A FEASIBILITY STUDY ON THE USE OF WIND TUNNEL EXPERIMENTS FOR HYDROKINETIC TURBINES

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ABSTRACT

An experimental methodology to assess the performance of axial hydrokinetic turbines, based in wind tunnel experiments, is presented in the present paper. The goal is to propose an experimental approach using airflow and reduced scale models in order to evaluate a real axial turbine running in water flow conditions. Scaling arguments had shown that it is possible to obtain dimensionless performance parameter under a set of similarity conditions (geometrical, kinematical and dynamical) using air flow and, at last, to transpose the model results to the prototype real scale in water flow. Experimental results for the power coefficient as a function of the tip speed ratio are presented for a 1:23 model. The prototype is a three blade axial rotor hydrokinetic turbine, with 10m of diameter, designed to produce 500 kW. The control of the rotation velocity of the rotor arises as a key element of the methodology. The experiments were carried out in a wind tunnel facility for a range of undisturbed velocities between 6m/s and 15m/s. Comparisons with numerical results from 3D RANS simulations are made to evaluate the limits of application of the methodology.

Keywords: Hydrokinetic turbines, reduced (small) scale experiments, hydrodynamics of axial turbines.

INTRODUCTION

In reason of economic and populational growth, the energy consumption has steadily increased. The projection for consumption by the year 2030 is more than twice the amount of energy consumed in 1980. This growth scenario leads to a search for sources of clean and renewable energies with low environmental impact (Kaygusuz and Güney, 2010).

The hydrokinetic energy is an emerging class of renewable technology that is being widely recognized as a unique and unconventional solution to the use of water resources (Khan, Bhuyan, Quaicoe and Iqbal, 2009). The hydrokinetic energy conversion process involves the use the kinetic energy contained in any water flow, which may be the source of drive seas or even the normal flow of a river. The term hydrokinetic turbine is dedicated to hydraulic machines capable of converting kinetic energy from rivers or ocean currents into electricity (Lula, Brazil, Salomon, Walnut and Maruzewski-Gaud, 2006).

Different from one conventional hydroelectric power plant, the process of using hydrokinetic energy does not require the construction of a dam, it is only necessary a submerged turbine capable of converting kinetic energy contained in the water stream into shaft work able to activate the generator, allowing the conversion into electricity. Thus one need not interfere with the natural course of the river. However, the hydrokinetic system has lower efficiency, limited to 59.3% of kinetic energy incident on the turbine rotor (Betz, 1926).

There are few references in the technical literature on the design and use of hydrokinetic turbines, and also the knowledge available in this application area is restricted. Generally, this type of turbine is derived from the wind turbines, since the operation of both are similar.

This paper presents an experimental and numerical study of a small scale hydrokinetic turbine tested in wind tunnel. The prototype is a 10 meter diameter axial hydrokinetic turbine with three blades, designed to use the remaining potential of a hydro power plant and generate 500kW. The scaling factor between the prototype and the model is 1:23. The study of the scale model is important because the prototype is a complex machine, with it one can predict phenomena that will occur during operation of the turbine, thus avoiding possible failures. The study model is also used to find the best conditions for prototype work.

For the construction and testing of a scale model is important to follow the theory of similarity. This ensures that the prototype and the model will have their similar characteristics, thus validating the test. The similarity theory says that one machine will be similar to your model only if they have the three possible types of homogeneities: dimensional, kinematics and dynamics (White, 2011).

A prototype and a scale model are geometrically similar if only all the dimensions of the body in three coordinates have the same ratio of linear scale. The kinematic similarity requires the prototype and the model have the same ratio of length scale and time. The result is that the speed scale will be the same for both. In flow machines, it is possible to association the kinematic similarity with the triangles of velocities. To maintain the similarity of triangles speed is necessary that the model preserves the tip speed ratio from the prototype$\left(\lambda_{model} = \lambda_{prototype}\right)$. The dynamic similarity exists when the model and the prototype have the same reasons of scale length, time and strength. With the dynamic homogeneity, it is possible to find a relation between the potencies. This relationship can be presented by the power coefficient $(Cp_{model} = Cp_{prototype})$ (White, 2011).

