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NUMERICAL ANALYSIS OF THE OSCILLATING WATER COLUMN (OWC) WAVE ENERGY CONVERTER (WEC) CONSIDERING DIFFERENT INCIDENT WAVE HEIGHT

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ABSTRACT

The ocean wave energy conversion into electricity has been increasingly researched in the last years. There are several proposed converters, among them the Oscillating Water Column (OWC) device has been widely studied. The present paper presents a two-dimensional numerical investigation about the fluid dynamic behavior of an OWC Wave Energy Converter (WEC) into electrical energy. The main goal of this work was to numerically analyze the optimized geometric shape obtained in previous work under incident waves with different heights. To do so, the OWC geometric shape was kept constant while the incident wave height was varied. For the numerical solution it was used the Computational Fluid Dynamic (CFD) commercial code FLUENT®, based on the Finite Volume Method (FVM). The multiphasic Volume of Fluid (VOF) model was applied to tackle with the water-air interaction. The computational domain is represented by the OWC device coupled with the wave tank. This work allowed to check the influence of the incident wave height on the hydropneumatic power and the amplification factor of the OWC converter. It was possible to identify that the amplification factor increases as the wave period increases, thereby improving the OWC performance. It is worth to highlight that in the real phenomenon the incident waves on the OWC device have periods, lengths and height variables.

1. INTRODUCTION

Currently one of the greatest challenges is to supply the world energetic demand. In this context, there are several discussions about generation and consumption of electrical energy. One of the main variables to define the development indices of a country is the population's access facility to the infrastructure services, as basic sanitation, transport, telecommunications and energy (ANEEL, 2008).

The global energy consumption in 2011 was approximately 1.6×10^{7} MW, which is about 60 % higher than the 1980 energy consumption (Zabihian and Fung, 2011). Moreover, the main source of energy to reach this demand is based on the consumption of fossil fuels.

Very large energy fluxes can occur in deep water sea waves. The power in the wave is proportional to the square of the amplitude and to the period of the motion. Therefore, the long period (~10 s) and large amplitude (~2 m) waves represent a considerable interest for power generation, with energy fluxes commonly averaging between 50 and 70 kW/m width of oncoming wave (Twidell and Weir, 2006).

Based on these aspects, recently the countries have been invested in the explanation of new energy sources, especially in so-called renewable energy sources. Among them, the conversion of ocean wave energy into electrical energy has been highlighted. The energy contained in oceans can have different origins, generating different classifications. No doubt, the most relevant are the ocean tidal energy (caused by interaction between the gravitational fields of sun and moon), the ocean thermal energy (direct consequence of solar radiation incidence), the ocean currents energy (originated in the gradients of temperature and salinity and tidal action) and, finally, the ocean wave energy (which is result of the wind effect over the ocean surface) (Cruz e Sarmento, 2004).

The criterion usually adopted to classify the Wave Energy Converter (WEC) devices is related with its installation distance from the coast. In accordance with this classification, the WECs are grouped in: onshore (integrated with coastal structures, facilitating the access), near-shore (devices located in depths of 8 to 20 m) and offshore (installation depths upper than 25 m) (Cruz e Sarmento, 2004).

Another possible classification is associated with the principle adopted to transform the wave energy into electricity, existing three principal groups: Oscillating Water Column (OWC), Wave Activated Bodies (WAB) and Overtopping Devices (OTD). This classification does not end the possibility of other operating principle to be able for convert the ocean wave energy, being an example the submerged plate device (Carter, 2005).

The present work presents a 2D numerical study about the operating principle of an OWC-WEC, being the main goal to analyze its fluid dynamic behavior under the incidence of ocean waves with different heights, while the period and the length of the waves were kept constants. To do so, the OWC shape was defined as the optimized geometry obtained from the study of Gomes et al. (2013).

The computational domain (OWC coupled to a wave tank) was created and discretized in GAMBIT® software, while the numerical simulations were carried out by means a computational modeling implemented in the Computational Fluid Dynamic (CFD) commercial software FLUENT®, which is based on the Finite Volume Method (FVM) (FLUENT, 2007; Versteeg and Malalasekera, 2007). The multiphase Volume of Fluid (VOF) model was employed for the treatment of water-air interaction, as already performed by: Gomes (2010), Horko (2007), Liu et al. (2008a), Liu et al. (2008b), Liu et al. (2011) and Ramalhais (2011). The wave generation was promoted by the imposition of the vertical and horizontal velocity wave components as boundary condition.

