NUMERICAL STUDY ABOUT THE SHAPE INFLUENCE OF THE HYDRO-PNEUMATIC CHAMBER IN AN OWC WAVE ENERGY CONVERTER

Juliana do Amaral Martins Grimmler, engenheiraju@gmail.com
Nathalia da Rosa Lopes, nathaliapel@hotmail.com
Jeferson Avila Souza, jasouza@furg.br
Elizaldo Domingues dos Santos, elizaldosantos@furg.br
Liércio André Isoldi, liercioisoldi@furg.br
Universidade Federal do Rio Grande (FURG) - Av. Itália km 8. Rio Grande-RS, Brasil

Mateus das Neves Gomes, mateus.gomes@ifpr.edu.br
Instituto Federal do Paraná (IFPR) - Rua Antônio Carlos Rodrigues, 453. Paranaguá/PR, Brasil.

Luiz Alberto Oliveira Rocha, luizrocha@mecanica.ufrgs.br
Universidade Federal do Rio Grande do Sul (UFRGS) – Av. Osvaldo Aranha, 99, 3º andar. Porto Alegre/RS, Brasil.

Abstract. *The oceans represent one of the major energy natural resources, which can be used to supply the World energy demand. In the last decades some devices to convert the wave ocean energy into electrical energy have been studied. In this work the operating principle of an Oscillating Water Column (OWC) converter was analyzed with a transient 3D numerical methodology, unsing the Finite Volume Method (FVM) and the Volume of Fluid (VOF) model.The incident waves on the OWC hydro-pneumatic chamber cause an oscillation of the water column inside the chamber producing an alternative air flow through the chimney. The air drives a turbine that is coupled to a electric generator. The aim of this work was to investigate the influence of the hydro-pneumatic chamber geometry in the air flow. For this, four cases were studied and the results showed that the variation of the OWC chamber shape can improve around 5% the amount of air flow.*

Keywords*: Wave Energy, Oscillating Water Column (OWC), Computational Modeling, FLUENT.*

1. INTRODUCTION

Nowadays, a large part of the electrical energy produced in world is obtained from the burning fossil fuel, i.e., by a non-renewable source (Echarri, 2009). However new technologies have been developed aiming to expand the use of renewable energy sources (Mendonça e Gutierez, 2010). In this context the conversion of the wave energy into electrical energy must be considered (Dean and Dalrymple, 1991). The wave energy potential is about 2 TW and it is known that up to 25% of this value could be converted into electrical energy (Barstow and Molisson, 2008). There are several ways to promote this conversion, among which the Oscillating Water Column (OWC) device has excelled. Some numerical techniques have been used to simulate the fluid dynamic behavior of the OWC device (Horko, 2007; Conde e Gato, 2008; Liu et al., 2008; Gomes et al., 2009; Lopes et al., 2011; Grimmler et al. 2012).

An OWC converter can be defined as a device with a hydro-pneumatic chamber having at least two openings, one in communication with the atmosphere and one with the sea. Under the incidence of waves the water column inside the chamber oscillates and causes a compression and decompression of the air above the free surface. This air is forced to flow through the chimney where a turbine generates the electrical energy. Usually a Wells turbine is employed; such turbines, once started, turn in the same direction to extract power from air flowing in either axial direction, i.e. the turbine motion is independent of the fluid direction (Twidell and Weir, 2006).

The aim of this work was to do a numerical analysis of the OWC operating principle, evaluating the influence of the hydro-pneumatic chamber geometry in the total mass flow rate of air passing through the chimney. This air flow is responsible for driving the turbine, which is coupled to a generator, producing the electric energy. Thus, if a larger amount of energy is absorbed from incident waves consequently a higher amount of electric energy will be generated. To do so, four different geometries for the hydro-pneumatic chamber of an OWC wave energy converter were considered. The transient 3D computational domain is composed by the OWC device coupled a wave tank of regular waves. The governing equations were solved by the FLUENT software, based on the Finite Volume Method (FVM), where the Volume of Fluid (VOF) method was adopted to represent a more realistic interaction among water, air and OWC converter.

2. COMPUTATIONAL MODELING

Laboratory scale dimensions for the wave tank and the OWC converter (Fig. 1) were adopted and four different geometries for the hydro-pneumatic chamber were considered (Fig. 2). Figures 2(a), 2(b), 2(c) and 2(d) depict the Cases

1, 2, 3 and 4, respectively. The cross sectional area in the bottom of chamber, the total volume of the chamber and of the chimney were kept constant in all cases.

