NUMERICAL EVALUATION OF HYDROPNEUMATIC POWER FOR TWO OSCILLATING WATER COLUMN (OWC) DEVICES COUPLED USING CONSTRUCTAL DESIGN

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Abstract. *The present work presents a two-dimensional numerical study on the hydropneumatic power and geometry of two oscillating water column (OWC) wave energy devices (WEC) coupled. The Constructal Design method associated to the exhaustive search method is used to geometrically optimize the coupled converters. The objective is to maximize hydropneumatic power considering different combinations of height and length for the hydropneumatic chambers of the converting devices. The constrains of the problem are: the input volume of the first positioned device (V_{E1}), the input volume of the second device (V_{E2}), the total volume of the first device (V_{T1}) and the total volume of the second device (V_{T2}). The*

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degrees of freedom considered are: H_1/L_1 (ratio between height and length of the hydropneumatic chamber of the first device), H_2/L_2 (ratio between height and length of the hydropneumatic chamber of the second device). In the present work the degrees of freedom H_4/l_1 (ratio between height and length of the chimney of the first device), H_5/l_2 (ratio between height and length of the chimney of the second device) and H_6 (depth of immersion of the devices) are kept constant. For the numerical solution, is employed a computational fluid dynamics code, based on the Finite Volume Method (FVM). The multiphase model, Volume of Fluid (VOF), is used in the treatment of water-air interaction. The results show that the maximum total hydropneumatic power of 12729.98 W is obtained for the degrees of freedom H_1/L_1 and H_2/L_2 = 0.0344, while the case with lower performance presents a total hydropneumatic power of 1047.37 W for the degrees of freedom H_1/L_1 and H_2/L_2 = 1.3226. Then, a gain of 91.77 % is reached in comparison between the best and worst cases.

Keywords: *Constructal Design, OWC Coupled, Wave Energy.*

1 INTRODUCTION

Energy demand has been increasing considerably over the past decades, coupled with the fact that the energy generation methods associated with burning fossil fuels are causing irreversible environmental impacts. Based on these aspects, many countries are investing in research and exploration of new energy sources (Cruz and Sarmento, 2004; Clément et al., 2002).

The energy contained in the oceans can have different origins, which generates different classifications. The most relevant are, without doubt, tides energy (concerned with the interaction of gravitational fields of moon and sun), and the thermal energy of the oceans (consequence of incident solar radiation), the energy of the sea currents (whose origin is in the gradients of temperature, salinity and tidal action) and wave energy (which results from the effect of the wind on the surface of the oceans) (Cruz and Sarmento, 2004).

Initiatives to convert wave energy are quite old, and the earliest data records comes from seventeenth century. However, the investment in this kind of energy was more expressive from the 70's, due to the oil crisis, in the search for alternative energy sources to supply demand (Tolmasquim, 2016).

The sea waves are a consequence of the energy transfer of the winds along a strip on the ocean surface. The energy contained in the waves is thus a form of solar energy, but more concentrated, being about 10 to 30 times denser than in normal form (Tolmasquim, 2003).

There are several technologies for the conversion of sea wave energy, which can be classified in different ways, one of which is in relation to its location of installation that can be: onshore (integrated devices on the coast, with easy access), nearshore (installed in locations with water depths between 8 and 20 m) and offshore (installed in locations with a depth greater than 25 m). Another way of classifying sea wave energy converters relates to their physical principle of operation. There are three main groups: Oscillating Water Column (OWC), floating bodies, which can be of punctual or progressive absorption and overtopping (Cruz and Sarmento, 2004).

The present work deals with the operating principle of an Oscillating Water Column (OWC) type device. Through the computational modeling associated with the Constructal

Design method and the exhaustive search method, it is sought to numerically simulate two coupled OWC devices and to evaluate the influence of the geometric variation of the hydropneumatic chamber on the flow of air through the interior of the device. More precisely, with the purpose to maximize the hydropneumatic power.

For the considered two-dimensional geometry the constraints of the problem are: the input volume of the first positioned device (V_{E1}), the input volume of the second device (V_{E2}), the total volume of the first device (V_{T1}) and the total volume of the second device (V_{T2}). The degrees of freedom considered are: H_1/L_1 (ratio between height and length of the hydropneumatic chamber of the first device), H_2/L_2 (ratio between height and length of the hydropneumatic chamber of the second device). In the present work the degrees of freedom H_4/l_1 (ratio between height and length of the chimney of the first device), H_5/l_2 (ratio between height and length of the chimney of the second device) and H_6 (depth of immersion of the device) are kept constant and equal to $H_4/l_1 = H_5/l_2 = 3$ and $H_6 = 9.5$m.

The use of the Constructal Design method is one of the differentials of this research. The Constructal Theory explains deterministically how the design of flow systems are generated in nature (hydrographic basins, lungs, vascular tissues, etc.) based on an evolutionary principle of access, more easily, to the flow in time. The Constructal Law states that for a flow system to persist in time (to survive), it must evolve in such a way that it provides easier access to the currents flowing through it (Bejan and Lorente, 2008).

Constructal Design associated with the exhaustive search method is applied in this work to obtain the geometric optimization of the WEC devices, thus seeking to achieve the combination of the geometries that present the best performance in relation to the total hydropneumatic power, that is, when adding the power of the two attached devices. There is a range of works which use Constructal Design for the geometric optimization of sea wave energy converters in electrical energy, among them the research developed by: Gomes et al., (2009); Gomes et al., (2013); Lima, (2016).

Some papers will be presented in more detail. As can be seen in: Gomes (2014), a two-dimensional numetical study is realized on the optimization of the geometry of a OWC device, using Constructal Design, taking into account the wave climate of a given region and, from this, size the device so that it has performance optimizated. In the same work an investigation was also done on the influence of turbine load loss through a physical restriction.

In Espinel (2015), the hydropneumatic power maximization converted to an oscillating water column (OWC) is treated, the Constructal Design method, associated to the exhaustive search method, is applied to improve the geometry and the submersion depth of the device.

