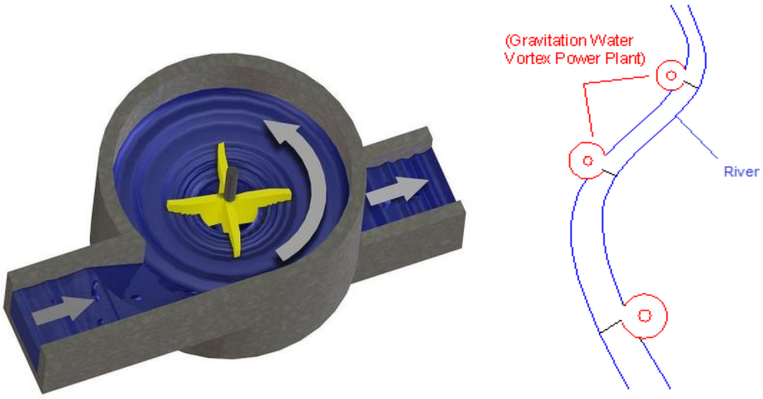


Figure 2.5: Gravitational Water Vortex and Power Plant. Source: ZOTLOTERER, 2006

The Austrian engineer, Franz Zotlöterer had constructed a low-head gravitational water vortex power plant that works with a coaxial turbine which converts kinetic energy in rotational speed to supply the generator. Ecological advantages, highlight by the engineer, covers clean water downstream, naturally aeration of the water and free passage to fishes in both way through the turbine, because of its low speed. Table 1 shows technical data from the 10kW-GWVPP (Zotlöterer, 2006).

The idea of GWVPP is based on the principles used by Viktor Schauberger (1930). The inventor proposed a hydropower machine, which uses a jet pipe to create a water vortex, where the energy of a jet of water can be used with purpose of power generation (Callum Coats, 1996). The water vortex stream always occurs at low head of water when there are two homogeneous fluids interacting at the boundary, normally, water and air (Wanchat et al., 2013).

Table 1: Zotlöterer Gravitational Water Vortex Power Plant

Head	1.5 m
Flow rate	0.9 m^3/s

Theoretical efficiency of turbine	80%
Electrical Power	8.3 kW

Source: Zotlöterer, 2006

2.4.1 Water Vortex

The vortex flow is defined by a fluid particle moving in circles about a centre of mass. In a vortex, the radius decreases as the speed increases until the centrifugal forces are greater than the centripetal forces. The water stream is accelerated to high velocity and gives it rotational kinetic energy to generate electric power (Massey, 1989).

In reason to simplify the calculation around the free vortex, all previous researches have been considered the vortex steady, axisymmetric and incompressible. The continuity Equation (2) and the Navier-Stokes equations for cylindrical coordinates (3, 4 and 5) are used to describe the behaviour of a fluid and are described for Chen, et al. (2007) as following:

$$\frac{\partial V_r}{\partial r} + \frac{\partial V_z}{\partial z} + \frac{V_r}{r} = 0 \qquad (2)$$

$$V_r \frac{\partial V_\theta}{\partial r} + V_z \frac{\partial V_\theta}{\partial z} + \frac{V_r V_\theta}{r} = v\left(\nabla^2 V_\theta - \frac{V_\theta}{r^2}\right) \qquad (3)$$

$$V_r \frac{\partial V_r}{\partial r} + V_z \frac{\partial V_r}{\partial z} - \frac{{V_\theta}^2}{r} + \frac{\partial p}{\rho \partial r} = v\left(\nabla^2 V_r - \frac{V_r}{r^2}\right) \qquad (4)$$

$$V_r \frac{\partial V_z}{\partial r} + V_z \frac{\partial V_z}{\partial z} + \frac{\partial p}{\rho \partial z} = g + v\nabla^2 V_z \qquad (5)$$

Rankine (1858), was the first author to describe an air core vortex, the author presents the tangential velocity (V_θ) as proportional to the vortex circulation (Γ) and inverse proportional to the tank radius. However, Wang, et al (2010) declare that these equations describe a linear distribution inside the vortex core and is not differentiable at $r=r_m$, where r_m is the vortex core radius.

Odgaard (1986) describes the tangential velocity and the head at free-surface air core vortex assuming that the vortex has a laminar core and the radial velocity is proportional to the tank radius ($V_r = -kr$). Which Wang, et al.(2010) highlight be inapplicable at $r > r_m$ because the author consider $r < r_m$. Odgaard (1986), also describes the axial velocity with the condition that $r \rightarrow \infty$, at the vortex. According to Wang, et al. (2010), both Rankine (1858) and Odgaard (1986) have lacks in theoretical basis to describe the vortex over the whole area.

Considering that, the vertical vortex has the shape of spiral lines. The authors improve the previous models for the radial, axial and tangential velocities based on Rankine (1858) and Odgaard (1986) at the vortex. However, there is an error of 14% for tangential velocity, 22.4% for radial velocity and for axial velocity an error on average of 21% between the theoretical and experimental values obtained in their research (Chen, et al., 2007).

Wang, et al. (2010), investigated an air-core vortex at hydraulics intake as it is shown at Figure 2.6. They describe three sets of formulas for tangential velocity on a free surface vortex, using Navier-Stokes equations. They insist that their equation for tangential velocity, is better than Rankine's (1858) and Odgaard's (1986) equations. However, the authors just mention the equations described by Chen, et al. (2007) and not present arguments to believe that their equation is more accurate.

It is believed that this differences on the modelling come from the different parameters, that the all the authors have been considering and what mechanism they used to study the vortex behave.