It is important to mention, that the OWC geometric optimization performed in Gomes et al. (2013) was conducted employing the Constructal Design method, which is based on the Constructal Theory developed by Adrian Bejan (Bejan, 2000; Bejan and Lorente, 2008; Bejan and Zane, 2012; Bejan and Lorente, 2013). The Constructal theory explain deterministically how the generation of shape in flow structures of nature (river basins, lungs, atmospheric circulation, animal shapes, vascularized tissues, etc) is based on an evolutionary principle of flow access in time. That principle is the Constructal law: for a flow system to persist in time (to survive), it must evolve in such way that it provides easier and easier access to the currents that flow through it (Bejan and Lorente, 2008).

2. OSCILLATING WATER COLUMN (OWC)

The OWC devices are, basically, hollow structures partially submerged, with an opening to the sea below the water free surface, as can be seen in Fig. 1. In accordance with Cruz and Sarmento (2004), the electricity generation process has two stages: when the wave reaches the structure, its internal air is forced to pass through a turbine placed in its chimney, as a direct consequence of the augmentation of pressure inside the hydropneumatic chamber; and when the wave returns to the ocean, the air again passes by the turbine, but now being sucked from the external atmosphere, due to the chamber internal pressure decreasing. So, to use these opposite air movements usually the Wells turbine is employed, which has the property of maintaining the rotation direction irrespective of the flow direction. The set turbine/generator is the responsible for the electrical energy production.

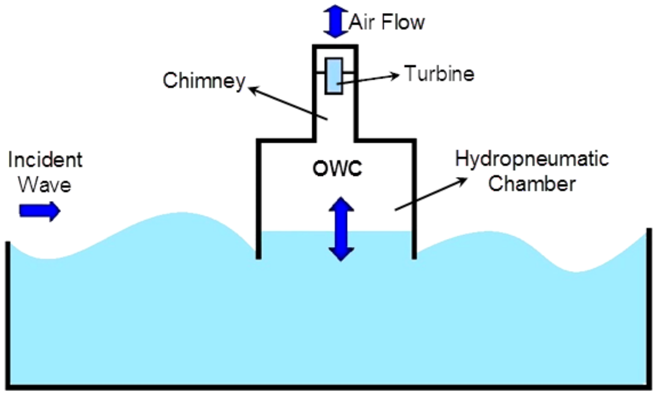


Figure 1. Oscillating Water Column (OWC) system.

3. COMPUTATIONAL DOMAIN

Based on the of the period (T), height (H) and propagation depth (h) of the wave, it is possible to define the length (L_T) and height (H_T) of the wave tank (Fig. 2). There is no a general rule to establish these dimensions, however some aspects must be taken into account. The wave propagation depth is adopted as the wave tank mean water level, i.e., the wave tank water depth (h). For the wave tank length it is necessary to consider the wave length, being recommended that the wave tank length has at least five times the wave length. Thereby, a numerical simulation without effects of wave reflection can be performed, during a satisfactory time interval and without an unnecessarily increase of the computational domain length (which would cause an increase in the computational effort and in the processing time). Regarding the wave tank height, the propagation depth and the height of the wave must be considered. So, it is possible to define the wave tank height as the propagation depth plus three times the wave height.

