

GEOMETRIC AND NUMERICAL ANALYSIS OF THE SEMICIRCULAR TRANSITION REGION BETWEEN THE HYDROPNEUMATIC CHAMBER AND THE CHIMNEY OF AN OSCILLATING WATER COLUMN DEVICE USING CONSTRUCTAL DESIGN

Gabriel Barbieri Dumont, gabriel.dumont@ufrgs.br

Yuri Theodoro Lima, yuri_vo@hotmail.com

Luiz Alberto Oliveira Rocha, laorocho@gmail.com

Universidade Federal do Rio Grande do Sul, Programa de Pós Graduação em Engenharia Mecânica - PROMEC. Rua Sarmento Leite, 425, Porto Alegre, RS, CEP 90.050-170, Brazil

Liércio Isoldi, liercioisoldi@gmail.com

Elizaldo dos Santos, elizaldodossantos@gmail.com

Universidade Federal do Rio Grande, Escola de Engenharia. Av. Itália, Km 8, Bairro Carreiros, Rio Grande, RS, CEP 96.201-900, Brazil

Mateus das Neves Gomes, mateusufpel.gomes@gmail.com

Instituto Federal do Paraná, Campus Paranaguá, Rua Antônio Carlos Rodrigues, 453, Bairro Porto Seguro, Paranaguá, PR, Brasil

Abstract. *This paper presents a two-dimensional numerical study about the transition region between the hydropneumatic chamber and the chimney of a device that converts wave energy into electrical one, whose operating principle is the Oscillating Water Column (OWC). The objective is to maximize the hydropneumatic power, considering the semicircular geometry of the OWC device's transition region, situated between the hydropneumatic chamber and the chimney. The results are compared through the obtained value of hydropneumatic power, which changes based on the different geometry ratios applied to the OWC device's transition region. Constructal Design was employed to define the geometry that maximizes the hydropneumatic power, and a parametric study is executed through numerical evaluation, based on the Exhaustive Search method. In this case, the degrees of freedom are: the radius (r) and the ratio between the height of the hydropneumatic chamber and the length of the OWC chamber (H_1/L). The constraints are: the area of the hydropneumatic chamber, the total area of the OWC chamber and the ratio between the height and length of the device's chimney (H_2/l). Finally, the objective function is the maximization of the hydropneumatic power. For the numerical solution, a commercial code of computational fluid dynamics, FLUENT®, which is based on the Finite Volume Method (FVM), is employed. The multiphase model Volume of Fluid (VOF) is applied in the treatment of water-air interaction. The computational domain is represented by a wave tank with a fixed OWC device. The obtained results show that the hydropneumatic power is maximized when $r = 7.5361$ m and $H_1/L = 0.1346$. In this case, the hydrodynamic efficiency of the device was 75.625%.*

Keywords: *Constructal Design, Oscillating Water Column (OWC), parametric study, transition region*

1. INTRODUCTION

Considering the trend of increasing energy consumption in the world, along with newfound concerns about the environmental impact of traditional energy sources, particularly fossil fuels, the search for alternative forms of energy conversion has increased (Clement *et al.*, 2002). As the population's access to electrical energy is one of the main variables in determining the development of a country (ANEEL, 2008), many of them are starting to invest in the renewable energy field. This classification generally includes solar power, wind power, biofuels and marine power, and each of these alternatives has different methods of energy conversion within them, such as photovoltaic and thermal solar collectors, or the different types of wind turbines based on airfoil and axis design (Burton *et al.*, 2001).

In the case of marine power, there are five main classifications, which are: marine thermal power (which uses the temperature gradient between shallow and deep waters, a direct result of incident solar radiation on the ocean's surface), tidal power (which is a result of the interaction between the sun and the moon's gravitational fields, along with the earth's rotation), marine current power (which harnesses the kinetic energy of marine currents, a function of temperature, wind, salinity, bathymetry, and the rotation of the earth), osmotic power (which harnesses the salinity gradient power present in the flow of fresh water into the ocean), and, finally, ocean wave power (which exists due to solar energy creating temperature differentials that result in wind). Concerning wave power, the interaction between the atmospheric winds and the surface of the ocean creates waves, which once formed can travel for kilometers with very little energy loss. The power of a wave is proportional to the square of its amplitude and to its period, and ocean waves with high amplitudes (around 2 meters) and period (around 7 to 10 seconds) often exceed 50 kilowatts of power for each meter of wavefront (Cruz and Sarmento, 2004). The estimated global potential of wave power is about 3.7 terawatts (Mørk *et al.*, 2010).

To convert wave power into electric one, many devices have been created, and they can be classified according to their distance to the shore or operating principle. Regarding the distance to the shore, there are three main groups: onshore devices (integrated into the coast and easily accessible), near-shore devices (located where ocean depth is between 8 and 20 meters) and offshore devices (generally located where ocean depth is over 25 meters). Based on the operating principle, the classifications are Oscillating Water Column (OWC) and Floating Bodies, the latter which can be divided into Point Absorbers and Surface Attenuators or Overtopping Devices (Cruz and Sarmiento, 2004). The scope of this paper deals with offshore OWC wave energy converters.