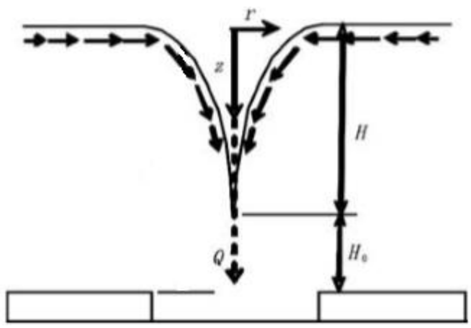


Figure 2.6. Surface Vortex. Source: Wang, et al., 2010

Dhakal, et al. (2014) analyse the effect of dominants parameters for a conical basin in a gravitational water power plant, using computational fluid dynamics. They obtained, by simulation, the relation between the basin opening and the inlet velocity of water into the basin, concluding that a small opening area increases the inlet velocity. This relation is represented by Equation (6).

$$v = 7.7143b^2 - 4.4457b + 0.809 \tag{6}$$

Where, v is the inlet velocity in m/s and b is the inlet width in meters. However, this equation was inefficient to be applied in a spiral basin and to greater heights that 0.7 m. Mulligan and Hull (2010), research the design and optimization of a water vortex hydropower plant and thoroughly suggest that optimum vortex strength occurs when the orifice diameter is 14% to 18% of tank diameter, for low and high head sites, respectively. The authors also describe that the maximum ideal theoretical power output is given by the equation below, where Hv is height of vortex, g is gravity and ρ is the water density.

$$P = \rho g Q H_v \tag{7}$$

Due to the vortex complexity, the mechanisms that cause this phenomenon and how it behaves, as velocity and pressure distribution, have not been described accurately. In this study, all the equations were tested in a computational program. In fact, as all the equations provide different results. In order to provide more reliable results, computational models using fluid dynamics, should be used to describe the water behaviour at the vortex in the tank.

2.5 Design and Aerodinamics

After the vortex is formated, the kinetic energy provide by the velocity of the water is captured by the turbine, which must be well designed to supply the generator.

The turbine performance is related to the flow inlet conditions scheme (laminar or turbulent) incompressibility or compressibility (depending on the Mach number of the flow), the clearance between rotor and hub, the guide vanes of the flow, the relationship between the hub and runner diameters (*Dh/Dt*), the diameter of the turbine, number of blades and the profile of the blades. Thus, these variables may be arranged into four groups as thermo-physical properties of the fluid, flow characteristics, geometric restrictions and properties of profiles (Dias et al., 2013).

The geometric restrictions include the arrange between head and volumetric flow, these parameters will define the turbine angular velocity and size. The specific speed (n_q), relates these three parameters and is an indication of the geometry of the turbine and the starting point for the design. This number must be between 70 and 300, values bigger than 250 tend to cause low efficiency and values lowers than 70 can result in lower efficiency and extra costs. The specific speed (n_q) is given by Equation (8). Where N is in rev/min, Q in m^3/s, H in m and n_q is dimensionless.

$$n_q = \frac{N\sqrt{Q}}{H^{0.75}} \tag{8}$$

In reason to increase the overall efficiency, the blade aerofoil must be designed to provide high lift values. The lift is caused by the pressure difference at the blade, which is achieved when the surface curvatures in the top and bottom are different, as shown in Figure 2.7. Other mechanism used to generate lift is incline the aerofoil at an angle relative to the horizontal, the angle of attack allows the flow remains attached on both surfaces (Marzocca, 2009). The blade shape has three variables: the angle of attack (α), the thickness (t), and the camber (m).

The chord is the line connecting the leading edge and the trailing edge. The camber is defined as the maximum distance from the chord to either surface and chord length, is the overall aerofoil length. The function of the blades is to use the water velocity to create the rotational speed of the turbine.

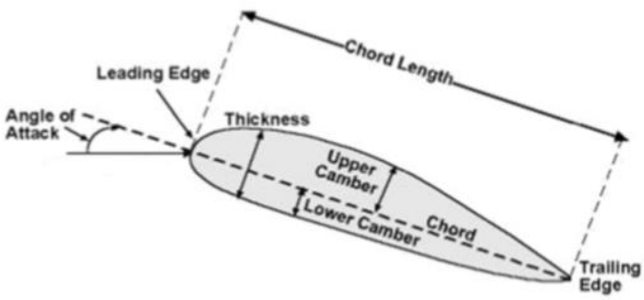


Figure 2.7: Blade Shape. Source: Marzocca, 2009

Axial and torque coefficients (C_A, C_T), can be described as a function of the lift and drag coefficients (C_L, C_D). Where s is the solidity and the flow coefficient can be described at Equation (11) (Dias et al., 2013).

$$C_A = C_L \cos \alpha + C_D \sin \alpha \tag{9}$$

$$C_T = C_L \sin \alpha - C_D s \cos \alpha \tag{10}$$

$$\phi = \tan \alpha \tag{11}$$

Considering these equations, aerodynamics efficiency can be described by

Equation (12) and the torque by the Equation (13). Where, *W* is the flow velocity, ρ the water density, *b* is the length and *c* blade chord (Dias et al., 2013).

$$\eta = \frac{C_T}{C_A \phi} \tag{12}$$

$$T = \frac{\rho W^2 ZbcRC_T}{2} \tag{13}$$

The National Advisory Committee for Aeronautics (NACA), developed in the 1930s the NACA aerofoils. Most of these aerofoils are based on simple geometrical descriptions of the section shape, using analytical equations that describe the camber and section's thickness distribution along the length of the aerofoil. First family of aerofoils designed using this technical was the NACA Four-Digit Series. This name is given according to its characteristics, where the first number is the maximum camber in percentage of the chord, the second is the position maximum distance from the surface to the centre line and the last two digits provide the maximum thickness of the aerofoil in percentage of chord (Marzocca, 2009).