In Martins (2016), the author uses the Construtal Design in the geometric optimization of a overtopping device, indicating that the reduction of the period leads to a reduction of the available power.

In Gomes et al. (2016), the authors use the Constructal Design method to optimize a two-dimensional OWC type device, seeking the maximization of hydropneumatic power when subjected to a Pierson-Moskowitz wave spectrum.

For the computational modeling of the operating principles of the OWC converter, the computational domain consists of two coupled devices and both are in a wave tank. The numerical simulations were developed using a computational fluid dynamics code, FLUENT®, based on the Finite Volume Method (FVM) (Fluent, 2016; Maliska, 2004). The multiphase Volume of Fluid (VOF) model is employed in the treatment of water-air interaction (Gomes et al., 2012; Liu et al., 2008).

2 OSCILLATING WATER COLUMN (OWC) DEVICE

2.1 Main Operational Principle

One of the first conceptions for the use of wave energy was the oscillation of a water column in a partially submerged structure containing a certain amount of air (Tolmasquim, 2016). The differential of this work is in the existence of two OWC devices coupled, as can be observed in Fig. 1.

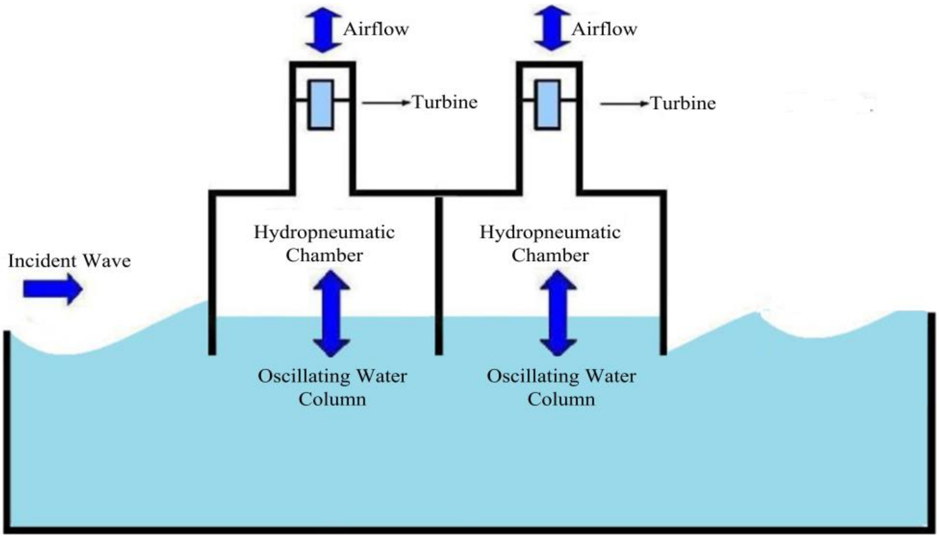

Figure 1. Representation of the main operational principle.

The Oscillating Water Column (OWC) wave energy extraction equipment is probably the most studied so far, both theoretically and experimentally, is one of the few to arrive at the state of real-scale installation. One of these projects that stands out is the pilot center of Pico Island in the Açores (Portugal) (Cruz and Sarmento, 2004).

The process of electricity generations follows two phases: with the passage of the wave through the device, the water column rises causing the air inside to be forced through a turbine, as a direct in the hydropneumatic chamber. After the wave returns to the sea, the air passes back into the turbine, this time in the opposite direction, given the lower pressure inside the hydropneumatic chamber. These processes are named as compression and decompression, respectively.

A Wells type turbine and its generator are used for energy conversion, having the property of maintaining the same direction of rotation of its blades regardless of the direction of flow (Cruz and Sarmento, 2004; Tolmasquim, 2016). The OWC mechanism can be represented by four main components: hydropneumatic chamber, chimney, turbine and generator. With regard to their dimensions, they should be appropriate for the type of wave present at the installation site (Gomes, 2014).

2.2 Computational Domain

The two-dimensional computational domain presented in this research consists of two coupled OWC devices, inserted in a wave tank. In the computational modeling of a wave tank with an inserted OWC device some aspects such as length and height of wave to be generated must be taken into account.

The wave characteristics are defined by: wave period (T), wave height (H) and depth in relation to the free surface (h). Thus, it is possible to determine the length of wave tank (L_T) and the height of the wave tank (H_T), which are presented in Fig. 2. There is no general rule that establishes the dimension of the wave tank, but some issues must be considered.