This paper presents a methodology for a scale model of hydrokinetic turbine tested in wind tunnel. It is intended to find the performance of the turbine through the curves of Cp versus λ. The results will be compared with the numerical results of a 3D RANS simulation.

1 EXPERIEMENTAL METHODOLOGY

1.1 Wind tunnel

The tests were conducted in an open loop wind tunnel from the Laboratory of Fluid Mechanics, Department of Mechanical Engineering, University of Brasilia (UNB). The dimensions of the test section are 0,65x0,65 m and the tunnel extension is 10m . The fan is located at the exit of the tunnel and is driven by an electric motor of 40 hp, sucking air from the tunnel entrance to the exit. The possible variation of the speed free flowing between is 6 and 16 m / s. The boundary layer into the section test, where the turbine is positioned, is of 20 mm and the level of turbulence in the tunnel is less than 5%.

The wind speed is measured using a Pitot tube connected to a manometer. The pitot tube is located 3.6 m from the tunnel entrance and at 1.4 m from the model and in the middle of the cross section. The model is placed in the test section of the tunnel and at a distance of 5.0 m from the entrance center. The experimental error in the measured flow velocity is estimated at 5%. In Fig.1 is shown an image of the turbine within the wind tunnel during a test.

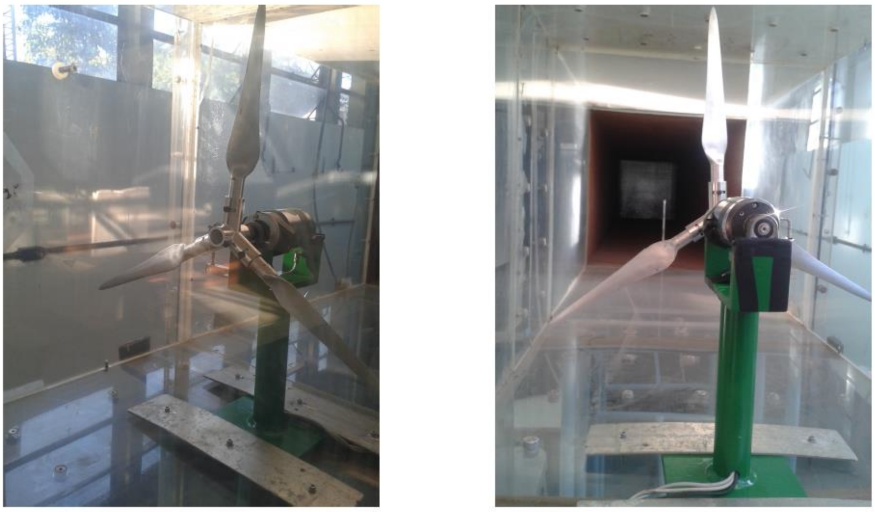

Figure 1 – Scale model into wind tunnel

1.2 Scale model

The model hydrokinetic turbine was built with a scale factor 1:23 using the same geometric details of the prototype. The model has diameter 520 mm and dimensions of the rest remains the same scale factor. The turbine is of the horizontal axis type rotor with three blades. The profiles of the vanes are NACA type 65(3)618. The model was built from aluminum using a CNC machine three axes.

The rotor blades are attached directly to the shaft of a DC permanent magnet motor Electro-Craft 110W. To apply load on the rotor, a DC motor was connect in the shaft working as a brake. The electric motor is integrated in a circuit of variable resistors, working as a brake and as a variable load that can control the rotational speed of the turbine. The motor is supported on two ball bearings set in such structure that supports the turbine system. Therefore, the brake balance was in order to measure the torque of the system directly from a load cell. The load cell was constructed with a digital scale SensorDisc SF-400. The transmission of force between the brake and the balance is carried by an arm fixed to the metal brake, as can be seen in Fig.2. Load cell was calibrated using a system known weights. The torque is calculated as the product of the force measured in the load times the distance from the cell axis by the end of the arm. The typical error in the measurement of torque is less than 0.01 N cm.

The rotation speed of the rotor is measured with an inductive speed sensor SCHMERSAL IFL3B-10E-8M. The rotation sensor was used measuring the rotational frequency of the shaft turbine. This sensor was calibrated using an oscilloscope.

The data acquisition was performed using the open source microcontroller Arduino Leonardo. The circuits of the sensors were integrated on a single card and controlled via the Arduino board.