In this paper, the objective is to maximize the hydropneumatic power of a simulated offshore OWC device by changing the geometry of the semicircular transition region between the device's hydropneumatic chamber and its chimney. This is done through computational modeling and Constructal Design, by means of the Exhaustive Search method, and shows how the airflow, and therefore power, varies according to the different geometries applied in the transition region.

The objective function is the maximization of hydropneumatic power, and, in the bidimensional computational domain, the constraints are the area of the hydropneumatic chamber and the area of the OWC chamber plus the area of the chimney. As for the degrees of freedom, they are as follows: the radius (r) and the ratio between the height of the hydropneumatic chamber and the length of the OWC chamber (H_1/L). The ratio between the height and length of the device's chimney (H_2/l), as well as the depth of immersion (H_3), are kept constant.

Constructal Design is a broad concept, and its precedent, the Constructal Theory, covers many physical processes, as can be seen in (Bejan and Zane, 2012). It has been applied in the study of many engineering problems, among them the conversion of ocean wave power into electric power (Gomes *et al.*, 2009; Lara, 2015; Dos Santos *et al.*, 2013).

The computational domain, represented by a wave tank with a fixed OWC device, was discretized in the software GAMBIT®, and the numerical simulations were run in FLUENT®, a commercial code of computational fluid dynamics, which is based on the Finite Volume Method (FVM). The multiphase model Volume of Fluid (VOF) is applied in the treatment of water-air interaction (Ramalhais, 2011).

2. OSCILLATING WATER COLUMN DEVICE

2.1 Operating Principle

The Oscillating Water Column devices (OWC) are structures that generate electric power through the vertical motion of water within a hydropneumatic chamber, which is caused by the ocean waves and currents. The devices consist of hollow, partially submersed concrete chambers that have an open bottom, which serves as an entrance for the ocean water. The oscillatory motion of the water inside the chamber moves the air contained within it, pushing it vertically according to the elevation of the free surface of water within the chamber and through a chimney that has an opening to the atmosphere (Cruz and Sarmiento, 2004).

The energy conversion occurs in two phases, and both utilize the kinetic energy of the displaced air that moves through the chimney. In the first phase, a wave enters the partially submersed chamber and increases pressure, which forces the air to pass through the chimney to the atmosphere. In the second phase, the wave leaves the device, and the lower pressure inside the chamber makes the air move from the atmosphere to the chamber through the chimney (Cruz and Sarmiento, 2004). In both cases, a Wells turbine and its associated generator convert the energy into electric power. Figure 1 shows a schematic of the device:

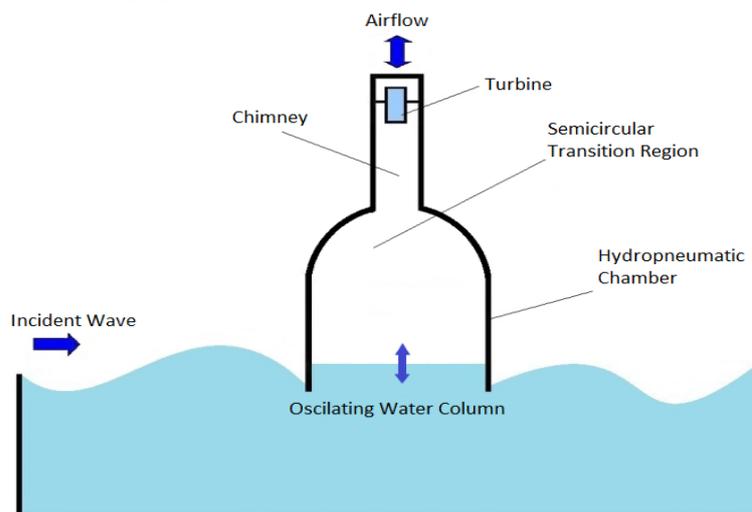


Figure 1. Schematic of the operating principle of an OWC device. Adapted from Lima *et al* (2015).

2.2 Computational Domain

As the computational domain is represented by a wave tank with a fixed OWC device, it is necessary to define parameters for the waves and the tank. While there isn't a general rule that defines the dimensions of the tank, it is necessary to consider the wavelength (λ) of the simulated waves, as a relatively long tank will maximize the simulation time in which waves propagate without reflection. Due to this factor, it is recommended that the tank's length be, at least, five times the wavelength (Lima *et al.*, 2015). In this study, the regular wave is defined by the following parameters: $H = 1,0$ m, $\lambda = 37,6$ m, $h = 10,0$ m, $T = 5$ s, where H is the height of the waves, h is the water depth, T is the wave period, and λ is the wavelength, as mentioned above. The dimensions of the tank were defined as follows: $L_T = 188$ m and $H_T = 13$ m, where L_T is the length of the tank and H_T is the height of the tank.