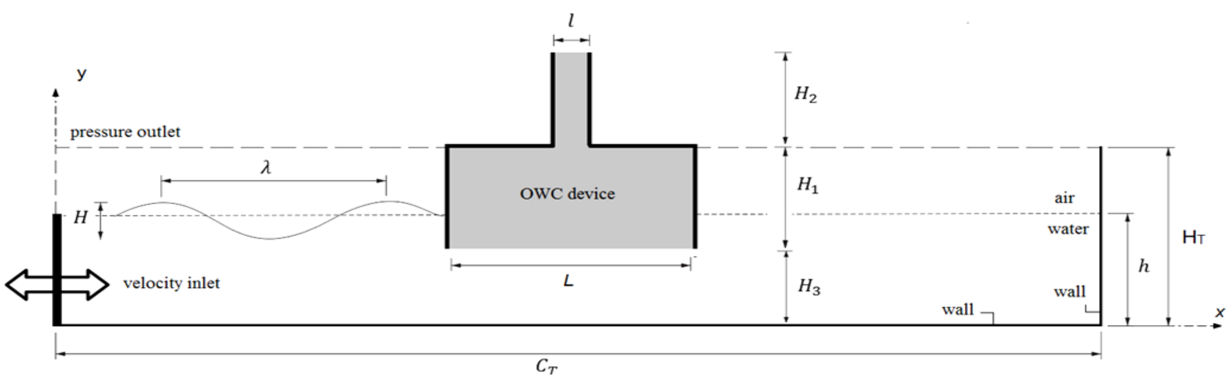


Figure 2. Schematic representation of the computational domain.

With respect to the tank height it is necessary take into account the water depth (h) and the wave height (H). It is suggested that the tank height must be equal to the value of water depth plus three times the value of wave height. Therefore all the characteristic dimensions of the problem are presented in Tab. 1.

Table 1. Characteristic dimensions of the incident waves and the wave tank.

Characteristic Dimensions	Values
Wave period (T)	5.0 s
Wave height (H)	variable
Wave length (λ)	37.6 m
Wave propagation depth (h)	10.0 m
Wave tank length (L_T)	188.0 m
Wave tank height (H_T)	13.0 m

Besides, as already mentioned, the hydropneumatic chamber length (L) and height (H_1), chimney outlet length (l) and its height (H_2), and the submergence depth (H_3) of the device were defined in agreement with the best OWC shape proposed by Gomes *et al*. (2013), being these values given by: L = 16.7097 m, H_1 = 2.2501 m, l = 2.3176 m, H_2 = 6.9529 m and H_3=9.5 m.

3.1. Boundary Conditions

As can be observed in Fig. 2, the wave maker is placed in the left side of the wave tank. For the regular wave generation it was employed the called Function Methodology (Gomes *et al*., 2009). This methodology consists of applying the horizontal (u) and vertical (w) components of wave velocity as boundary conditions (prescribed velocity inlet) of the computational model, by means an User Defined Function (UDF) in the FLUENT® software. These velocity components vary as functions of space and time and are based on the Stokes 2nd order theory. So these wave velocity components are given by (Dean and Dalrymple, 1991):

$$u = Agk\frac{\cosh(kz+kh)}{\omega\cosh(kh)}\cos(kx-\omega t)+A^2\omega k\frac{\cosh 2k(k+z)}{sen^4(kh)}\cos 2(kx-\omega t) \tag{1}$$

$$w = Agk\frac{senh\,(kz+kh)}{\omega senh\,(kh)}sen(kx-\omega t)+A^2\omega k\frac{senh\;2k(k+z)}{\cos^4(kh)}sen\;2(kx-\omega t) \tag{2}$$

where: H is the wave height (m); g is the gravitational acceleration (m/s^2); λ is the wave length (m); k is the wave number, given by $k = 2\,\pi/\lambda$ (m^{-1}); h is the depth (m); T is the wave period (s); ω is the frequency, given by $\omega = 2\pi/T$ (rad/s); x is the streamwise coordinate (m); t is the time (s); and z is the normal coordinate (m).

Concerning the other boundary conditions, in the upper surfaces of wave tank and chimney and above the wave maker (dashed line in Fig. 2) it was considered the atmospheric pressure (pressure outlet). In the bottom and right side of computational domain a no slip and impermeability conditions (wall) were adopted.

3.2 Mesh

In all numerical simulations the mesh follows a pattern where a special refinement is employed in some specific regions of the computational domain. As can be observed in Fig. 3, in the vertical direction the wave tank is divided in three regions nominated A, B and C. In the water free surface region (B region) it is adopted a refinement with 40 volumes in z direction (interval size equivalent to H/20) and with 250 volumes in the x direction (interval size equivalent to λ/50). Furthermore 10 and 90 volumes are used in z direction for the spatial discretization of A and C regions, respectively, in accordance with Barreiro (2009) and Gomes *et al*. (2012). To complete the computational domain mesh, squares with 0.1 m were used in the OWC discretization (region E).