3 MATERIALS AND METHODS

The base turbine design was developed using the guidelines from 'Design of propeller turbine for pico hydro' described by Robert Simpson and Arthur Williams (Simpson and Williams, 2011). Following these guidelines, the first step is to choose the head (*H*) and volumetric flow (*Q*) in which, the scheme will work. After that it is possible, using Equation (7) and the guidelines, to define *Dh/Dt*, number of blades and specific velocity.

Sequentially, using these guidelines it is viable to calculate thickness (*t*), angle of attack (*α)* and camber (*m*) based on the previous step. With, the basic blade design parameters, an aerofoil can be generated in the NACA four-digit generator, for each section of the blade. The NACA 4-digit was chosen for this project in reason to be used for symmetrical aerofoils and horizontal tails (Ladson, et al., 1996).

The NACA aerofoils are generated using analytical equations to describe the camber curvature and thickness distribution along the length of the aerofoil. The lift coefficient to aerofoil blades can also be obtained using the NACA system to generate an aerofoil based on the preview data obtained by Equation (11). Once that the new aerofoil is generated the XFOIL 6.9 software can be used to calculate a new lift coefficient with base on the NACA aerofoil, the angle of attack and Reynolds number, presented at Equation (14), in each section of the blade. Where, W is the inlet velocity of the flow relatively to the blade, L the length and ν is the water viscosity. The guidelines from Simpson and Williams (2011) are used to calculate the inlet cross section. Whereas, the tank radius was calculated considering that the output diameter is 14% of the tank radius (Mulligan & Hull, 2010).

$$R_e = \frac{WL}{\nu} \tag{14}$$

Aiming to evaluate the turbine performance, Autodesk CFD, is used as a computational fluid dynamics (CFD) tool, to simulate its behaviour under a determined condition. Autodesk CFD is an important tool to simulate fluids and heat transfer. Being widely used to evaluate the efficiency of the equipment and gives, as result, the angular velocity (ω) and torque (T) of the turbine.

$$P_{mec} = T\omega \tag{15}$$

Turbine efficiency can be defined as the ratio between the Equation (15), which is the mechanical power generated (P_{mec}) by the turbine, and Equation (7) the theoretical power. As a matter of comparison, the theoretical torque and the aerodynamics efficiency can be calculated using Equations (12) and (13). Achieving the angular velocity of the turbine, it is possible to choose an adequate generator for this propose.

4 PROPOSED PROJECT

According to the guidelines from ‘Design of propeller turbine for Pico hydro’, the overall turbine dimensions and parameters are shown in Table 2. These values were obtained in reason to satisfy the environmental friendly parameters proposed at the literature review, as tip velocity smaller than 6 m/s and volumetric flow bellow 3 m³/s to avoid cavitation and extreme turbulences. Also to maintain its configuration as low-head, micro run-of-river scheme and an specific speed higher than 75. These parameters were selected based on the theories presented in sections 2.2 and 2.3.

Table 2: Overall Turbine Dimensions

Parameter	Results
Head (m)	2
Flow rate (l/s)	3,000
Theoretical Power (kW)	56
Specific Speed	103
Number of blades	5
Diameter of runner (m)	0.8
Dh/Dt	0.72
Hub Diameter (m)	0.58
Axial velocity (m/s)	10.33
Hub velocity (m/s)	2.72
Tip velocity (m/s)	4.20

Source: The Author

In reason to provide a range of details about the blade design, the aerofoil is separated in six sections. The first section represents tip and last section represents the hub. Table 4, provide the values of radius (*R*), chord (*L*), blade pitch (*x*), Reynolds Number, angle of attack (α), camber (%) and actual blade setting angle (β) to all the sections with constant thickness of 6%. In the last line of the Table 3 the NACA 4-Digit aerofoil is chosen based on camber and thickness.

Table 3: Blade dimensions

Section	1	2	3	4	5	6
R (mm)	110	101.75	93.5	85.25	81.125	77
x (mm)	138	128	117	107	102	97
L (mm)	220	200	160	140	130	120
α (^{o})	1.25	2	2.75	4.5	6.5	9
Camber	3	4	5	7	8	9
β (^{o})	21	22	24	26	26	26
Aerofoil	3506	4506	5506	7506	8506	9506

Source: The Author

The blades have a surface area equals to 3.13451 m^2, each one with 0.163 m^2 and 0.10342 m^3 of volume, as the radius is of 400 mm, the total area of the turbine is 0.50 m^2. Solidity is defined as the number of blades times its surface area by the total area of the turbine, it results in 1.62 of solidity. Considering these coefficients, the theoretical torque is 13,788kN and the aerodynamic efficiency is 65.15%. The Figure 4.1, shows the lateral view of the turbine and its dimensions, without the length of the hub.