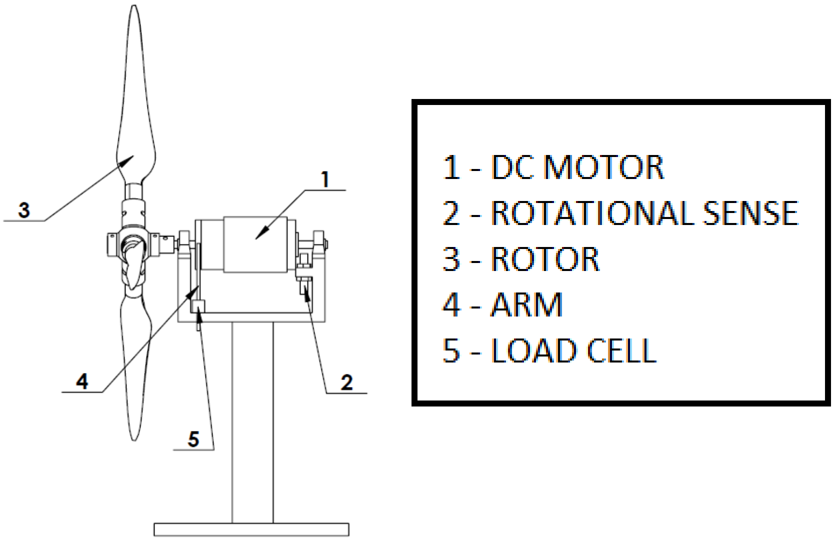

Figure 2 - Details of sensors

The tests of the reduced model were performed for different free flow speeds. Wind speeds were adjusted values 13,14 e 15 m/s. These speeds were measured by the Pitot tube and manometer. For each average flow velocity of the rotational speed of the turbine is controlled and gauged with the inductive rotation sensor. Speed control is accomplished by applying load on the motor through a series of variable resistors. Maintaining a constant flow speed for each speed of rotation of the torque obtained from the model system was measured with the load cell. The signals obtained by the rotation sensor and the load cell was sent to the microcontroller Arduino for automation of the assay.

To analyze the performance of the turbine curves λ versus Cp and Cq are constructed versus λ, and the power coefficient Cp, Cq torque coefficient λ and the ratio of blade tip speed. These are determined by eq. (1), (2) and (3). The speed ratio is the speed ratio between the farthest point on the rotor blade and the speed of free-flowing.

$$C_p = \frac{P}{E_0} = \frac{P}{\frac{1}{2}\rho A U_\infty^3} \quad (1)$$

$$C_q = \frac{\tau}{\frac{1}{2}\rho A U_\infty^2} \quad (2)$$

$$\lambda = \frac{\omega r}{U_\infty} \quad (3)$$

In the above equations, P is the power in the brake shaft, E_0 is the energy contained in the flow area of the turbine housing (hydrokinetic power from the free stream), ρ is the density of air and $A = \pi r^2/2$corresponds to the area perpendicular to the flow of the turbine inlet section. The angular velocity ω is the rotor radius is r and $U_\infty$is the speed of free-flowing. The shaft power can be determined by:

$$P = \tau\, \omega \quad (4)$$

where τ is the torque on the shaft which is determined by the product of the force measured by the load cell times the size of the arm.

2 NUMERICAL CALCULATION

The three-dimensional model was generated on SOLIDWORKS software based on the design characteristics of the reduced model. The software used for generating numerical grid was ANSYS ICEM CFD. The computational domain was divided into two parts: an inner, rotatable, with high density of elements and an outer stationary with low density elements. The rotating field is shaped like a cylinder 0.3 meters radius and 0.1 meters long. Already the stationary domain is shaped like a cube, which contains the rotating field with the approximate dimensions of the wind tunnel with section 0.65 meters tall and wide and 2 feet deep in the face of affluence and 6 meters downstream as can be observed in Fig. 3.