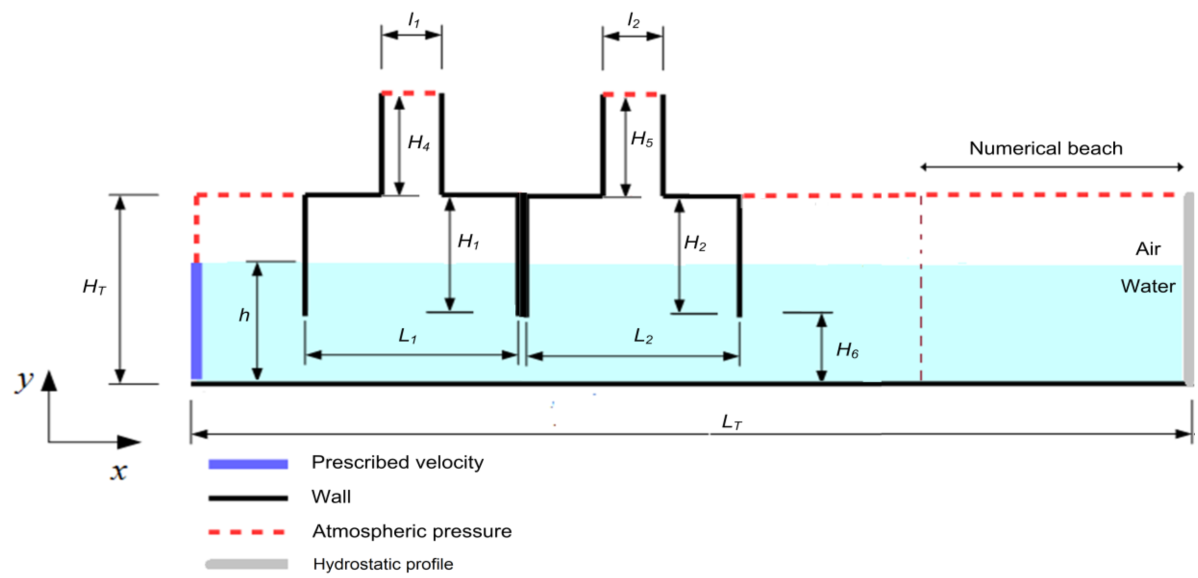

Figure 2. Schematic representation of the computational domain.

The propagation depth of the wave is the same as that of the tank, represented by h. For the length of the tank, it is necessary to consider the wavelength (λ). For the proposed problem, it is additioned a numerical beach in the right hand side of the tank to avoid wave reflections in devices, so the length of the tank is divided in two parts. The part in which the devices are located is approximately three times the wavelength, while the region comprising the numerical beach has a length twice times higher than the wavelength.

With regard to the height of the tank, it is necessary to consider a depth plus the height of the wave. Thus, it is recommended that the height be given by depth plus at least three times a height of the wave.

The regular and in real scale wave in the present work has the following characteristics: T = 7.5 s, H = 1.0 m, λ = 65.4 m, h = 10.0 m, L_T = 327 m and H_T = 13 m. The dimensions of the device are: height of the hydropneumatic chamber of the first device (H_1), height of the hydropneumatic chamber of the second device (H_2), chimney height of the first device (H_4), chimney height of the second device (H_5), length of the first device's chamber (L_1), length of second device's chamber (L_2), chimney length of the first device (l_1) and chimney length of the second device (l_2). It is important to note that the H_6, considered a degree of freedom, is related to how much the OWC device is submerged in relation to the free surface and in this study was kept fixed and equal to H_6 = 9.5 m.

2.3 Boundary Conditions

As can be seen in Fig. 2, the numerical wave generator is positioned on the left side of the wave tank, with the prescribed speed boundary condition. For the generation of the regular wave is used the Methodology Function, used by Gomes et al., (2009). This methodology, developed by Horko (2007), consists of applying the horizontal components (u) and vertical (w) of the wave velocity through a User Defined Function (UDF) in FLUENT®.

The velocity varies according to space and time based on the second-order Stokes Theory. Thus, the equations imposed in the inlet region of the tank are given by (McCormick, 1976; Dean and Dalrymple, 1991; Chakrabati, 2005):

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

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

where H is the height of the incident wave (m); g is the acceleration of gravity (m/s²); k is the number of wave given by $k = 2\pi/\lambda$ (m^{-1}), h is the water depth (m), T is the wave period (s), ω is the frequency given by $\omega = 2\pi/T$ (rad/s), x is the coordinate that represents the main flow direction (m), z is the normal coordinate (m) and t is the time (s).

Concerning the other boundary conditions, in the upper part of the lateral surface, as well as in the upper surface of the tank and the exit of the chimney of the OWC device is applied a prescribed atmospheric pressure (see the dashed surface on Fig. 2). In the lower surface of the wave tank it is imposed non-slip and impermeability condition (velocity null). The right side surface has a hydrostatic profile contour condition.

The initial conditions imposed consider that the fluid is at rest, with depth h = 10.0 m. It is still possible to check in the Fig. 2 a region called numerical beach associated with the condition of hydrostatic profile, which has the purpose of reducing the reflection effect of the wave. The length of the numeric beach region has 130.8 m.

2.4 Numerical Beach

To assist in reduction of wave reflection, a numerical beach was inserted. This methodology adds a sink term (S) in the momentum equation to perform the damping of incident waves, whose mathematical formulation is show in Eq. (3) (Zwart et al., 2007; Park et al., 1999).

$$S = -\left[C_1 \rho V + \frac{1}{2} C_2 \rho |V| V\right]\left(1 - \frac{z - z_{fs}}{z_b - z_{fs}}\right)\left(\frac{x - x_s}{x_e - x_s}\right)^2 \quad (3)$$

where C_1 and C_2 are linear and quadratic damping coefficients, respectively, ρ is the density, V is the velocity, z is the normal position, z_{fs} and z_b are the vertical positions of the free surface and the bottom, x is the horizontal position, x_s and x_e are the horizontal position at the beginning and end of the numerical beach.

One of the greatest problems of the numeric beach imposition is in the definition of the coefficients of linear and quadratic damping. According Lisboa et al., (2017), C_1 = 20 e C_2 = 0.

2.5 Mesh Generation

For the generation of the mesh, as can be seen in Fig. 3, a strategy was adopted that aims to build a more refined mesh in certain regions of interest in the computational domain, such as the free surface, for example. This methodology is based on the technique of stretched meshes (Mavripilis, 1997).