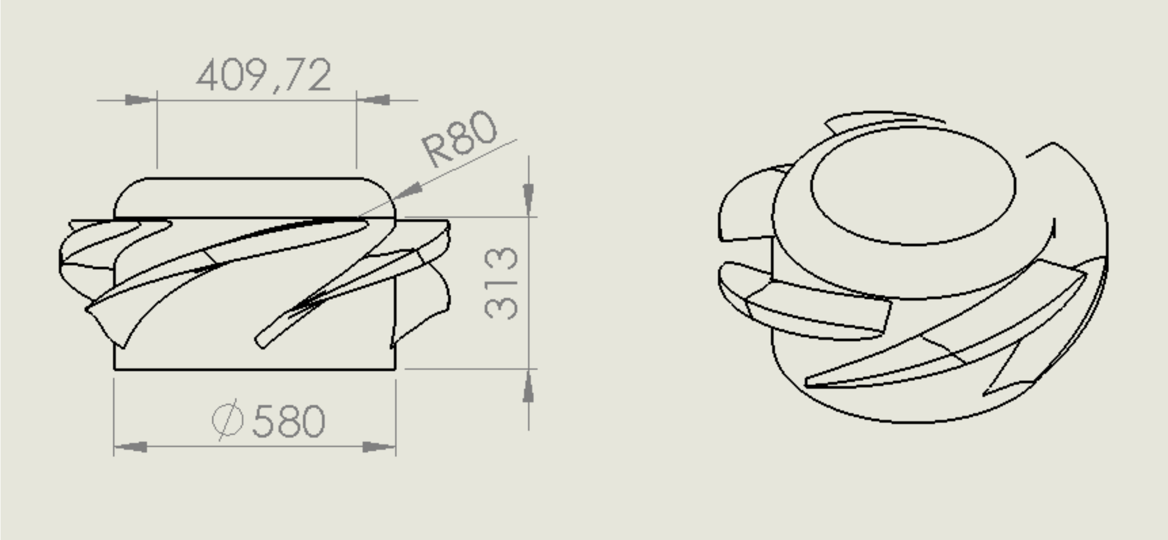


Figure 4.1- Lateral and isometric view of the turbine (in millimetres). Source: The Author

The leading edge or the space between blades is equal to 33 mm, which could allow eggs, larvae, juveniles fishes to go through the turbine. Details about the blade geometry, length, angle of attack and setting angle are provided in Appendix A, which shows all the six aerofoils.

According to the guidelines from ‘Design of propeller turbine for pico hydro’ and Equation 6 and section 2.4.1, the overall tank dimensions were calculated in reason to create a free vortex. The tank has radius of 2.85 meters, head of 2 meters and an orifice diameter of 845 mm, as it is shown at the Figure 4.2.

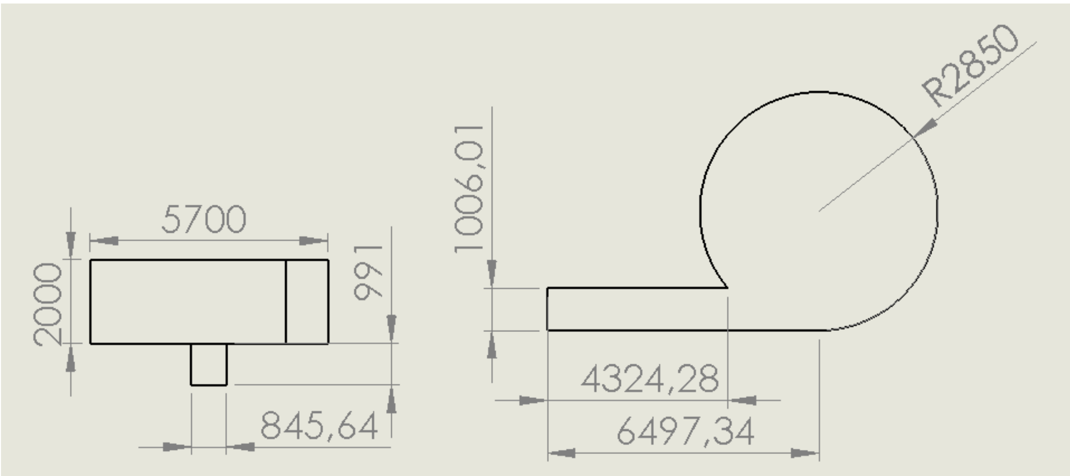


Figure 4.2- Overall tank dimensions (in millimetres). Source: The Author

5 RESULTS AND DISCUSSION

Each aerofoil was evaluated separately in reason to generate lift, drag, torque and axial coefficients, as it is presented in Table 4. The efficiency of the aerofoil is proportional to the lift and torque coefficients, as it is possible to see in Table 4. All the coefficients increase with radius, where the angle of attack is bigger as the camber.

Table 4 - Aerofoil Parameters

	CL	CD	CT	CA
NACA3506	0.5262	0.00452	0.0042035	0.5259762
NACA4506	0.7315	0.00546	0.0167437	0.7308638
NACA5506	0.9332	0.00717	0.0332428	0.9317813
NACA7506	1.3283	0.01026	0.0877495	1.3234003
NACA8506	1.3906	0.02611	0.1156535	1.3787053
NACA9506	1.6235	0.05079	0.1732062	1.5955667

Source: The Author

5.1 Vortex Evaluation

Based on the equations presented at the literature review and in the methodology, the velocities at the vortex were calculated. Considering a head of 2 meters, a volumetric flow of 3,000 l/s and a k-epsilon turbulence model, the vortex is performed in a computer fluid dynamics software as it is shown in Figure 5.1, the model has 1,444 nodes and 6,631 elements, it was obtained using *Autodesk CFD* (Mohammadi and Pironneau, 1993).