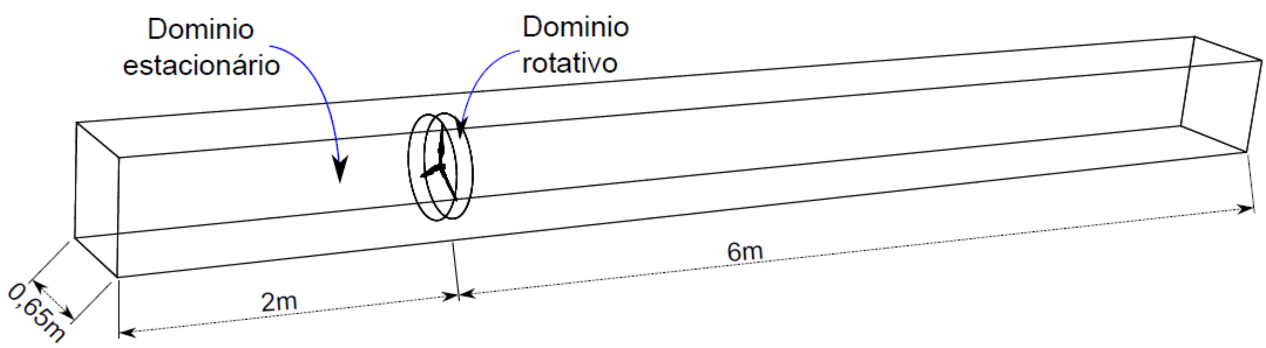

Figure 3 - Numerical domain

The numerical grid generated showed 2.51 x 106 us, with great refinement in the region close to the wall next regions. The turbulence model used in this modeling was the SST, known for showing good results for both laminar flow sublayer as in free stream. To this end, the treatment was made close to the wall so that the values of y + 2 are smaller than Another important factor is the mesh refinement near the mat due to the high velocity gradient in this region as illustrated in Fig.4.

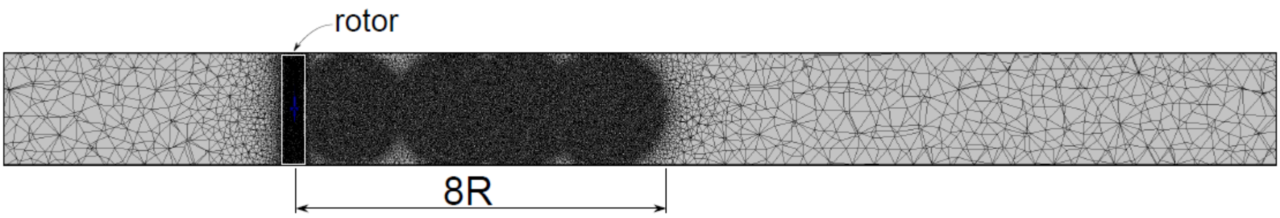

Figure 4 - Numerical mesh

The mesh is imported into CFX and then the boundary conditions are applied in the computational domain as shown in Fig 5 Attempted to perform with maximum fidelity of the experiment in wind tunnel.

• Input speed: is a Dirichlet boundary condition, which is attributed to the constant fluid velocity and normal to face with turbulence intensity of 5%, according to the experimental conditions. Already the pressure is determined so as to satisfy the equations of motion.

• Outlet pressure: the downstream face a condition of Dirichlet, which defined the boundary condition as the atmospheric pressure (101325 Pa) and consequently the velocity field is determined by the equation of motion was applied.

• No Slip: was imposed on all solid components of the rotor, this means that the relative velocity of the fluid particle in the wall to the wall is zero.

• Free slip: was imposed on the walls of the tunnel, so that does not influence the flow. Thus, the shear stress between the tunnel wall and the fluid is zero.

• Interface: The internal surfaces defining the cylindrical rotary connection between the subdomain that contains the rotor and the stationary field, have been linked, the condition of frozen rotor ("rotor Frozen"). Thus the components of the fixed domain are transformed into a moving reference system, adding the Coriolis and centrifugal acceleration, enabling local flow characteristics are transported through the interface.