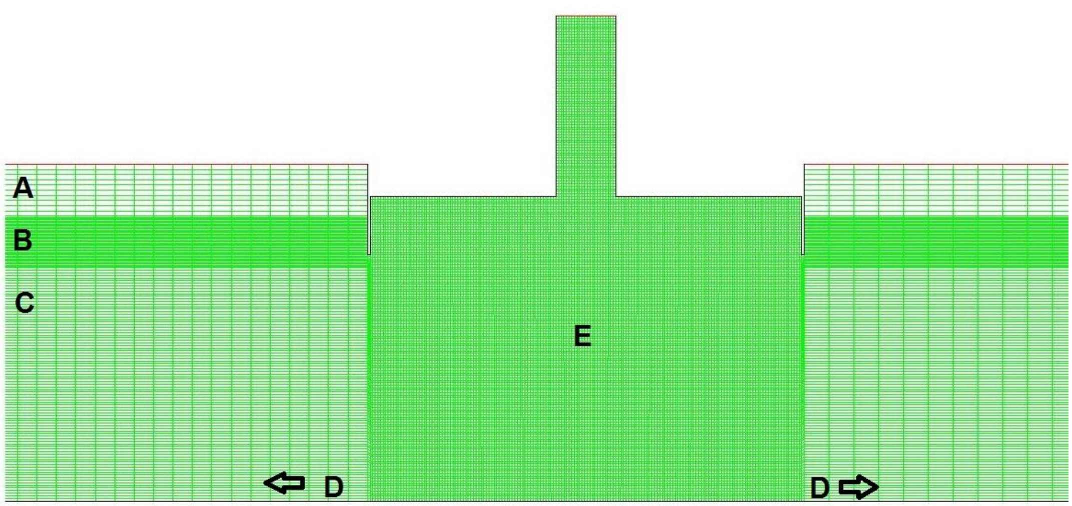


Figure 3. A, B ,C, D, and E regions used in the computational domain discretization.

4. MATHEMATICAL AND NUMERICAL MODELS

The analysis consists in finding the solution of a water-air mixture flow. For this, the conservation equations of mass, momentum and one equation for the transport of volumetric fraction are solved with the Finite Volume Method (FVM) (Patankar, 1980; Versteeg *et al*., 2007).

The conservation equation of mass for an isothermal, laminar and incompressible flow with two phases (air and water) is the following:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{v} \right) = 0 \tag{3}$$

where ρ is the mixture density (kg/m³) and $\vec{v}$ is the velocity vector of the flow (m/s).

The conservation equation of momentum is:

$$\frac{\partial}{\partial t}\left(\rho \vec{v} \right) + \nabla \left(\rho \vec{v}\vec{v} \right) = -\nabla p + \nabla \left(\overline{\overline{\tau}} \right) + \rho \vec{g} + \vec{F} \tag{4}$$

where p is the pressure (N/m²), $\rho \vec{g}$ and $\vec{F}$ are buoyancy and external body forces (N/m³), respectively, and $\overline{\overline{\tau}}$ is the deformation rate tensor (N/m²), which, for a Newtonian fluid, is given by:

$$\overline{\overline{\tau}} = \mu \left[\left(\nabla \vec{v} + \nabla \vec{v}^{T} \right) - \frac{2}{3} \nabla \cdot \vec{v} I \right] \tag{5}$$

where μ is the dynamic viscosity (kg/m·s), I is a unitary tensor and second right-hand-side term is concerned with the deviatoric tension (N/m²).

In order to deal with the air and water mixture flow and to evaluate its interaction with the device, the Volume of Fluid (VOF) method is employed. The VOF is a multiphase model used for fluid flows with two or more phases. In this model, the phases are immiscible, that is, the volume of one phase cannot be occupied by another phase (Hirt and Nichols, 1981; LV *et al*., 2011).