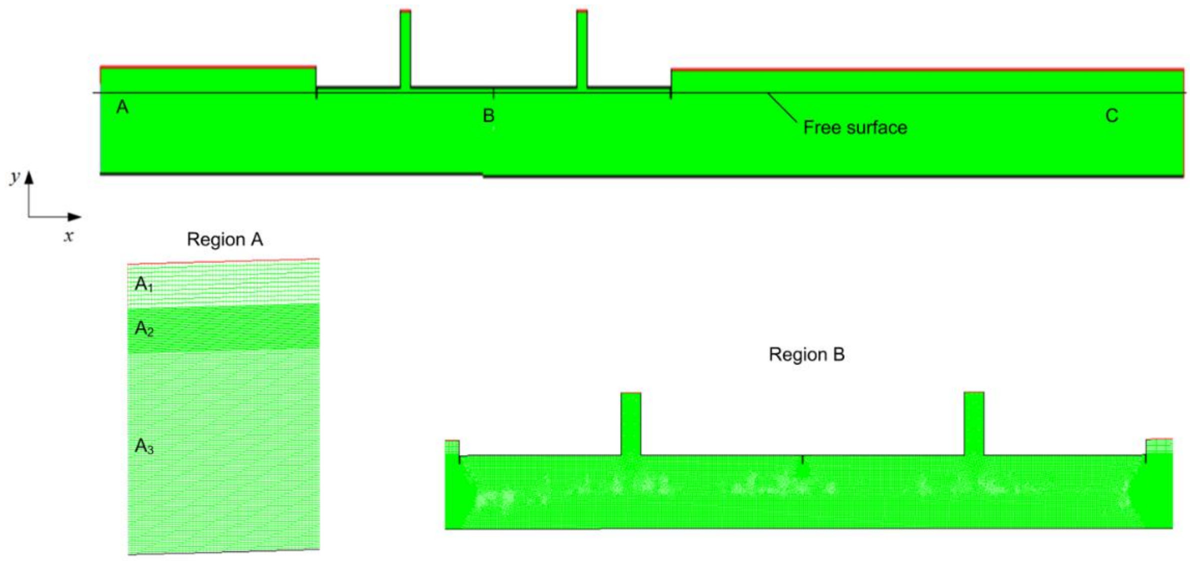

Figure 3. Discretization of the computational domain.

In the vertical direction (region A) the wave tank is divided into three regions called A_1, A_2 e A_3. In the region A_1 which is above the free surface is adopted a vertical discretization of 10 volumes, in the region A_2 which comprises the free surface of the mesh refining considered 40 volumes. In the region A_3 a 90 volumes vertical mesh is adopted. The region A presentes a mesh with 120 horizontal volumes, the region C contains a mesh with 100 horizontal volumes and the region where the converters (region B) has a mesh with 620 horizontal volumes.

In the region B, where the device OWC is located, as in the other region, quadrilaterals are used with 0.1 m side. These values are in accordance with the recommendations in Barreiro (2009) and Gomes et al. (2012).

3 FORMULATION WITH CONSTRUCTAL DESIGN

The Constructal Design is a method used to obtain optimal geometric forms of systems submitted to some kind of flow. According to this method, the flow is malleable and the geometry is deduced from a principle of maximizing overall performance. In addition, geometry must be subject to global constraints and varied according to its degrees of freedom (Bejan, 2000).

Constructal Design is also known as Design with Constructal Theory (DCT), where this theory explains how the generation of structures submitted to some kind of flow that are seen anywhere in nature can be based on a principle of access to the flow in time. This principle is the Constructal Law, which states that for a given system to persist over time (survive) its geometric configuration must evolve in order to facilitate the access of the currents of the flow through this system (Bejan and Lorente, 2008).

If an exhaustive search method is associated with the Constructal Design method, all geometries will be listed and tested, so it will be possible to determine optimal geometry that maximizes system performance in a given search range. In order to apply Constructal Design to the geometric optimization of a physical system, an objective function is required (an amount that will be optimized: mass flow rate, power, energy, etc.), degrees of freedom (geometric parameters that may vary during the optimization process) and geometric limitations of the problem or global constraints (parameters that are kept constant during the optimization process) (Bejan and Lorente, 2008).

The constraints to the problem are: the input volume of the first positioned device (V_{E1}), the input volume of the second device (V_{E2}), the total volume of the first device (V_{T1}) and the total volume of the second device (V_{T2}). They are described by:

$$V_{E1} = H_1 L_1 L \,. \tag{4}$$

$$V_{T1} = V_{E1} + H_4 l_1 L \tag{5}$$

$$V_{E2} = H_2 L_2 L \tag{6}$$

$$V_{T2} = V_{E2} + H_5 l_2 L \,. \tag{7}$$

The dimension L is held constant and equal to one, since the problem is considered two-dimensional. A criterion is adopted for the definition of the restriction of the chambre input volumes of the OWC device, it is considered the initial situation where the length of the device is equal to the length of the incidente wave (λ) and that the height of the devices is equal to the height of the incident wave (H) (Gomes, 2014). To determine the constraint of the total volumes of the device it is defined that V_E represent 70% of V_T. In this study it is V_{E1} = V_{E2} = 65.4 m³ e V_{T1} = V_{T2} = 93.4 m³.

In the presente work the degrees of freedom analyzed are: the ratio between height and length of the hydropneumatic chamber of the first device (H_1/L_1) and the ratio of the height and length of the hydropneumatic chamber of the second device (H_2/L_2). The degrees of freedom H_4/l_1 (ratio between height and length of the chimney of the first device), H_5/l_2 (ratio between height and length of the chimney of the second device) and H_6 (depth of immersion of the device) are kept constants and equal to $H_4/l_1 = H_5/l_2 = 3$ ($H_4 = H_5 = 9.17$m e $l_1 = l_2 =$

3.06m) e H_6 = 9.5m. Table 1 presents the dimensions tested in this work, which are determined by the equations that follow.

From the Eq. (4) it is possible to obtain equations that determine the dimensions for the length (L_1) and for the height (H_1) of the hydropneumatic chamber of the first OWC device, respectively:

$$L_1 = \left[\frac{V_{E1}}{\left(H_1 / L_1 \right) L} \right]^{1/2} \tag{8}$$

$$H_1 = L_1 \left(\frac{H_{1'}}{L_1} \right) \tag{9}$$

Table 1. Geometric variation of OWC devices.