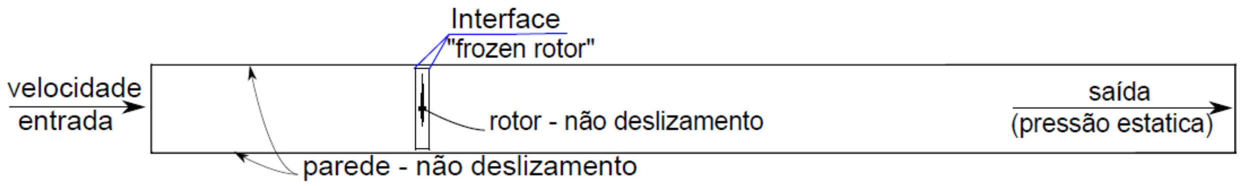

Figure 5 - Contour conditions

3 RESULTS AND DISCUSSIONS

The rotor performance was evaluated for three speeds of the wind tunnel: 13; 14:15 m / s. For each speed, the brake applied was varied and the torque and speed mesurados rotation, allowing the calculation of the coefficient of power and coefficient of torque. Cp and Cq versus λ versus λ curves are shown in Figures below.

In Fig.6 the power coefficient for various velocities of free flow is presented. It can be seen that the maximum value of Cp is around 0.11 and is obtained for λ = 3.8 and a free-flow speed of 13m / s. For speeds 14:15 m / s the maximum value of Cp is at λ = 3.2. All experimental curves were fitted by a third-order polynomial.

In Fig.7 the coefficient of torque for various free flow speeds is presented. It can be seen that the maximum value is obtained Cq for λ = 2.9 and a free-flow speed of 13m / s. For speeds 14:15 m / s the maximum value of Cp is at λ = 2.6.