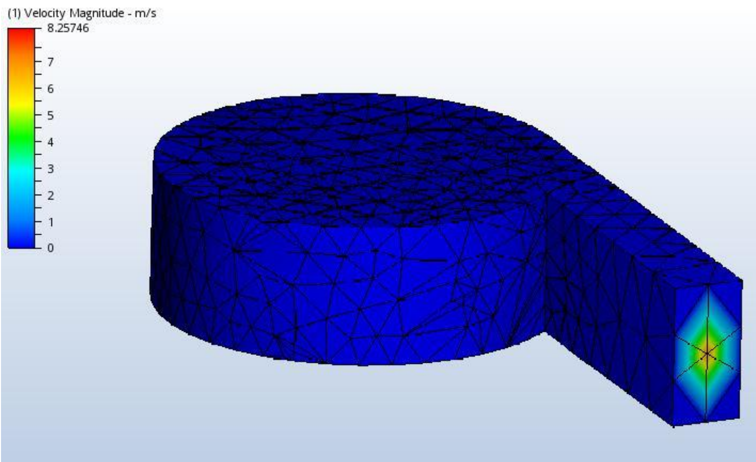


Figure 5.1 - Free Vortex Mesh. Source: THE AUTHOR

Table 5 shows the results obtained from the CFD simulation, where it shows its Reynolds and Mach number confirming that the flow is turbulent and incompressible. The Table also presents the maximum pressure and velocities in x, y and z axis.

Table 5 - Vortex results

Variable	Maximum Value
Vx (m/s)	26.76
Vy vel (m/s)	6.21
Vz vel (m/s)	16.94
Outlet Mach number	$4.22\ 10^{-7}$
Reynolds number	$4.02\ 10^{6}$

Source: The Author

5.2 Evaluation of the Scheme Performance

Considering the same boundaries conditions as in the section 4 and a k-epsilon turbulence model, the vortex is performed in a computer fluid dynamics software. The model has 8,520 nodes and 40,199 elements, as it is shown in Figure 5.2 (Mohammadi and Pironneau, 1993).

The overall Reynolds number increased to 2,104,860 and Mach number is now $1.13\ 10^{-7}$, maintaining the vortex turbulent and incompressible. It is important to notice that, the inlet cross section velocity is 1.51 m/s in the x-axis. Nonetheless, the inlet bottom velocity is 7.11 in the y-axis, what represent an increase of 4.71 times in the water velocity.

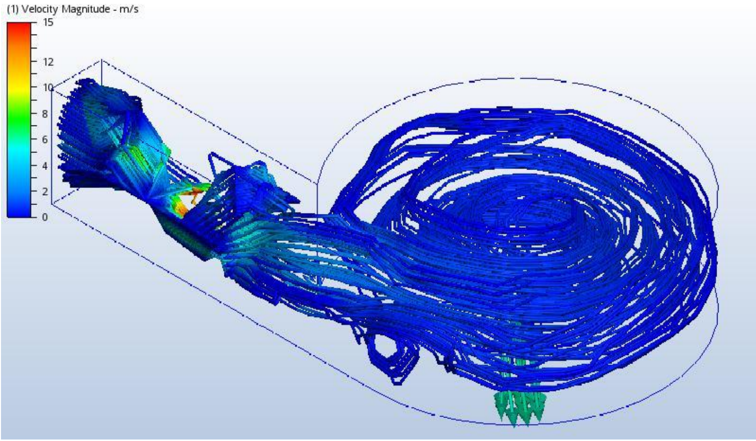


Figure 5.2- Free Vortex. Source: The Author

Considering this configuration, the turbine will run at 100 rpm, with a Torque equals to 3,018.79 Nm on the y-axis, resulting in 31.61 kW and an efficiency of 56.45%. As a matter of comparison, a Kaplan turbine working with a specific speed of 103 has an efficiency of 92%.

4.3 Evaluation of the Scheme Performance in a real site

It was observed that the volumetric flow should remained constant, in order to preserve its fish-friendly characteristic of the hydropower scheme and also to maintain it level of efficiency. Considering that usually the flow rate in rivers varies during the seasons, in reason to investigate, how far the volumetric flow can change without prejudice its performance and environmental standards, all the system is simulated using real data from the river Pedras, from Cubatão, Brazil.

The region of the Pedras river represents an important area regarding the representativeness of the fish fauna of the middle part of the Paraíba do Sul river basin, covering 40% of the species that occur in the basin. Several groups of fish species, of restricted distribution, that require high quality of water are found in the region, demonstrating the need of good environmental conditions of this River. In addition, *Brycon opalinus*, an endemic species listed as threatened with extinction, uses the Pedras river as a migration corridor and spawning area, being one of the few areas in the basin where this species maintains a stable reproductive population (De Britto, et al.,2014).

In natural operation, the site presents the follow profile of volumetric flow rate, at Figure 4.6 and an average of 3.59 m^3/s, these data were collected from ONS, the Brazilian Nacional Operator of the Electrical System (Operador Nacional do Sistema, 2008).

In particularly, this river has a maximum volumetric flow rate on the summer, of 5.87 m^3/s. That could cause cavitation and extreme turbulence if the system was closed. However, as the vortex is open surface the drops of pressure can be avoided. To avoid tip velocities higher than 6 m/s, angular velocity should remain below 143 rpm.