The full computational domain, including the oscillating water column device, present variables and boundary conditions, is represented in the scheme shown in Fig. 2:

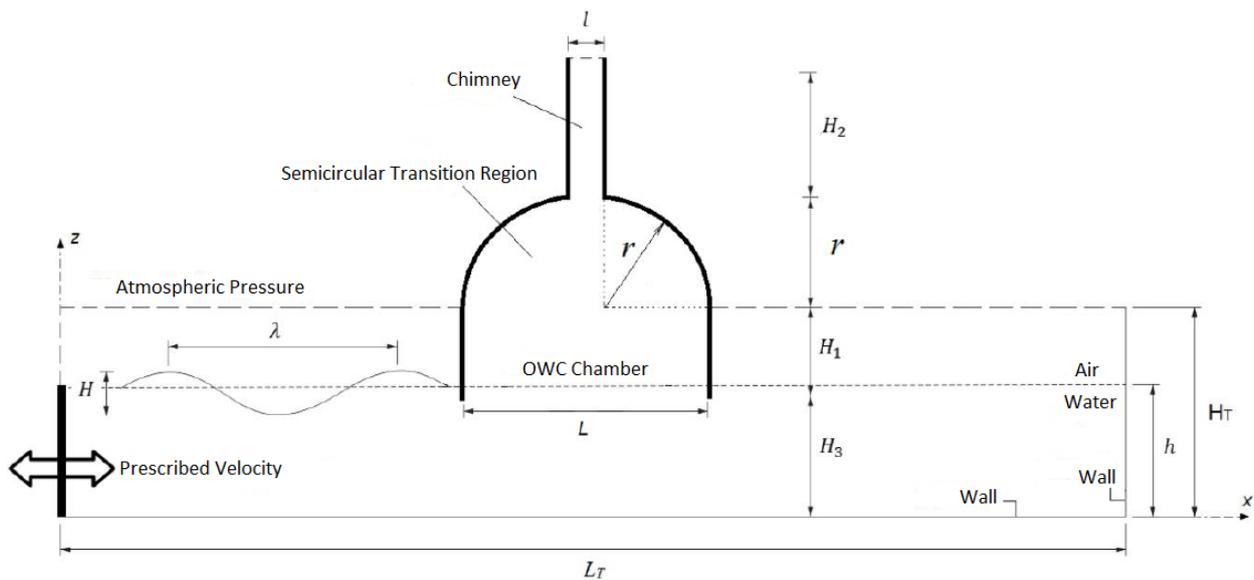


Figure 2. Scheme of the computational domain. Adapted from Lima *et al* (2015).

2.3 Boundary Conditions

As shown in Fig. 1, the numeric wave generator is placed in the left side of the tank. To generate the regular waves, the Function Methodology (Gomes *et al.*, 2009) is employed. This method consists in creating a function defined by the user, called UDF (User Defined Function), which is loaded into FLUENT® after the model has been defined, and applied in the entrance region, at the left side of the tank. The user defined function separates the wave's velocity profile into horizontal and vertical components, based on the Second Order Stokes Wave Theory (Lima *et al.*, 2015). The velocity component equations are given by (McCormick, 1976; Dean and Dalrymple, 1991; Chakrabarti, 2005):

$$u = \frac{H}{2} gk \frac{\cosh(kz+kh)}{\omega \cosh(kh)} \cos(kx - \omega t) + \frac{3}{4} \left(\frac{H}{2}\right)^2 \omega k \frac{\cosh 2k(k+z)}{\sinh^4(kh)} \cos 2(kx - \omega t) \quad (1)$$

$$v = \frac{H}{2} gk \frac{\sinh(kz+kh)}{\omega \cosh(kh)} \sin(kx - \omega t) + \frac{3}{4} \left(\frac{H}{2}\right)^2 \omega k \frac{\sinh 2k(k+z)}{\sinh^4(kh)} \sin 2(kx - \omega t) \quad (2)$$

In regards to the other boundary conditions, an atmospheric pressure boundary condition is applied in the upper section of the left side surface, as well as in the upper surface of the tank and in the exit of the OWC device's chimney, as shown by the hatched lines in Fig. 1. In all the other surfaces, a non-slip, impermeability, and null velocity boundary condition is applied. The initial condition has the fluid at rest, with a depth of $h = 10.0$ m.

3. CONSTRUCTAL DESIGN

The Constructal Design method is based on the Constructal Law developed by Adrian Bejan (Bejan and Zane, 2012). The Constructal Law explains, deterministically, the way flow develops and evolves in nature (such as in lungs, atmospheric circulation, river basins, the shape of animals, etc) based on the principle that finite-size systems must

evolve in such a way that it provides easier access to the imposed currents that flow through them (Bejan and Lorente, 2008). When applying Constructal Design to optimize the geometry of a physical problem, it is necessary to define the objective function (the variable to be optimized), the degrees of freedom (geometric parameters that may vary during the optimization process) and the restrictions (parameters that are kept constant during the optimization process) (Bejan and Lorente, 2008).