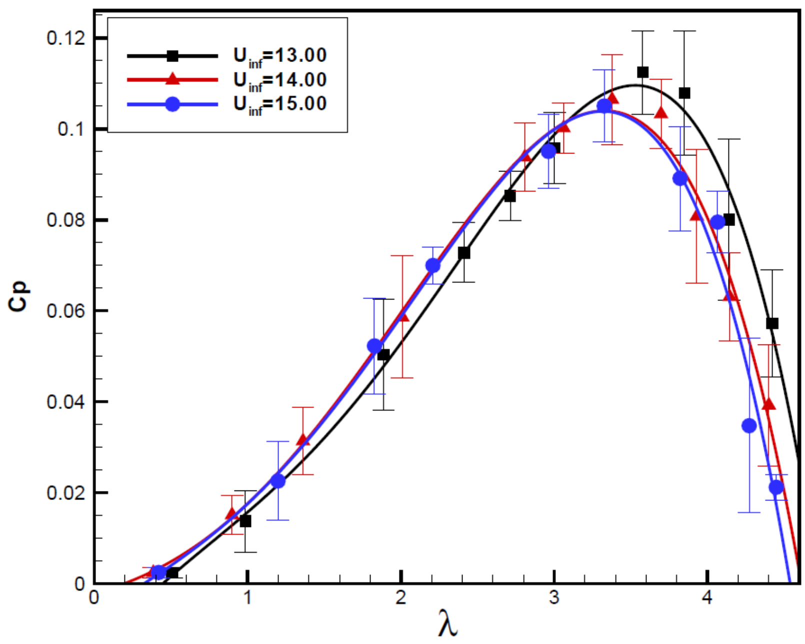

Figure 6 - Experimental curve: Cp x lambda

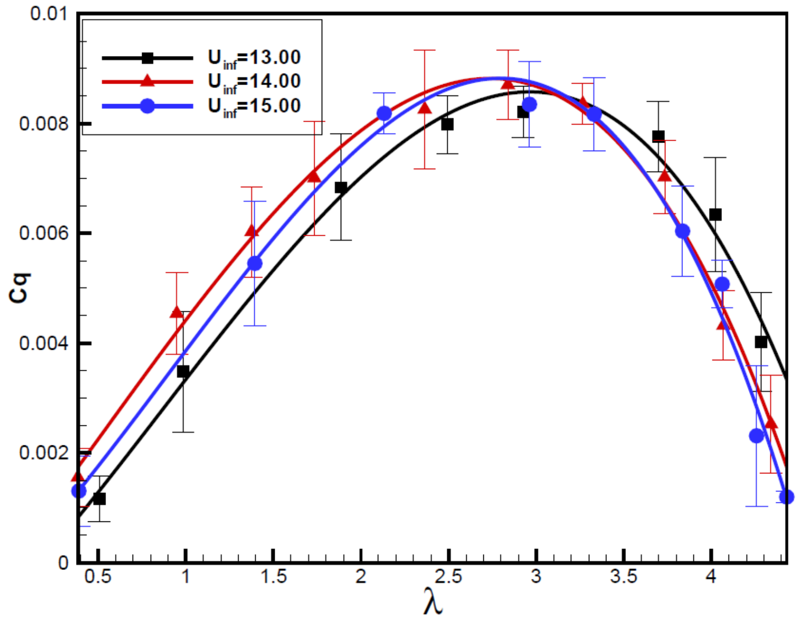

Figure 7 - Experimental curve: Cq x lambda

The Fig.8 shows the comparison of the experimental and numerical case for the speed of 13m / s tunnel.

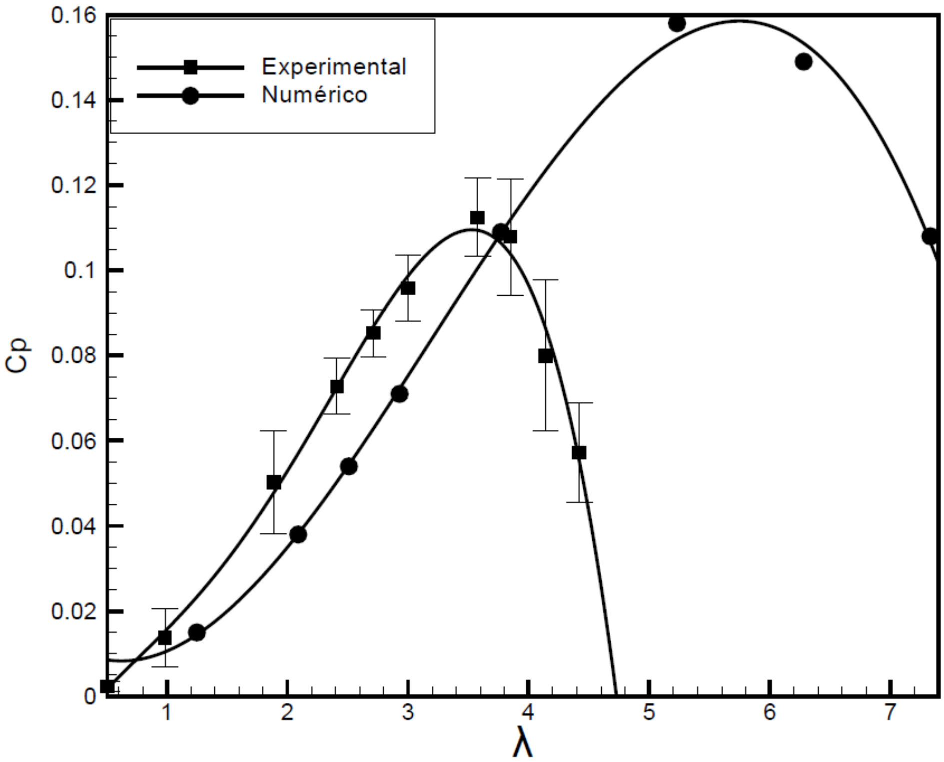

Figure 8 - Numerical and experimental points for 13 m/s

How widely studied in the literature, in studies such as Muljadi et al. (1999) and Burton et al. (2001), the variation of the pitch angle is a direct effect on the power converted by the turbine. The manual assembly process and the small size of the model contribute significantly to the occurrence of unwanted pitch angles, since this displacement of about 0.17 mm in the positioning of the blade axis represents a one degree change in pitch angle. Thus, it is believed that the discrepancies found between the numerical and experimental results shown in Fig. 8 is related to incorrect assembly or even the instrumental error in the manufacturing process of the blade, which are ignored in the numerical modeling. However this uncertainty still needs further investigation in metrological and numerical studies.