In the simulations of this study, two different phases are considered: air and water. Therefore, the volume fraction concept (α_q) is used to represent both phases inside one control volume. In this model, the volume fractions are assumed to be continuous in space and time and the sum of volume fractions, inside a control volume, is always unitary, i.e., $0 \leq \alpha_q \leq 1$. Consequently, if $\alpha_{water} = 0$ the cell is empty of water and full of air ($\alpha_{air} = 1$) and if the fluid has a mixture of air and water, one phase is the complement of the other, that is $\alpha_{air} = 1 - \alpha_{water}$. Thus, an additional transport equation for one of the volume fractions is required:

$$\frac{\partial \left(\rho \alpha_q \right)}{\partial t} + \nabla \cdot \left(\rho \alpha_q \vec{v} \right) = 0 \tag{6}$$

It is worth mentioning that the conservation equations of mass and momentum are solved for the mixture. Therefore, it is necessary to obtain values of density and viscosity for the mixture, which can be written by:

$$\rho = \alpha_{water} \rho_{water} + \alpha_{air} \rho_{air} \tag{7}$$

$$\mu = \alpha_{water} \mu_{water} + \alpha_{air} \mu_{air} \tag{8}$$

Computational modeling using the VOF method has been largely employed to numerically simulate the WECs. Validations and verifications of these methodologies can be found in Horko (2007), Liu *et al*. (2008a), Liu *et al*. (2008b), Gomes *et al*. (2009), Gomes (2010), Ramalhais (2011), Liu *et al*. (2011) and Gomes *et al*. (2012).

In the present work, the solver is pressure-based and all simulations were performed by upwind and PRESTO for spatial discretizations of momentum and pressure, respectively. The velocity-pressure coupling is performed by the PISO method, while the GEO-RECONSTRUCTION method is employed to tackle with the volumetric fraction. Moreover, under-relaxation factors of 0.3 and 0.7 are imposed for the conservation equations of continuity and momentum, respectively. All numerical simulations were carried out in a computer AMD Athlon 2 Core with 3.0Gb of RAM. To reduce the simulation time the parallel processing technique was adopted (FLUENT, 2006).

5. RESULTS AND DISCUSSION

The computational model verification was performed comparing the transient water free surface elevation numerically obtained, in a specific position, with the respective analytical solution, which is defined by (Dean and Darlymple, 1991):

$$\eta = A\cos(kx-\omega t) + \frac{A^2 k \cosh(kh)}{4\,senh^3(kh)}\left[2+\cosh(2kh)\right]\cos 2(kx-\omega t) \tag{9}$$

where: A is the wave amplitude (m), given by $H/2$.

In Fig. 4 one can observe the qualitative behavior of the wave propagation, showing a good agreement between the numerical and analytical solutions. During the interval time of 15 s $\leq t \leq$ 30 s, after the stabilization of the numerical wave, the maximal difference encountered was 5.00 %, verifying the computational model for the wave generation.

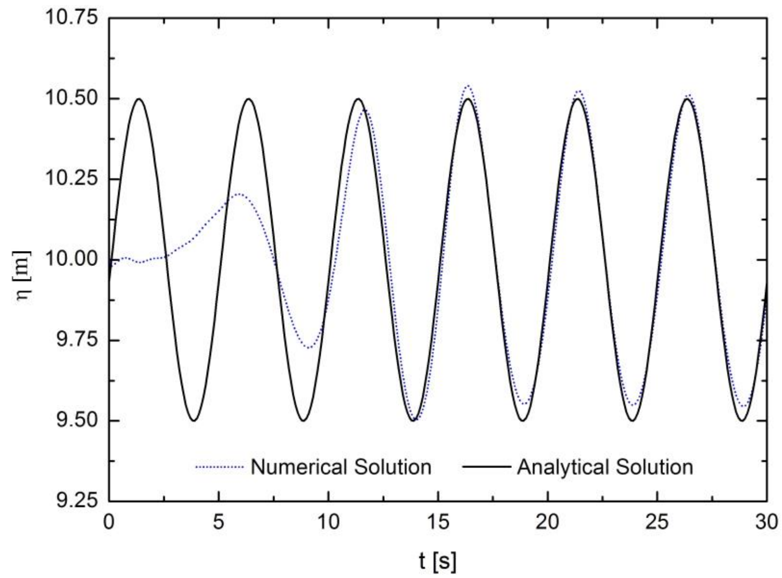


Figure 4. Water free surface elevation in x = 50 m with time step of T/500.