In this paper, the objective function is the hydropneumatic power, and the geometry that was optimized for it is the semicircular transition region. The constraints are the area of the OWC chamber (A_E) and the area of the OWC chamber plus the area of the chimney (A_4), where $A_E = 37.6 \text{ m}^2$ and $A_4 = 53.77 \text{ m}^2$. They are given, respectively, by:

$$A_E = H_1 L \quad (3)$$

$$A_4 = H_1 L + H_2 l \quad (4)$$

The degrees of freedom are the radius (r) and the ratio between the height of the hydropneumatic chamber and the length of the OWC chamber (H_1/L). The ration between the height and the length of the chimney (H_2/l), as well as the immersion depth (H_3) are kept fixed, at a value of $H_2/l = 6$ and $H_3 = 9.5 \text{ m}$, respectively, as shown in Lima *et al* (2015).

Through the variation of H_1/L , it is possible to calculate H_1 and L through the following equations:

$$H_1 = L \left(\frac{H_1}{L} \right) \quad (5)$$

$$L = \sqrt{\frac{A_E}{(H_1/L)}} \quad (6)$$

Therefore, the radius (r) of the transition region is also varied, and is defined by:

$$r = \frac{L-l}{2} \quad (7)$$

Where l is a function of H_2 , and both are defined by the following equations:

$$l = \sqrt{\frac{A_4 - A_E}{(H_2/l)}} \quad (8)$$

$$H_2 = l \left(\frac{H_2}{l} \right) \quad (9)$$

4. NUMERICAL MODEL

The model employed in the simulations was the Volume of Fluid (VOF) model, which is based on the Finite Volume Method (FVM) (Fluent, 2009) and used in the simulation of flows that involve two or more immiscible fluids. The model utilizes the Volume Fraction (α) concept to find how the phases are distributed along the control volume, as more than one phase cannot occupy the same volume simultaneously, and, therefore, the volume fraction in each cell must be the sum of α_{AIR} and α_{WATER} and always equal to one (Lima *et al.*, 2015).

In the VOF model, the continuity and momentum equations are applied to all fluids that make up the flow, and the volume fraction of each fluid in each cell is considered in the whole computational domain through the volume fraction equation. The continuity, volume fraction and momentum equations are respectively defined as:

$$\frac{\partial p}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (10)$$

$$\frac{\partial(\alpha)}{\partial t} + \nabla \cdot (\alpha \vec{v}) = 0 \quad (11)$$

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\mu \tau) + \rho \vec{g} \quad (12)$$

Where t is the time (s), ρ is the density (kg/m^3), v is the flow velocity (m/s), p is the static pressure (N/m^2), μ is the viscosity ($\text{kg/m}\cdot\text{s}$), τ is the stress tensor (N/m^2), and g is the gravitational acceleration (m/s^2).

As the mass and momentum conservation equations are solved for a mixture of air and water, mean values are determined for density and viscosity, shown in the equations below:

$$\rho = \alpha_{WATER} \rho_{WATER} + \alpha_{AIR} \rho_{AIR} \quad (13)$$

$$\mu = \alpha_{WATER}\mu_{WATER} + \alpha_{AIR}\mu_{AIR} \quad (14)$$

In all simulations, the Upwind scheme was used in the treatment of the advective terms. Pressure discretization was done through the PRESTO method, and the GEO-RECONSTRUCTION method was employed for the volumetric fraction. Pressure-velocity coupling was done through the PISO algorithm, and the under-relaxation factors for the continuity and momentum equations were 0.3 and 0.7, respectively. The Gauss-Seidel method with an algebraic multigrid was employed to solve the system of equations generated after the discretization. Further details about the numerical methodology can be found at (Patankar, 1980); Versteeg and Malalasekera, 2007).

All simulations were run in an Intel Core i7 computer with 16 GB of RAM, using serial processing. The time required for each simulation was approximately 3 h. The employed turbulence model was the k-ε model.

5. RESULTS AND DISCUSSION

The validation of the computational model is achieved through a comparison between a computational simulation where the Free Surface Elevation (η) is measured through time and the corresponding values obtained in the analytic equation defined by (Dean & Darlymple, 1991):

$$\eta = A\cos(kx - \omega t) + \frac{A^2 k \cosh(kh)}{4 \sinh^3(kh)} [2 + \cosh(2kh)] \cos 2(kx - \omega t) \quad (15)$$

Where A is the wave amplitude (m); t is the time (s); x is the position (m); h is the depth (m); ω is the frequency, given by $2\pi/T$, where T is the wave period (s); and k is the wave number, given by $2\pi/\lambda$, where λ is the wavelength (m).

Figure 3 shows, for the position $x = 22.5 \text{ m}$, the comparison between the numerical results and the analytic results obtained through Eq. (15). To minimize the effects of reflection and interference, the validation was done in the interval between 20 s and 30 s, when the wave is stable. The average error, which is the mean relative difference between the analytic and numerical solutions in each instant, was 1.24%. Additionally, for this interval, the maximum error was 2.33%, and the minimum error was 0.0054%. These results show that the numerical model is sufficiently accurate.