H_1/L_1	H_2/L_2	H_1 [m]	L_1 [m]	H_2 [m]	L_2 [m]
0.0229	0.0229	1.2247	53.3989	1.2247	53.3989
0.0344	0.0344	1.5000	43.6000	1.5000	43.6000
0.0516	0.0516	1.8371	35.5993	1.8371	35.5993
0.0774	0.0774	2.2500	29.0667	2.2500	29.0667
0.1161	0.1161	2.7557	23.7328	2.7557	23.7328
0.1742	0.1742	3.3750	19.3778	3.3750	19.3778
0.2613	0.2613	4.1335	15.8219	4.1335	15.8219
0.3919	0.3919	5.0625	12.9185	5.0625	12.9185
0.5878	0.5878	6.2003	10.5479	6.2003	10.5479
0.8817	0.8817	7.5938	8.6123	7.5938	8.6123
1.3226	1.3226	9.3004	7.0320	9.3004	7.0320

From the Eq. (5) it is possible to obtain equations that determine the dimensions for the length (l_1) and for the height (H_4) of the chimney of the OWC chamber, respectively:

$$l_1 = \left[\frac{V_{T1} - V_{E1}}{\left(H_4 / l_1 \right) L} \right]^{1/2} \tag{10}$$

$$H_4 = l_1 \left(\frac{H_4}{l_1} \right) \tag{11}$$

From the Eq. (6) it is possible to obtain equations that determine the dimensions for the length (L_2) and height (H_2) of the second coupled device, respectively:

$$L_2 = \left[\frac{V_{E2}}{\left(H_2 / L_2 \right) L} \right]^{1/2} \tag{12}$$

$$H_2 = L_2 \left(\frac{H_2}{L_2} \right) \tag{13}$$

As in previous formulations, from the Eq. (7) it is possible to obtain equations that determine the dimensions for the length (l_2) and height (H_5) of the OWC chamber of the second device, respectively:

$$l_2 = \left[\frac{V_{T2} - V_{E2}}{\left(H_5 / l_2 \right) L} \right]^{1/2} \tag{14}$$

$$H_5 = l_2 \left(\frac{H_5}{l_2} \right) \tag{15}$$

The objective functions to be considered throughout this work are the average RMS of the following magnitudes: mass flow, pressure and hydropneumatic power.

4 MATHEMATICAL AND NUMERICAL MODEL

4.1 Volume of Fluid Model

The model used in the simulations was the Volume of Fluid (VOF) (Hirt e Nichols, 1981). The VOF methodology consists of reproducing the interaction between the fluids involved in the numerical simulation of the OWC device, which are air and water in this case. In this formulation, all phases are defined and the volume occupied by one phase can not be occupied by another phase. Thus, to represent the phases contained in each control volume, the concept of volume fraction (α). The volumetric fraction is defined as being a continuous variable in space and time, which repersents the presence of a fluid within the control volume.

Consequently, it is necessary that the sum of all phases in each cell is always equal to one. In the numerical model presented in this work, only two phases are considered: water and air. Therefore, cell with α_{water} between 0 and 1 contains the interface between water and air (in this case $\alpha_{air} = 1 - \alpha_{water}$). The ones that $\alpha_{water} = 0$ they are without water and complete with air ($\alpha_{air} = 1$); and, in turn, those that present $\alpha_{air} = 0$ they are full of water ($\alpha_{water} = 1$).

In addition, when the VOF method is empleyed, only a single set of equations, formed by the momentum and continuity equations, is applied to all componentes fluids of the flow. Then, the volume fraction of each fluid in each cell (control volume) is considered throughout the computational domain through the transport for the volumetric fraction. Thus, the model is composed by the equation of continuity:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{16}$$

the equation of the volumetric fraction

$$\frac{\partial(\alpha)}{\partial t} + \nabla \cdot (\alpha \vec{v}) = 0 \tag{17}$$

and the momentum equations

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot \left(\mu \bar{\bar{\tau}}\right) + \rho \vec{g} \tag{18}$$

where: ρ is the specific mass of the fluid (kg/m³). t it's the time (s), $\vec{v}$ is the velocity vector of the flow (m/s), p is the static pressure (N/m²), μ is the viscosity (kg/m·s), $\bar{\bar{\tau}}$ it is the rensor of tensions (N/m²) and $\vec{g}$ is the acceleration of gravity (m/s²).

Since the conservation equations of mass and momentum are solved for the air and water mixture, it is necessary to calculate the mean values for the specific mass and the viscosity, respectively (Srinivasan et al., 2011):

$$\rho = \alpha_{water}\rho_{water} + \alpha_{air}\rho_{air} \tag{19}$$

$$\mu = \alpha_{water}\mu_{water} + \alpha_{air}\mu_{air} \tag{20}$$

4.2 Numerical Model

For the solution of the equations of mass conservation and momentum, a commercial code based on the Finite Volume Method - FVM. For all simulations, the advection scheme was considered upwind for the treatment of the advective terms, while the spatial discretization for the pressure was performed through the PRESTO method and the GEO-RECONSTRUCTION method for the volumetric fraction.

The PISO method was used for pressure-velocity coupling. For the solution of the system of equations generated after the discretization, the Gauss Seidel method with algebraic multigrid is used. Further details on the numerical methodology can be obtained in Patankar, (1980) and Versteeg and Malalasekera, (2007).

All solutions were performed using a computer with a processor Intel Xeon® with 32 Gb of RAM, using parallel processing. The processing time of each simulation is approximately 8h.

5 RESULTS AND DISCUSSIONS

5.1 Problem Verification

The verification of the present solution with the VOF model consists of generating the wave in a wave tank and observing its variation in the free surface of the water, that is, its amplitude, to later compare with the analytical equation for the free surface variation of the water at a given point in the wave tank.

The comparison of the numerical solution is performed with the analytical solution presented in Dean and Dalrymple (1991), which defines the free surface by:

$$\eta(x,t) = A\cos(kx-\omega t) + \frac{A^2 k \cosh(kh)}{4senh^3(kh)}\left[2+\cosh(2kh)\cos 2(kx-\omega t)\right] \quad (21)$$

where: A is the amplitude of the wave (m), given by $H/2$, x it's the position (m), t is the variation of time (s), k and ω are respectively the wave number (m^{-1}) and the wave frequency (rad/s).