Two variables were evaluated in order to evaluate the fluid dynamic behavior of the OWC: the amplification factor and the hydropneumatic power. So, using the verified computational model eleven numerical simulations were developed aiming to analyze the influence of incident waves with different heights (H = 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25, 2.50, 2.75, and 3.0 m) on these variables.

The amplification factor (Hm/H) is defined by the ratio between the average height of the water free surface inside the OWC hydropneumatic chamber (Hm) and the height of the incident wave (H). In a practical point of view, the amplification factor allows to quantify the piston effect caused by the incidence of the waves over the OWC WEC (Ramalhais, 2011).

In turn, the available hydropneumatic power in an OWC WEC can be defined as (Dizadji and Sajadian, 2011):

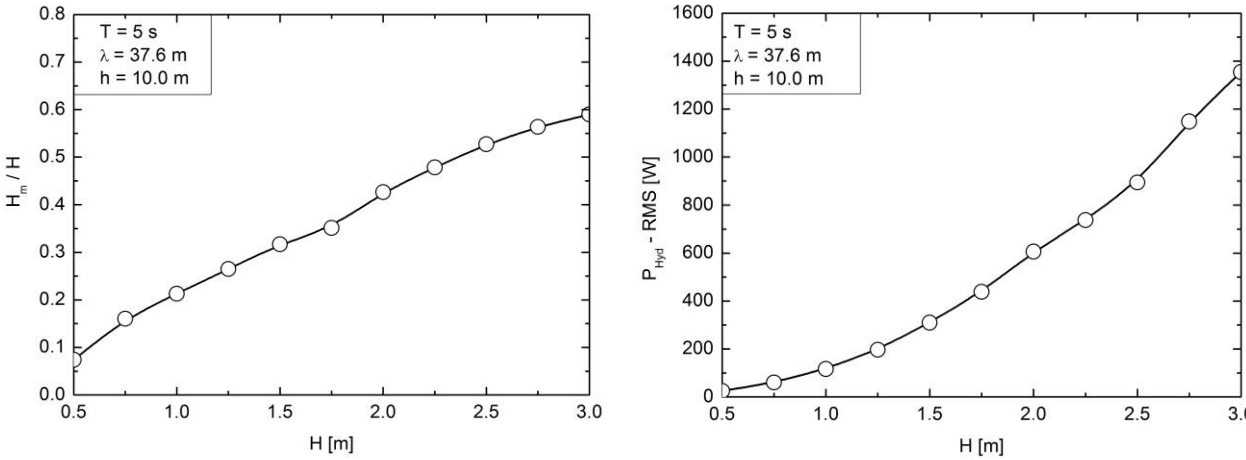
$$P_{Hyd} = \left(P_{air} + \frac{\rho_{air}\left(\dot{m}/A_c\rho_{air}\right)^2}{2} \right)\frac{\dot{m}}{\rho_{air}} \tag{10}$$

where: P_{air} is the static pressure in the OWC chimney (Pa), ρ_{air} is the air density (kg/m^3), $\dot{m}$ is the air mass flow rate crossing the chimney (kg/s), and A_c is the cross sectional area of the chimney.

It is important to highlight that the amplification factor and the available hydropneumatic power were calculated as average values. To do so, the Root Mean Square (RSM) statistical technique which is indicated for varying quantities was adopted, being given by (Marjani *et al*., 2006):

$$X = \sqrt{\frac{1}{T}\int_0^T x^2\, dt} \tag{11}$$

In Fig. 5(a) it is possible to observe how the amplification factor is affected by the variation of the height of the incident waves, while in Fig. 5(b) it is showed the influence suffered by the available hydropneumatic power of the OWC in virtue of the different heights of simulated waves.