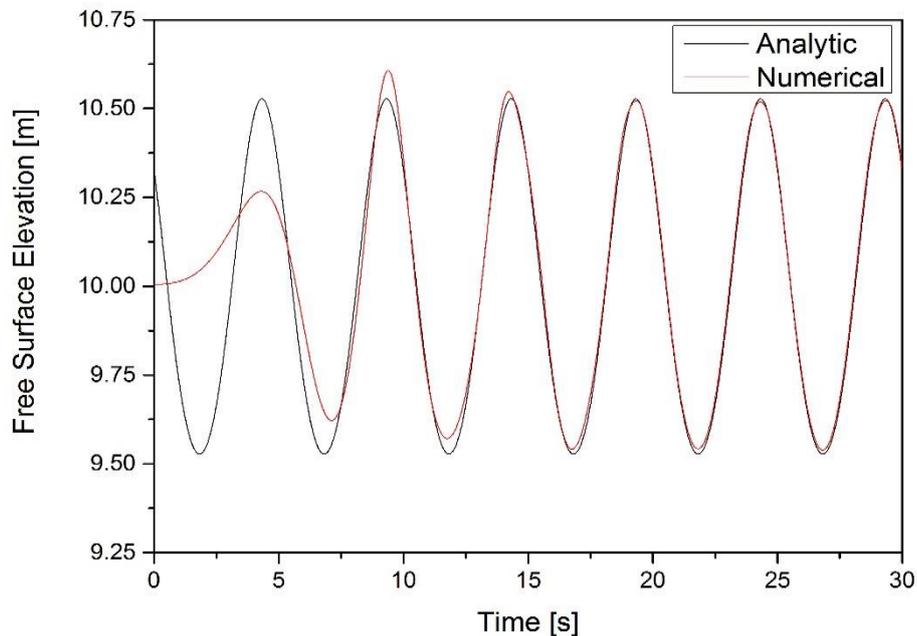


Figure 3. Comparison between numerical and analytic free surface elevation.

The mesh was generated in the software GAMBIT®, using the stretched mesh technique, in which the mesh is more detailed in areas that are of greater interest to the simulation (Mavripilis, 1997). As shown in Figure 4, the tank is divided into three regions, named A, B and C, in the vertical direction. In region B, which represents the free surface of water, a mesh refinement of 40 volumes in the vertical direction (the size of this interval is equivalent to $H/20$) and 250 volumes in the horizontal direction (this interval is equivalent to $\lambda/50$) is used. For the spatial discretization of regions A and C, respectively, 10 and 60 volumes are used in the vertical direction, according to (Gomes et al., 2012). To complete the computational domain, quadrilaterals with a length of 0,1 m were used in the discretization of the OWC device (regions E and F).

In the paper, the variables of interest were the mass flow rate (in the device's chimney), the pressure (inside the OWC chamber), the efficiency of the device and the hydropneumatic power. The average values were calculated using the arithmetic mean for transient problems Root Mean Square (RMS) (Marjani *et al.*, 2006).

$$X = \sqrt{\frac{1}{T} \int_0^T x^2 dt} \quad (16)$$

Where x is the parameter whose RMS needs to be found.

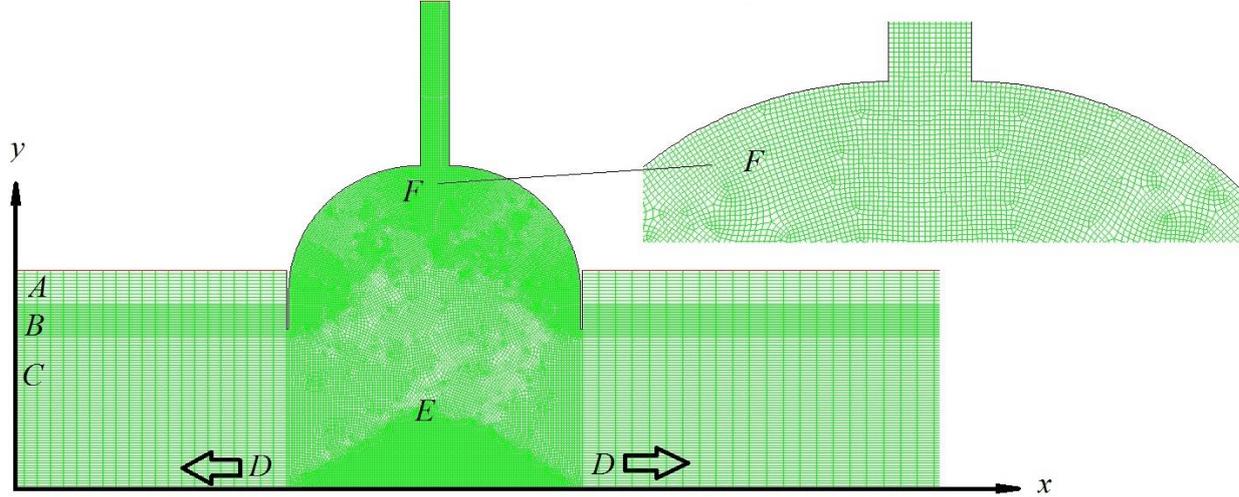


Figure 4. Discretization of the computational domain.