Figure 4 shows the graphical comparison between the free surface elevation obtained analytically and numerically, at the position x = 48 m over 225 s. The relative difference between the numerical and analytical solutions was measured instantaneously, and the mean differences were 6.41 %.

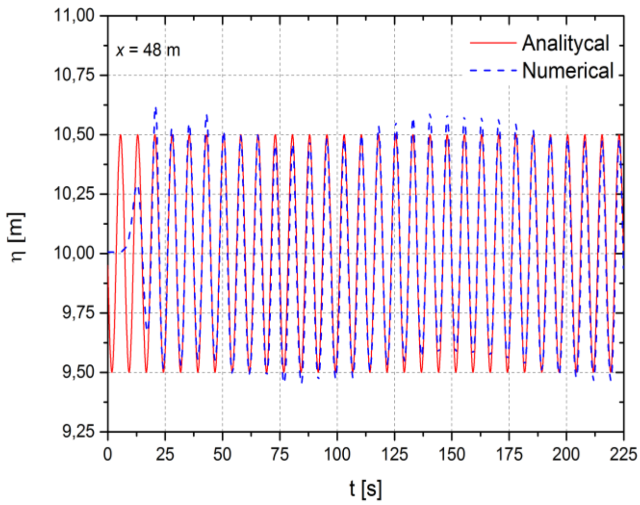

Figure 4. Free surface elevation comparison in x =48 m.

Due to the use of the numerical beach and the contour condition of the hydrostatic profile, it is possible to have a longer simulation time. Figure 5 shows the elevation of the free surface at the position x = 300 m, which is beyond the numerical beach, demonstrating its effectiveness, since the gradual decrease of the wave elevation is observed, to the point of becoming practivally negligible and thus do not cause the effect of reflection in the simulations of the devices.

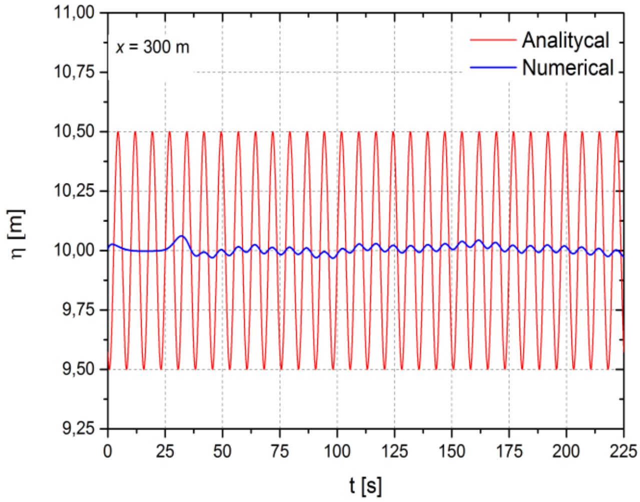

Figure 5. Free surface elevation comparison in x = 300 m.

5.2 Case Study

In this work, the proposal is to analyze numerically the effect of the geometric variation of the hydropneumatic chambers of the couple OWC. Eleven geometric configurations were evaluated as can be seen in Tab. 1.

For the simulations carried out it is considered a T = 7.5 s, λ = 65.4 m and H = 1.0 m. To calculate the mean values, the mean RMS (Root Mean Squad) is used (Marjani et al., 2006):

$$X = \sqrt{\frac{1}{T}\int_0^T x^2 dt} \tag{22}$$

where: X is the variable of interest (mass flow rate, pressure and others).

In Fig. 6 it is possible to observe the variation of the pressure inside the hydropneumatic chamber. As the magnitude of both degrees of freedom (H_1/L_1 e H_2/L_2) increases the average RMS of the pressure tends to decrease. On average a difference of about 2,7 kPa is observed and the magnitudes suffer smooth decrease until values of approximately 1 kPa for the highest ratios of H_1/L_1 and H_2/L_2. However, for the mass flow rate (in the OWC chimney), it is possible to note in Fig. 7, an intermediate magnitude of H_1/L_1 and H_2/L_2 in which the performance is better in relation to the other evaluated cases. Mean differences are obtained between the best and the wost performance of about 30 kg/s.

From the pressure and the mass flow rate, it is possible to calculate the hydropneumatic power through the following expression (Dizadji and Sajadian, 2011):

$$P_{hyd} = \left(P_{ar} + \frac{\rho_{ar} v_{ar}^2}{2} \right) \frac{\dot{m}}{\rho_{ar}} \tag{23}$$

where: P_{ar} is the static pressure in the chimney of the OWC device (Pa), ρ_{ar} is the density of air (kg/m³), $\dot{m}$ is the mass flow rate across the chimney (kg/s), v_{ar} is the velocity of air in the chimney (m/s) given by:

$$v_{ar} = \frac{\dot{m}}{A\rho_{ar}} \tag{24}$$

where: *A* representes a cross sectional área of the chimney (m²).

The expressions that determine the static pressure, total pressure, mass flow and incident wave power can be found in Gomes (2014).

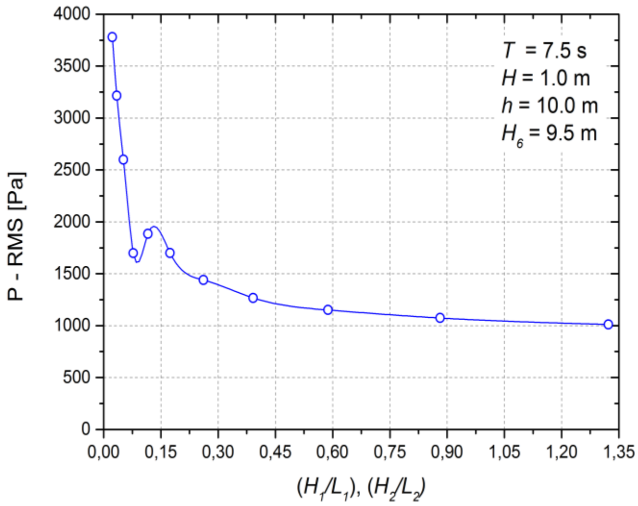

Figure 6. Average RMS, considering the variation of H_1/L_1 and H_2/L_2, for pressure.