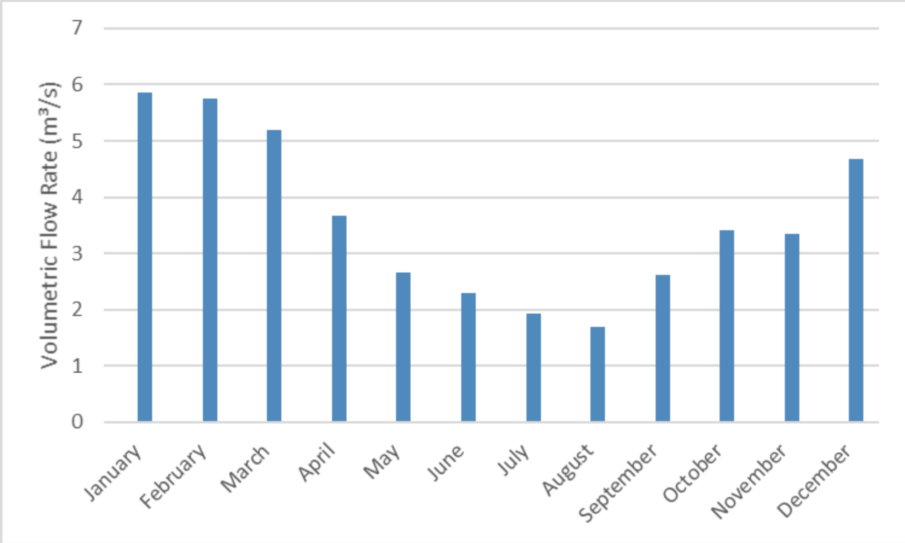


Figure 4.6- Volumetric flow profile. Source: (Operador Nacional do Sistema, 2008).

Based on the volumetric flow profile, the power available on the river is 70.27 kW annual average. Figure 4.7 shows the annual variation of the power available on the river and the power that could be generated using the hydraulic plant proposed.

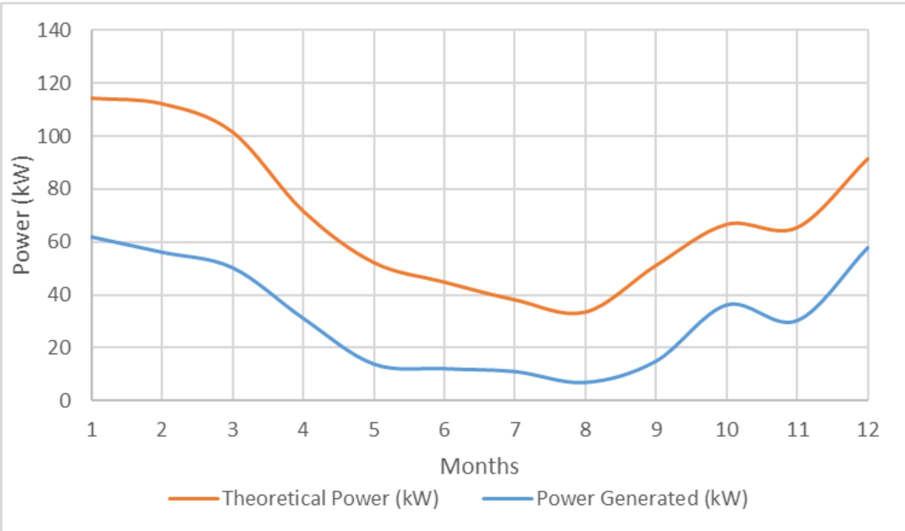


Figure 4.7 - Available and Generated Power. Source: The Author

Considering this specific site, 31.89 kW can be generated monthly, with and efficiency of 45.4% in average. This is equivalent to 115.128 MWh/year and could supply 145 houses with 157 kWh/month (Founier and Penteado, 2010). The efficiency for this case is close to the efficiency calculated for the turbine design of 56.45%. It was observed that the efficiency does not remain constant, but is proportional to the volumetric flow.

5 CONCLUSION

By carrying out this study it was possible to understand the importance of environmentally friendly hydropower schemes. However, was noticed a lack of quantitative information around fish-friendly turbine design parameters. Clearly, more environmental studies should be realized to cover this lack of information in order to improve further turbine designs. Quantitative data for damage-causing mechanisms would help the development of a performance criteria for turbine manufacturers designing a more fish-friendly turbine.

It was observed that the volumetric flow should be remained constant, in order to preserve the fish-friendly characteristics of the hydropower scheme and also to maintain the levels of efficiency. The flow variation evaluated in Pedras river will not interfere into the fish-friendly characteristics. On the other hand, the efficiency decreases with the volumetric flow. The increase of volumetric flow is healthier to fish, as was cited by Odeh (1999), and also to the energy production. However, the rotor should remain below 190 rpm to avoid blade strike.

Based on the information available is reasonable to conclude that this new turbine will improve fish survival and it will support a sustainable development to the society. However, the turbine evaluation of performance and also the fish survival rates can be deeply studied, if a model could be constructed and tested.

PROJETO E AVALIAÇÃO DE UMA TURBINA HIDRÁULICA AMBIENTALMENTE AMIGÁVEL

RESUMO

Frequentemente, as usinas hidrelétricas são apresentadas como benignas para o meio ambiente, particularmente os esquemas de fio d’água de pequena escala por terem sido projetados para manter um regime de fluxo natural do rio. No entanto, tem sido destacado em pesquisas que mesmo esses esquemas podem ser nocivos para o meio ambiente, sendo

que, a maioria dos danos causados aos peixes em turbinas hidráulicas é devido às lesões causadas pelas pás. Com o objetivo de aumentar a taxa de sobrevivência dos peixes através da turbina, este estudo propôs o projeto de uma turbina hidráulica de baixa pressão, que use um vórtice de água livre para extrair a energia na água e avaliar seu desempenho usando dinâmica computacional de fluídos.

Palavras-chave: Usinas Hidrelétricas. Fio d’água. Peixe-amigável, Dinâmica dos fluídos computacional.

REFERENCES

Agostinho, A. A., Júlio, H. F. & Borghetti, J. R., 1989. Considerações sobre os impactos dos represamentos na ictiofauna e medidas para sua atenuação, um estudo de caso: reservatório itaipu. Curitiba, s.n., pp. 89-108.