The hydropneumatic power is given by (Dizadji and Sajadian, 2011):

$$P_{hid} = \left(p_{air} + \frac{\rho_{air} v_{air}^2}{2} \right) \frac{\dot{m}}{\rho_{air}} \quad (17)$$

Where p_{air} is the static pressure in the chimney (Pa), \dot{m} is mass flow rate through the chimney (kg/s), ρ_{air} is the air density (kg/m³), and v_{air} is the air velocity through the chimney (m/s), which is calculated according to:

$$v_{air} = \frac{\dot{m}}{A \rho_{air}} \quad (18)$$

Where A is the transversal section area of the chimney (m²). As the model is bidimensional, this value corresponds to the Length of the chimney, which, as defined in section 3, is a constant $l = 2.3176$ m.

The static pressure is calculated through a weighted average over a certain area, which in this case is the center of the OWC device's chimney. The equation is given by:

$$\frac{1}{A} \int \phi dA = \frac{1}{A} \sum_{i=1}^n \phi_i |A_i| \quad (19)$$

Where ϕ is a field, which in this case is the static pressure p_e (Pa), n is the number of volumes and A is the area of the surface that is being measured (m²).

The mass flow rate is calculated through the following expression:

$$\int \rho \vec{v} \cdot d\vec{A} = \sum_{i=1}^n \rho_i \vec{v}_i \cdot \vec{A}_i \quad (20)$$

Where ρ is the air density (kg/m³), v is the velocity in the y direction (m/s), and A is the area of the surface that is crossed by the airflow.

As shown in (Zhang *et al.*, 2012) it is possible to define the hydrodynamic efficiency of a OWC device as:

$$\varepsilon = \frac{E_{OWC}}{P_{inc} T_w} \quad (21)$$

Where E_{OWC} is the Energy absorbed by the OWC device (J), P_{inc} is the Power of the incident wave (W), and T_w is the wave Period considered for the analysis (s). E_{OWC} can be calculated by:

$$E_{owc} = \int_0^T p(t)q(t)dt \quad (22)$$

Where T is the wave Period (s), $p(t)$ is the instantaneous pressure of the air inside the OWC chamber (Pa), and $q(t)$ is the volumetric flow rate (m³/s), defined by:

$$q(t) = v(t)LL_1 \quad (23)$$

Where $v(t)$ is the vertical velocity of the free surface (m/s), L is the length of the OWC chamber (m), and L_1 is the width of the OWC device (m), which, as the model is bidimensional, is set to 1.

Finally, the Power of the incident wave is determined by Eq. (24):

$$P_{inc} = \frac{\rho g A^2 \omega}{4k} \left(1 + \frac{2kh}{\sinh(2kh)} \right) \quad (24)$$

Where ρ is the water Density (kg/m³), g is the Gravitational Acceleration (m/s²), A is the wave Amplitude (m), ω is the wave Frequency (s⁻¹), h is the water Depth (m), and k is the Wave Number. The Power of the incident wave, calculated through Eq. (24), is equal to 5692.65 W

In total, eight different geometries were tested, with varying values for the degrees of freedom, which were calculated utilizing Eqs. (5-9). The dimensions of each geometry are shown in Tab. 1:

Table 1. Variations of the semicircular transition region's geometry

Cases	r [m]	(H_1/L)	l [m]	L [m]	H_1 [m]	H_2 [m]	H_3 [m]	A_E [m ²]
1	11.7168	0.0598	1.6415	25.0751	1.4995	9.8493	9.5	37.6
2	9.4161	0.0897	1.6415	20.4738	1.8365	9.8493	9.5	37.6
3	7.5361	0.1346	1.6415	16.7137	2.2497	9.8493	9.5	37.6
4	6.0025	0.2019	1.6415	13.6466	2.7553	9.8493	9.5	37.6
5	4.7500	0.3029	1.6415	11.1415	3.3748	9.8493	9.5	37.6
6	3.7275	0.4544	1.6415	9.0965	4.1335	9.8493	9.5	37.6
7	2.8926	0.6817	1.6415	7.4267	5.0628	9.8493	9.5	37.6
8	2.2112	1.0225	1.6415	6.0640	6.2005	9.8493	9.5	37.6

Finally, for each geometry applied to the transition region, shown as cases 1-8 in Tab. 1, mass flow rate, static pressure, hydropneumatic power and hydrodynamic efficiency were calculated. Figure 5 shows the hydropneumatic power as a function of H_1/L and r .

Table 2. Mass flow rate, static pressure, hydropneumatic power and hydrodynamic efficiency in each geometry.