Referring to Fig. 8, it can be seen that for $H_1/L_1 = H_2/L_2 = 0.0344$ the highest RMS hydropneumatic power is achieved. In Tab. 1 we have for these values of degrees of freedom the relations: $H_1 = H_2 = 1.50$ m and $L_1 = L_2 = 53.39$ m. Through these values, it is possible to relate the values found for the degrees of freedom analyzed with the height (*H*) of the wave and the wavelength (λ). Thus, it can be concluded that $L_1 = L_2 = 0.82\ \lambda$ and $H_1 = H_2 = 1.5\ H$. In this way, it is possible to verify the following theoretical relation for the optimal case:

$$\left(\frac{H_1}{L_1} \right)_O = \left(\frac{H_2}{L_2} \right)_O \cong 1{,}83 \frac{H}{\lambda} \tag{25}$$

The recommendations achieved here can be compared with the results already presented in the literature for just one device. Gomes et al. (2016) recommended that $L \sim 0.66\lambda$ and $H_1 \sim 1.5H$. The obtained results are in agreement with those of the mentioned author, indicating that an universal geometric relation in this kind of problem can exist, even for two coupled devices.

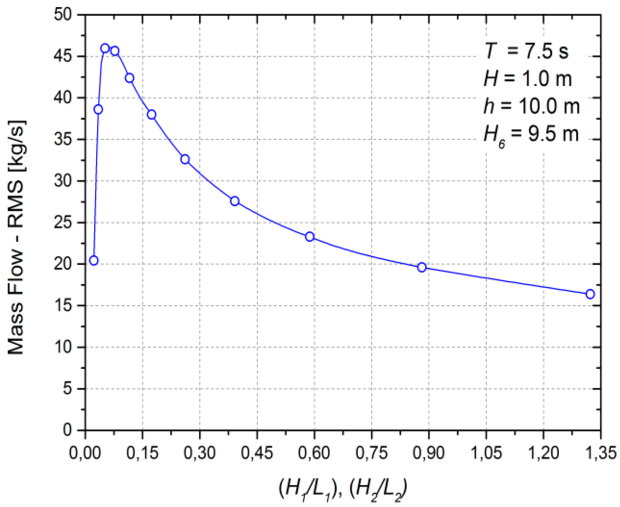

Figure 7. Average RMS, considering the variation of H_1/L_1 and H_2/L_2, for mass flow rate.

Since hydropneumatic, power is a function of mass flow rate and pressure, optimizing the OWC device is to find a geometric arrangement that allows the maximization of mass flow rate and pressure.

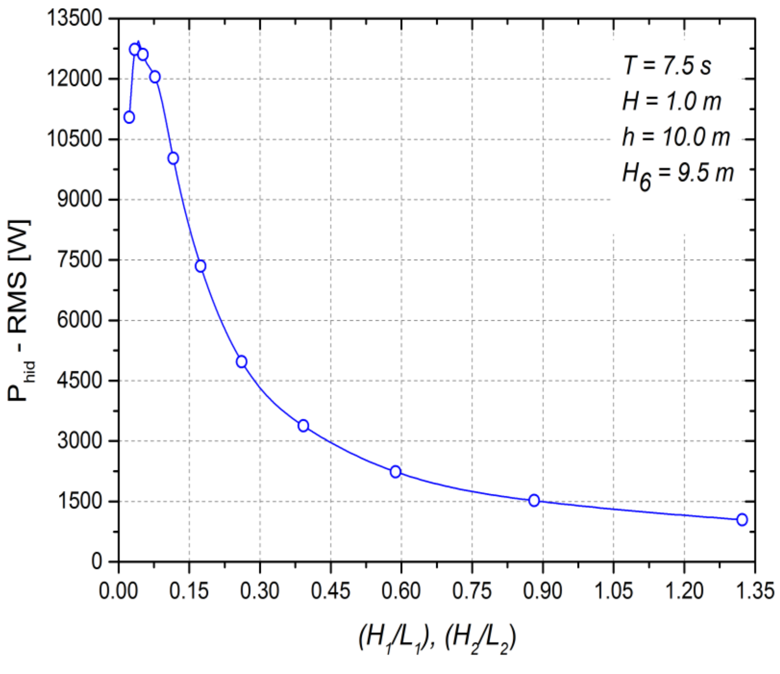

Figure 8. Average RMS for hydropneumatic power for the sum of the powers of the two devices.

Figure 9 and 10 shows the transient behavior of the pressure and mass flow rate in cases of better (H_1/L_1 = H_2/L_2 = 0.0344) and worse (H_1/L_1 = H_2/L_2 = 1.3226) performance. The