Binder, A. and Schneider, T., "Permanent magnet synchronous generators for regenerative energy conversion - survey". *Darmstadt University of Technology, 2005,* pp. 1-10.

Callum Coats. *Schauberger Information,* Bath, Nexus, 1996.

Chen, Y., Wu, C., Wang, B. and Du, M., "Three-dimensional Numerical Simulation of Vertical Vortex at Hydraulic Intake", *International Conference on Modern Hydraulic Engineering,* February 2012, pp55-60.

Chen, Y.-l., WU, C., YE, M. and JU, X., "Hydraulic Characteristics of Vertical Vortex at Hydraulic Intakes." *Journal of hydrodynamics,* Dezember 2007, pp. 143-149.

De Britto, M. R., Souza-Lima, R., Pascoli, J. C., Villa-Verde, L., Ferraro, G. A., Salgado, F. L. K., & Gomes, 2014. J. R. GUIA de Identificação das Espécies de PEIXES da Bacia do Rio das Pedras.

Deng, Z., Carlson, T. J., Ploskey, G. R., Richmond, M. C. and Dauble, D. D., "Evaluation of blade-strike models for estimating the biological performance of Kaplan turbines." *Ecological Modeling,* Issue 208, 2006, pp. 165-176.

Dhakal, S.; Timilsina, A. B.; Dhakal, R.; Fuyal, D. Bajracharya, T. R. and Pandit, H. P., "Effect of Dominant Parameters for Conical Basin: Gravitational Water Vortex Power Plant". *Pulchowk, Institute of Engineering*, 2014.

ELETROBRAS. "Relatório Anual de Sustentabiblidade.", *Eletrobras - Centrais Elétricas Brasileiras S.A.*, Rio de Janeiro, 2015.

Environment Agency, 2013. *Guidance for run-of-river hydropower.* Bristol, UK, Environment Agency.

Faria, I. D., 2012. *O que são usinas hidrelétricas "a fio d'água" e quais os custos,* Brasília: Núcleo de Estudos e Pesquisa do Senado.

Founier, A. C. P., and Penteado, C. L. C., 2010. "*Energia elétrica no setor residencial à luz do consumo consciente: resultados do estudo de caso no município de Santo André (SP).*" V Encontro Nacional da Anppas-4 a 7.

Halls, A. and Kshatriya, M., "Modeling the cumulative effects of mainstream hydropower dams on migratory fish population in the lower Mekong basin." *MRC Techinical Paper No. 25*, 2009, p. 101 pp.

International Energy Agency, 2012. *Technology Roadmap Hydropoer.* Paris, OECD/IEA.

Kibel, P. and Coe, T. "Archimedeam Screw risk assessment: strike and delay probabilities", *FISHTEK Consulting*, 2011.

Ladson, C. L., Brooks, C. W., Hill, A. S. and Sproles, D. W., "Computer Program To Obtaind Ordinates for NACA Airfoils." *National Aeronautics and Space Administration, Langley Research Center.* Virginia,1996.

Larinier, M., Environmental issues, dams and fish migration, *Dams, Fish and Fisheries. Opportunities, Challenges and Conflict Resolution.*, FAO Fisheries Technical Paper, 2001, pp. 45-89.

Li, H. and Chen, H., "Experimental and Numerical Investigation of Free Surface Vortex." *Journal of Hydrodymanics,* February, 2008, 4(20), pp. 485-491.

Massey, B., *MECHANICS OF FLUIDS.* 6th ed. London, CHAPMAN AND HALL, 1989

Meyers, J. M., Fletcher, D. and Dubief, Y., *Lift and Drag on an Airfoil.* ME 123: Mechanical Engineering Laboratory II: Fluids, n.y.

Ministério do Planejamento, 2013. Eixo Energia. Em: *PAC 2 - 7º BALANÇO janeiro/abril/2013.* Brasília: Imprensa Nacional, pp. 68-105.

Mohammadi, B. and Pironneau, O., 1993. Analysis of the k-epsilon turbulence model.

Mulligan, S. and Hull, P., "Design and Optimisation of a Water Vortex Hydropower Plant", *Sligo Institute of Technology,* 2010.

National Advisory Committee for Aeronautics, 2015. *Airfoil Tools.* [Online]
Available at: http://www.airfoiltools.com/ [Accessed January 2015].

Odeh, M., "A sumary of Environmentally Friendly Turbine Design Concepts." *U.S. Department of Energy, Operations Office*, Idaho, 1999.

Odgaard, A. J., "Free-Suface Air Core Vortex.", *Jounal of Hydraulic Engineering, ASCE*, 1986., 112(7), pp. 610-620.

Operador Nacional do Sistema, 2008. Atualização de séries históricas de vazões período de 1931 a 2007, Rio de Janeiro: s.n.

Ploskey, G. R. and Carlson, T. J., "Comparision of Blade-Strike Modeling Results with Empirical Data." *Pacific Northwest National Laboratory - U.S. Department of Energy*, March, 2004, pp1-36.

Rankine, W. J. M.,. *Manual of applied Mechanics.* London, C. Griffen Co., 1858

Robson, A., Cowx, I. G. and Harvey, J. P., "Impact of Run-Of-River Hydro-Schemes Upon Fish Population". *SNIFFER*, Endinburgh, 2011.

Simpson, R. and Williams, A. *Design of propeller turbines for pico hydro.* [Online]
Available at: www.picohydro.org.uk [Accessed November 2014]. July, 2010.