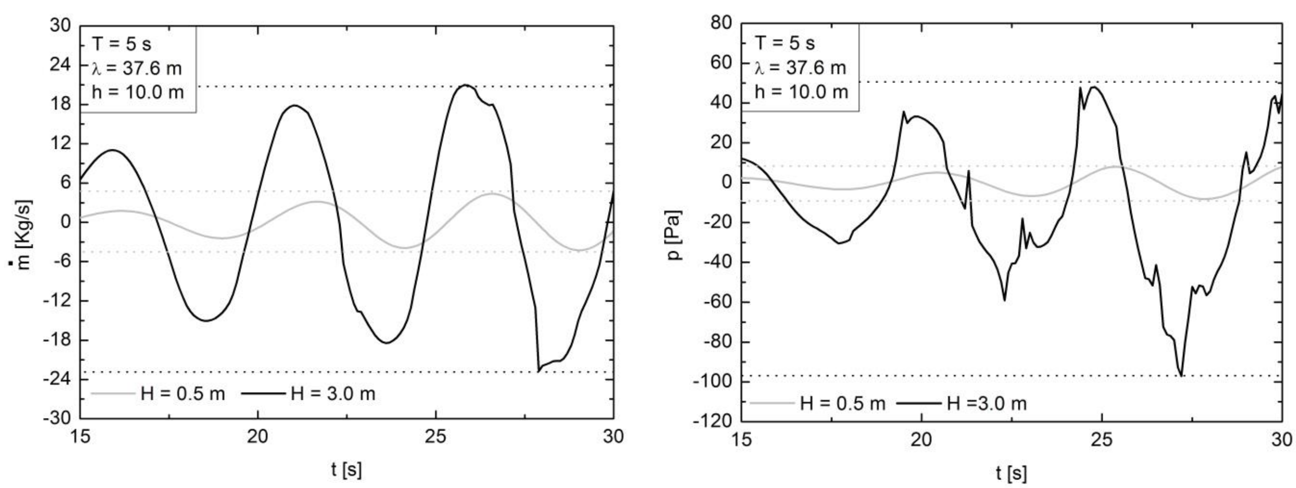
(a) (b)

Figure 5. Influence of the *H* variation on the: (a) amplification factor, and (b) RMS average hidropneumatic power.

From Fig. 5 one can note that the increase of the incident wave heights promotes an improvement of the amplification factor, as well as, of the hydropneumatic power. In addition, one can observe that there is an almost linear relationship between the wave height variation and the amplification factor (Fig.5(a)). The same trend it is observed between the wave height variation and the respective available OWC power (Fig. 5(b)).

It is possible to affirm that when the amplification factor increases the water oscillation of the column inside the hydropneumatic chamber of the OWC also increases, causing an augmentation of the pressure and of the mass flow rate of air. Hence, considering Eq. (10), is explained why the available power of the OWC is improved with the incident wave height increase.

This fact can be verified in Fig. 6(a), where the transient behavior of the air mass flow rate of the OWC is presented, and in Fig. 6(b), where the transient variation of the pressure inside the OWC hydropneumatic chamber is showed, for two specific incident waves: H = 0.50 m and H = 3.00 m.



(a) (b)

Figure 6. OWC transient behavior for: (a) air mass flow rate, and (b) hydropneumatic chamber pressure.

Figure 6 makes clear that the increase of the *H* value promotes a significant increase both in OWC air mass flow rate as in the pressure inside the OWC chamber. Therefore, these results are relevant for the optimized design of the turbine, which is a fundamental part of the process to convert the ocean wave energy into electrical energy.

6. CONCLUSIONS

In the present work it was performed a numerical study aiming to evaluate the influence of the height of the incident waves in the amplification factor and in the hydropneumatic chamber of an OWC WEC. To do so, numerical simulations were carried out considering the device coupled with a wave tank where waves in real scale with different height values were generated. The geometric configuration of the OWC device was defined based on the optimized shape obtained in Gomes *et al*. (2013).

The results indicates that the amplification factor and the available hydropneumatic power are directly proportional to the height of the incident waves on the OWC. In both cases an almost linear relationship was observed for both quantities due to the wave height variation.

As the waves in the ocean are not regulars, the results obtained in this work contribute to the better understand about the OWC behavior and can be used to design an optimized turbine for the this device.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE

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