Cases	\dot{m} [kg/s]	p [Pa]	P_{hid} [W]	ε [%]
1	12.9625	45.7940	122.4850	37.8644
2	15.4832	55.8463	187.5651	63.8545
3	16.1388	61.4958	215.7637	75.6250
4	15.5794	62.5424	208.7102	73.3967
5	14.3032	58.0328	182.7608	66.3674
6	12.6515	50.4143	144.6106	52.7714
7	10.9521	43.8452	108.0211	39.8251
8	9.3248	37.3546	78.8488	28.5454

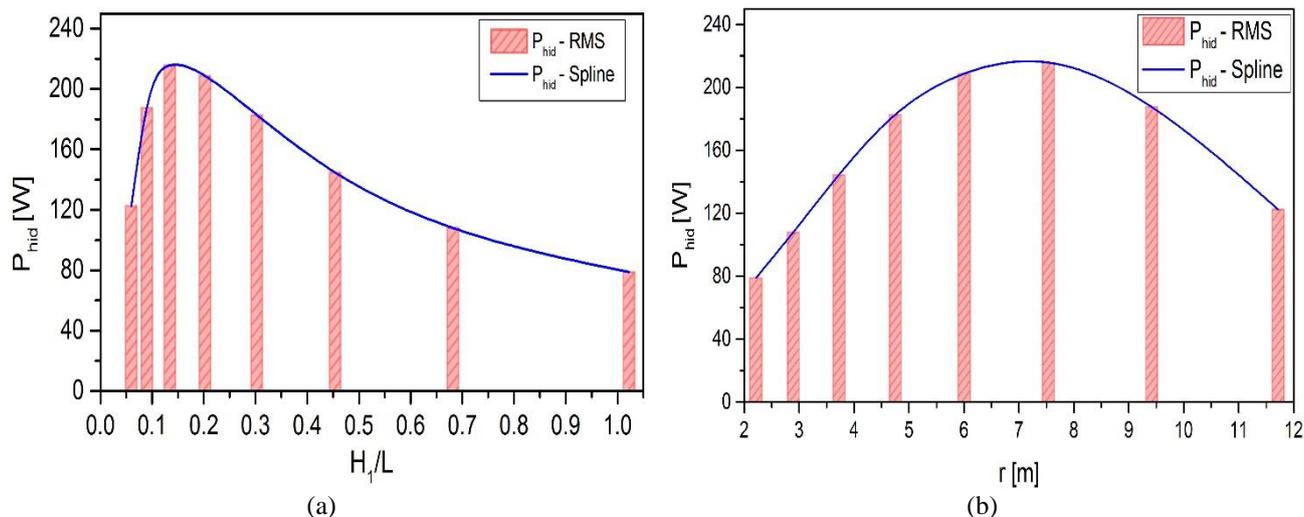


Figure 5. Hydrodynamic power as a function of H_1/L (a) and r (b).

6. CONCLUSIONS

In this study, numerical methods were employed to analyze the semicircular transition region between the chimney and the hydrodynamic chamber of an offshore, OWC type wave energy conversion device. The Constructal Design method was used to define all the variations of the transition region's geometry, allowing for the correlation between the geometry of the transition region and the hydrodynamic efficiency of the device, which was calculated numerically. Therefore, the main objective of this study was to find a theoretical recommendation for the degrees of freedom, which are r (which represents the radius of the semicircular transition region) and H_1/L (which represents the ratio between the height of the hydrodynamic chamber and the length of the OWC chamber), based on the values that yield the highest hydrodynamic power for an OWC device that is subjected to regular waves with a period of 5 s and a wavelength of 37.6 m.

The increase of both r and H_1/L increased the hydrodynamic power, but only up to an optimal value, as further increases led to a downward trend. For H_1/L , the optimal value was 0.1346; for r it was 7.5361 m. These values correspond to the ideal geometry, where $\varepsilon = 75.6250\%$. When $r = 2.2112$ m and $H_1/L = 1.0225$, the worst value of hydrodynamic efficiency was found, in which $\varepsilon = 28.5454\%$. This shows an increase of nearly 165% in performance from the worst to the optimal geometries.

The applicability of the Constructal Design method to the parametric study of wave energy converters was verified, as the results show a substantial increase in the device's performance. It is also possible to evaluate the evolution of the device's geometric configuration, which leads to the best performance.

In this study, the area of the hydrodynamic chamber was a problem constraint. However, it was a function of the radius, the height of the hydrodynamic chamber, and the length of the OWC chamber, which could change within that restriction. Hence, the results obtained can be compared to those of previous studies that considered a semicircular transition region without the same restriction. These definitions show the relevancy of the Constructal Design technique for this type of analysis, and, in future studies, it would be relevant to evaluate transition regions that have a different type of geometry.

7. ACKNOWLEDGMENTS

The authors thank the Federal University of Rio Grande do Sul (UFRGS), Federal University of Rio Grande (FURG), and the Federal Institute of Education, Science and Technology of Paraná (IFPR) for their assistance. Authors also thank the National Council for Scientific and Technological Development (CNPq) for financial support.

8. REFERENCES

- Aneel, 2008, *Atlas de Energia Eletrica no Brasil*, 3a ed., Agencia Nacional de Energia Eletrica.
- Bejan, A., & Lorente, S., 2008, *Design with Constructal Theory*, Wiley.
- Bejan, A. & Zane, J., 2012, *Design in Nature*, Doubleday.
- Chakrabarti, S. K., 2005. *Handbook of offshore engineering*. vol. 1, Elsevier, Illinois, Estados Unidos, 661 p.
- Clement, A. et al., 2002 Wave energy in Europe: current status and perspectives. *Renewable and Sustainable Energy Reviews*, v. 6, p. 405-431.