Wanchat, S. and Suntivarakorn, R., *Preliminary Design of a Vortex Pool for Electrical Generation.* Thailand, Khon Kaen University.

Wang, Y., Jiang, C. and Liang, D.,"Investigation of air-core vortex at hydraulic intakes." *Journal of Hydridynamics*, 2010, pp. 673-678.

Yaakob, O., Ahmed, Y. M., Elbatran, A. H. and Shabara, H. M., "A Review on Micro Hydro Gravitation Vortex Power and Turbine Systems." *Journal Technology*, 2014, pp. 1-7.

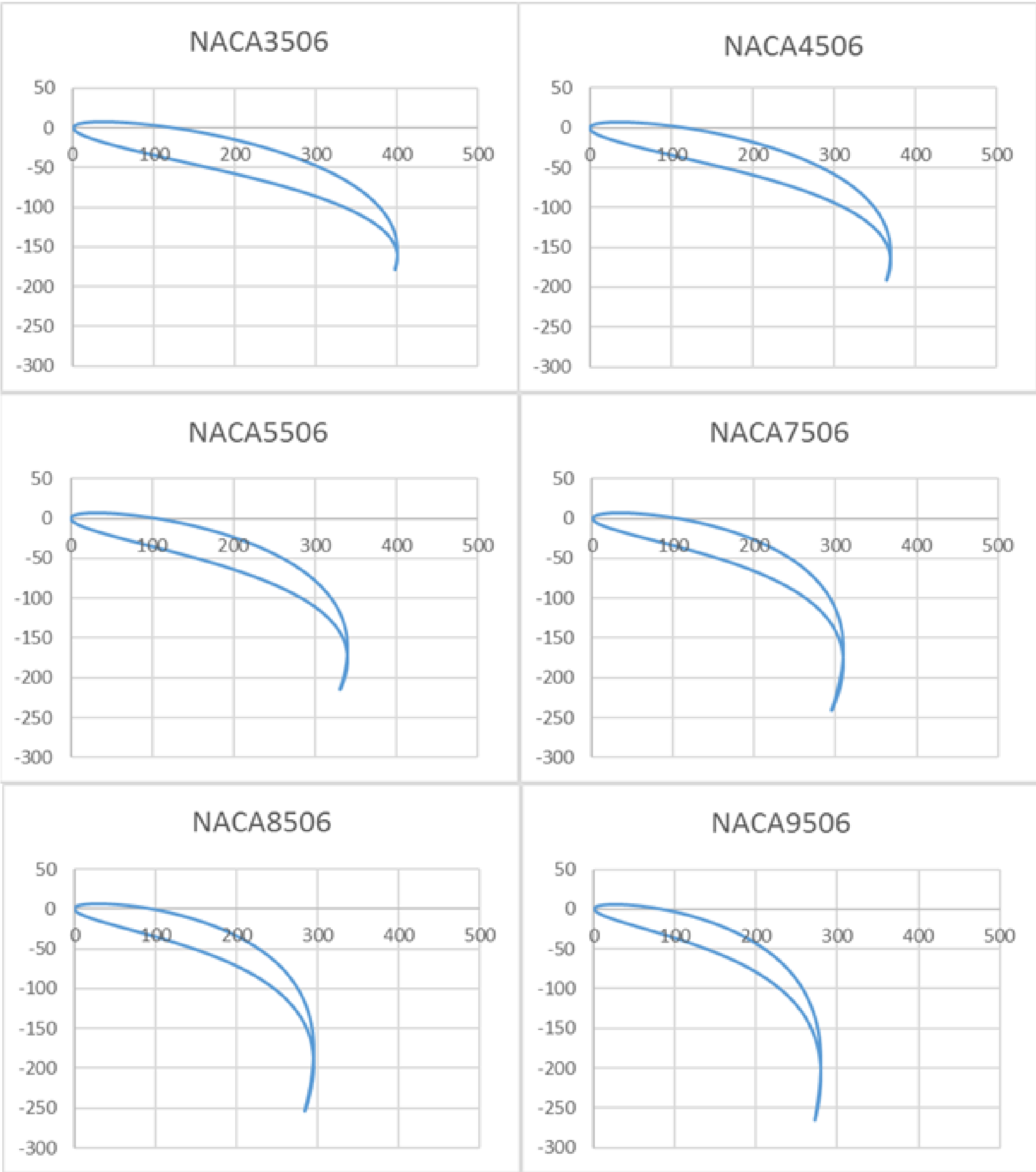
Zotlöterer, 2006. Gravitational Vortex Power Plant. Available at (http://www.zotloeterer.com/). Acess in 25/10/2014. Austria, ZOTLÖTERER - Smart Energy Systems.

ACKNOWLEDGMENTS

The author thanks Prof. Dr. Leonardo Elizeire Bremermann and Prof. Dr. Cesar Cataldo Scharlau for the advices, support and patience throughout this study; UFSC for the access to IEEE and Science Direct digital libraries; The University of Nottingham and Dr. Arthur Williams, for all the support and advices to conduct this project. The author also would like to thank the Brazilian program Science without borders who sponsored this research.

Above all, the author is deeply thankful for the support received from the family that was always there in any circumstance. Special regards to the ENEjr family, for all the friendship and support. Also to all my loved friends who always and undoubtedly believed in my potential. A special acknowledgment to the friends: Amanda, Angelo, Marcus, Marina, Leonardo, Pedro, Juliana, Joana, João Victor, João, Felipe, Vinicius, Bruno, Mathias and Gabriel for support and brotherhood. Also, Kabian for given me further insight on my research.

Appendix A - Aerofoils



Source: The Author