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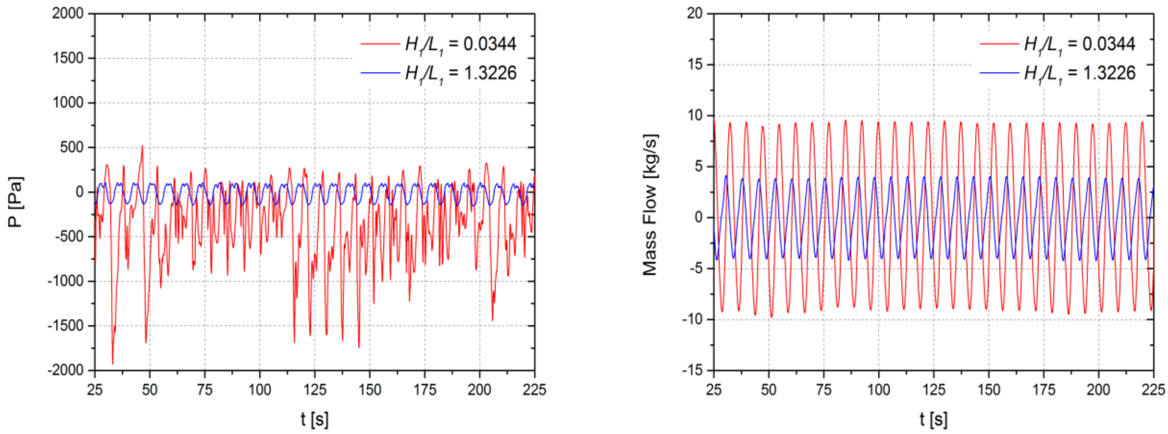
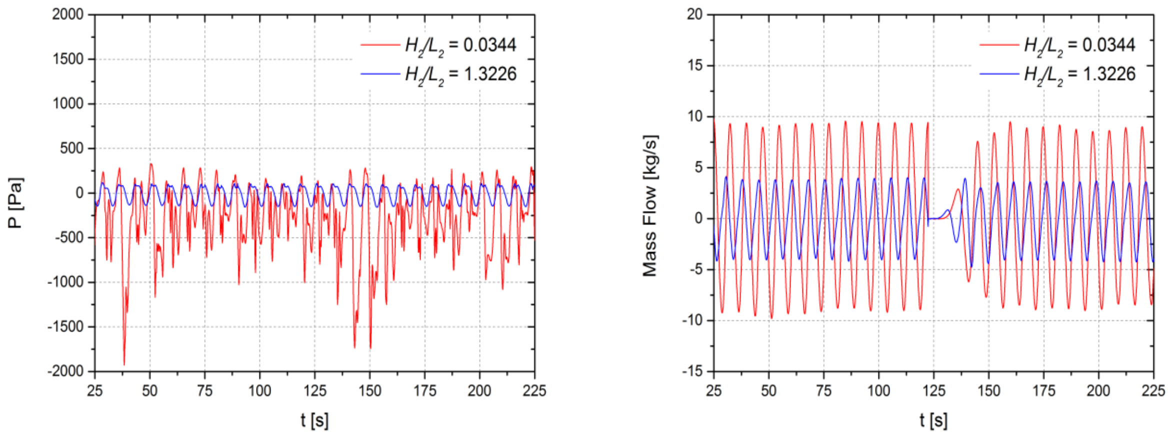
P.O. Faria, R.H. Lopez, L.F.F. Miguel, W.J.S. Gomes, M. Noronha (Editores), ABMEC, Florianópolis, SC, Brazil, November 5-8, 2017.

cases presented in the Fig. 9 (a) and Fig. 10 (a), pressure in the chambers of first and second devices, respectively, shows that the large pressure magnitudes occur in the decompression phase, reaching instantaneous differences of more than 1 kPa.



(a) (b)

Figure 9. Transient behavior for the case with H_1/L_1 = 0.0344 and H_2/L_2 = 1.3226 for the following variables: (a) pressure in the first device, (b) mass flow rate in the first device.



(a) (b)

Figure 10. Transient behavior for the case with H_1/L_1 = 0.0344 and H_2/L_2 = 1.3226 for the following variables: (a) pressure in the second device, (b) mass flow rate in the second device.

In Fig. 9 (b) and Fig. 10 (b) the values of the mass flow rate are shown for the first and second devices, respectively, where a symmetry can be noted in the results for the mass flow rate of the chimney of the first device, this aspect is important for the proper functioning turbine Wells. Figure 10 (b) shows an abrupt decrease in mass flow in the time interval of 125 and 130 s. One possible explanation for this phenomenon lies in the low distance between the devices and this graph represents the results obtained for the second OWC chamber. The influence of the first device over the wave flow characterized the low airflow in the chimney of the second device.

6 CONCLUSIONS

In the presente work, a numerical study was carried out with the objective of determining an optimum geometry for two coupled Oscillating Water Colum (OWC) wave energy converters (WEC). The differential of this work consisted in the use of two coupled devices, the employment of hydrostatic profile boundary condition and the numerical beach methodology, to decrease the reflection of the waves on the devices. Constructal Design method was used to determine the search space of geometries which will be evaluated, allowing to define which geometric arrangement led to the best performance of the two devices. Thus, the main objective was to obtain a theorical recommendation on the values of degrees of freedom H_1/L_1 (ratio between the height and length of the hydropneumatic chambre of the first device) and H_2/L_2 (ratio between the height and length of the hydropneumatic chambre of the second device) which maximizes the hydropneumatic power values for OWC devices when subjected to regular and real scale wave incidence with period of 7.5 s and incident wavelength equal to 65.4 m.

A numerical model verification study was also performed. Considering the generation of the wave, the numerical solution obtained for free surface elevation was compared with the analytical solution indicating the efficacy of the numerical model.

The best performance, the maximum RMS value for hydropneumatic power in the case of OWC chambers was obtained when $(H_1/L_1)_o = (H_2/L_2)_o = 0.0344$, $H_4/l_1 = H_5/l_2 = 3$ and $H_6 = 9.5$ m, being about twelve times better than the worst case. This difference demonstrated the importance of geometric evaluation in renewable sources devices.

The applicability of the Constructal Design method is also shown, since it is quite evident that simple geometric variations results in significant improvements on the performance of the OWC converter. The results are very promising, since they provide initial theoretical recommendations for coupled converters in wave tanks, making feasible future studies. In addition, according to the adopted Constructal formulation, it is possible to relate the dimensions of the OWC device with the characteristics of the incident waves. So, for known wave climate characteristics it is possible to estimate the most properly design for devices in such way to improve their performance.

For future work, it is interesting to evaluate the other degrees of freedom, which were constants in this research, and to analyze the use of irregular waves (wave spectrum), for the same geometries, comparing them.

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