- Cruz, J. M. B. P. & Sarmiento, A. J. N. A., 2004, *Energia das Ondas: Introdução aos Aspectos Tecnológicos, Econômicos e Ambientais*, Instituto do Ambiente, Amadora.
- Dean, R. G., Dalrymple, R. A., 1991, *Water wave mechanics for engineers and scientists*, vol. 2, World Scientific, Singapura, 353 p.
- Dizadji N., Sajadian S. E., 2011, Modeling and optimization of the chamber of OWC system, *Energy*, Vol. 36, pp. 2360 – 2366.
- Dos Santos, E. D.; MACHADO, B. N. ; Lopes, N. ; Souza, J. A. ; TEIXEIRA, P. R. F. ; GOMES, M. N. ; ISOLDI, L. A. ; ROCHA, L. A. O. . *Constructal Design of Wave Energy Converters*. In: L. A. O. Rocha; S. Lorente; A. Bejan. (Org.). *Understanding Complex Systems*. 1ed.: Springer New York, 2013, v. 1, p. 275-294
- Fluent Inc., 2009, *FLUENT 12.0 Theory Guide*.
- Gomes, M. das N., Olinto, C. R., Rocha, L. A. O., Souza, J. A. & Isoldi, L. A., 2009, *Computational Modeling of a Regular Wave Tank*, *Engenharia Térmica*, Vol. 8, No.1, pp. 44-50.
- Gomes, M. das N., Isoldi, L. A., Santos E. D. & Rocha, L. A. O., 2012, *Análise de Malhas para Geração Numérica de Ondas em Tanques*, em: VII Congresso Nacional de Engenharia Mecânica. São Luiz, MA, pp. 1-10.
- Gomes, M. das N., 2014, *Constructal Design de Dispositivos Conversores de Energia das Ondas do Mar em Energia Elétrica do Tipo Coluna de Água Oscilante*, Tese de Doutorado, PROMEC-UFRGS, Porto Alegre, RS.
- Lara, M. F. E. *Estudo Numérico Bidimensional com Aplicação de Constructal Design para a Otimização da Geometria e da Profundidade de Submersão de um Dispositivo Conversor de Energia das Ondas do Mar do tipo Coluna d'água Oscilante*. Dissertação de Mestrado. Programa de Pós-Graduação em Engenharia Mecânica, da Escola de Engenharia da Universidade Federal do Rio Grande do Sul. Porto Alegre. Abril, 2015.
- Lima, Y.T.B; Rocha, L.A.O; Plamer, C.B.; Isoldi, L.A.; Santos, E.D.; Gomes, M.N. *Análise numérica com constructal design da forma geométrica na região de transição entre a câmara hidropneumática e a chaminé de um dispositivo do tipo coluna de água oscilante*. *Proceedings of the XXXVI Iberian Latin-American Congress on Computational Methods in Engineering*, ABMEC, Rio de Janeiro, RJ, Brazil, November 22-25, 2015
- Marjani, A. E., Castro, F., Bahaji, M., & Filali, B., 2006, *3D Unsteady Flow Simulation in a OWC Wave Converter Plant*, em: *Proceedings International Conference on Renewable Energy and Power Quality*, Mallorca, Espanha.
- Mavriplis, D. J., 1997. *Unstructured Grid Techniques*. *Annual Reviews Fluid Mechanics* , Vol. 29, pp: 473-514.
- McCormick, M. E., 1976. *Ocean engineering wave mechanics*. John Wiley & Sons, USA, New York.
- Mørk, G., Barstow, S., Kabuth, A., Pontes, M.T. *Assessing the global wave energy potential*. In: *Proceedings of OMAE2010 29th International Conference on Ocean, Offshore Mechanics and Arctic Engineering*. June 6-11, 2010, Shanghai, China. Available at: http://www.oceanor.com/related/59149/paper_OMAW_2010_20473_final.pdf.
- Patankar, S., V., 1980, *Numerical Heat Transfer and Fluid Flow*, McGraw-Hill, USA, 196 p.
- Ramalho, R. dos S., 2011, *Estudo Numérico de um Dispositivo de Conversão da Energia das Ondas do Tipo Coluna de Água Oscilante (CAO)*, Dissertação de Mestrado, Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa, Lisboa, Portugal.
- T. Burton, D. Sharpe, N. Jenkins, E. Bossanyi, *Wind Energy Handbook*. Wiley, 2001.
- Versteeg, H. K., Malalasekera, W., 2007, *An Introduction to Computational Fluid Dynamics*, Malaysia: Pearson.
- Zhang, Y., Zou, Q. P., Greaves, D., 2012, *Air-water two-phase flow modelling of hydrodynamic performance of an oscillating water column device*, *Renewable Energy*, v. 41, pp. 159-170.