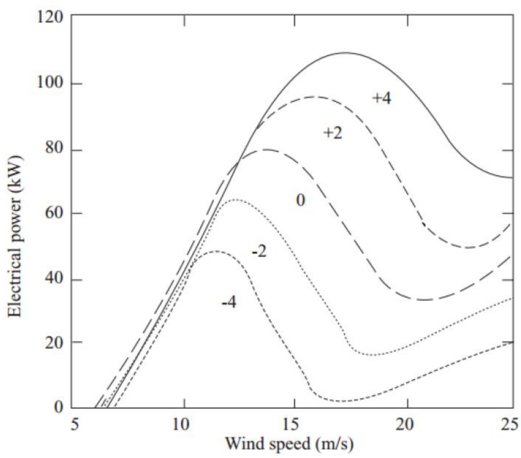

Figure 9 - difference of power caused by the angle of the blade. (Burton et al., 2001)

Applying a method similar to the scale model, the prototype of hydrokinetic turbines have been numerically simulated in real scale to a wide range of values of λ as shown in Fig. \ Ref {}

prototype. We note that the reduced model in air and water in the prototype show significant differences in the values of power coefficient for similar values of λ While the similarity in the values of λ, which ensure proportionality in the forces acting on the blade, the Reynolds number the prototype comes to submit two orders of magnitude greater than the reduced model magnitude, being reduced in 4x105 and 2.2 x 106 in the prototype model. This difference has a major influence on the flow dynamics, which in turn interferes with the power values.

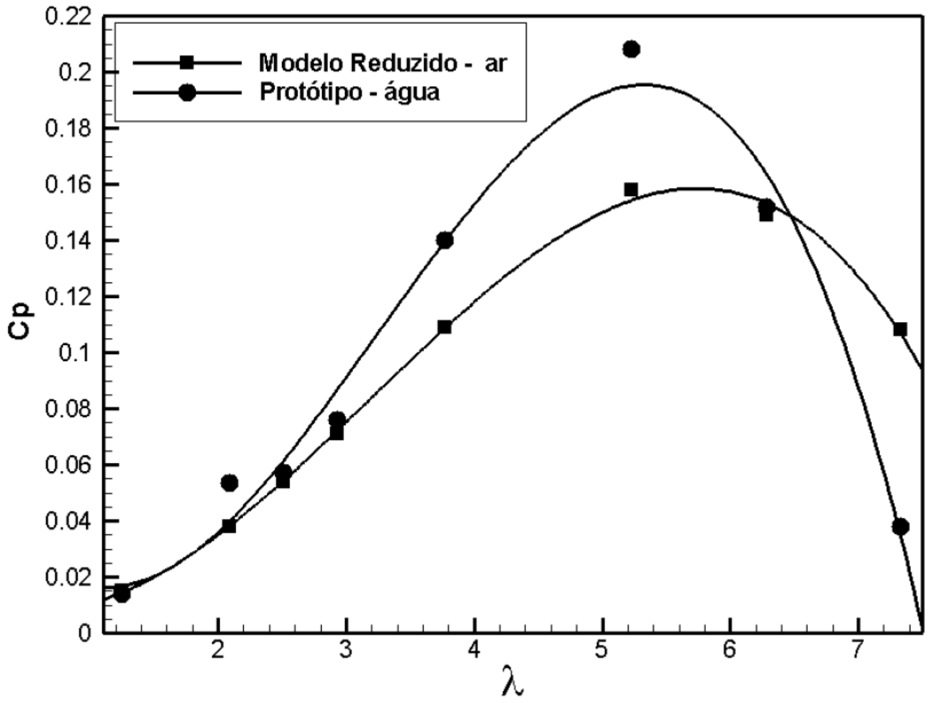

Figure 10 - Numerical comparison between prototype and scale model

4 CONCLUSIONS

The t of the maximum power value of 0.11 was obtained for the experimentally reduced to a free-flow speed of 13 m / s model. The speed ratio corresponding to peak power coefficient is around the value of 3.8.

The experimental results of this study allow to obtain the characteristics of the reduced model of hydrokinetic turbines in various operating conditions. For translating the results of the model to the prototype further investigation due to the large difference in Reynolds number, thus having a hard time to transpose results is necessary. Besides deepening the errors involved in assembling the experimental test.

NOMENCLATURE

A	Rotor area	[m^2]
Cp	Coefficient of potency	
Cq	Coefficient of torque	
E_0	Hydrokinetic potency	[W]
P	Potency	[W]
r	Rotor radius	[m]
U_∞	Flow velocity	[m/s]
λ	Tip speed ratio	
ρ	Specific mass	[kg/m^3]
τ	Torque	[N.m]
ω	Rotational speed	[rad/s]

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