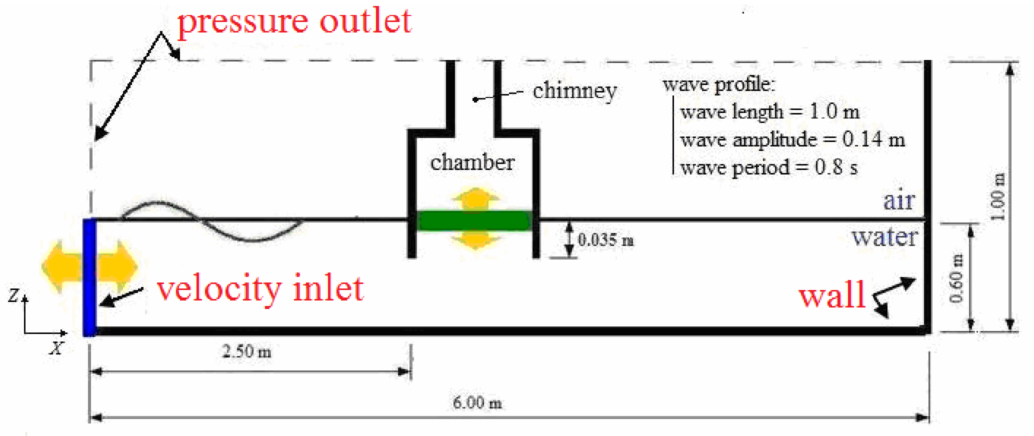
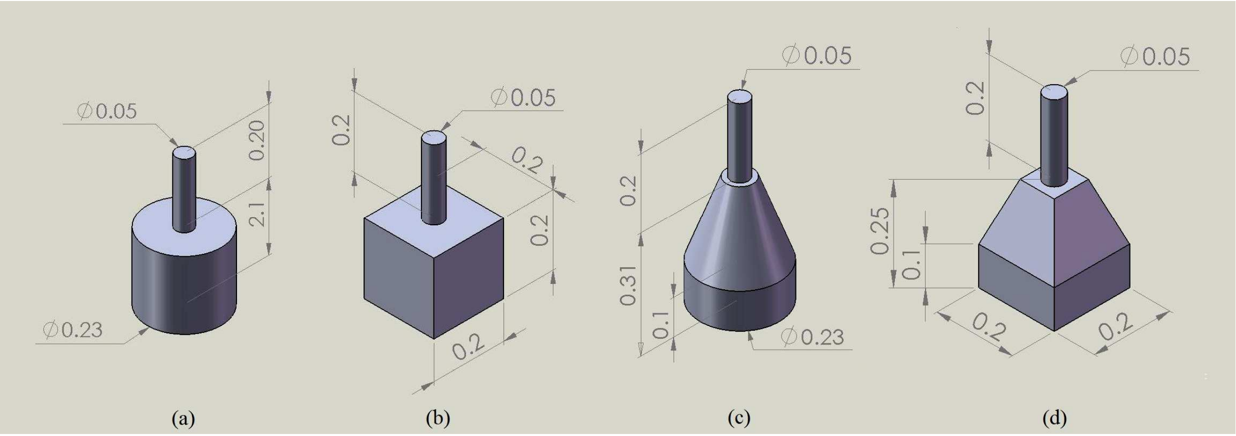


Figure 1. Computational domain in a 2D representation.



(a) (b) (c) (d)

Figure 2. OWC geometries (in m).

The computational domain has been constructed and discretized with GAMBIT software. It was divided in three regions along its length: one central region, where the OWC converter is placed; and other two regions, called left and right regions, which are the wave tank extremities. The mesh inside the OWC device was generated with 0.01m tetrahedral elements and the remainder of the central region was discretized with 0.02 tetrahedral elements, while the left and right regions of the computational domain has a regular hexahedral mesh with an interval size of 0.02m. The total number of elements for each case is indicated in Tab 1.

Table 1. Total number of elements used in computational domain discretization.

Case	Number of elements
1	944582
2	849582
3	979582
4	905582

Regular waves were generated by enforcing prescribed velocity boundary condition in *x* and *z* (horizontal and vertical) directions at the inlet section (Fig. 1). According to the second order Stokes theory, these velocities can be defined as (Dean and Dalrymple, 1991):

$$u = \frac{Hgk}{2\omega}\frac{cosh\,k\left(h+z\right)}{cosh\,kh}cos\left(kx-\omega t\right) + \frac{3H^2\omega k}{16}\frac{cosh\,2k\left(h+z\right)}{senh^4 kh}cos\left(kx-\omega t\right) \tag{1}$$

$$w = \frac{Hgk}{2\omega}\frac{senh\,k\left(h+z\right)}{cosh\,kh}sen\left(kx-\omega t\right) + \frac{3H^2\omega k}{16}\frac{senh\,2k\left(h+z\right)}{senh^4 kh}sen\left(kx-\omega t\right) \tag{2}$$

where H is the wave amplitude (m), g the gravity acceleration (m/s), k the wave number (m^{-1}), h the water level (m), ω the wave frequency (Hz), x and z the Cartesian coordinates (see Fig. 1) and t the time (s). The wave and frequency numbers are defined, respectively, by:

$$k = \frac{2\pi}{L} \tag{3}$$

$$\omega = \frac{2\pi}{T} \tag{4}$$

being L the wave length (m) and T wave period (s).

As already been showed in Fig. 1, the characteristics of the regular generated waves are: period of 0.8s, high of 0.14m and length of 1m. According to Chakrabarti (2005) this wave is classified as a Stokes of 4th order wave. However, the imposition of the 2nd order Stokes theory was a simplification adopted in this work.

In addition to the prescribed velocities at the inlet section, the other boundary conditions used in the current simulations are: prescribed pressure equal to zero (gauge) at the sections represented with a dashed line in Fig. 1, no-slip condition at the bottom and right walls and no-slip condition at the chamber and chimney walls.

The Volume of Fluid (VOF) method was used to model the multiphase flow comprised by the water and air movement inside the wave tank. In this formulation, the free water surface can be identified by the volume fraction (f) variable. Inside each grid cell (element), if $f = 1$ the element contains only water. When $f = 0$ there is only air and the element and when $0 < f < 1$, both water and air coexists simultaneously inside the element. Only one set of continuity and momentum equations are written for both fluids in the VOF model. For a Newtonian fluid, the continuity and momentum equations can be written as (FLUENT):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{v}\right) = 0 \tag{5}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{v}\right) + \nabla \cdot \left(\rho \vec{v}\vec{v}\right) = -\nabla p + \nabla \cdot \left(\overline{\overline{\tau}}\right) + \rho \vec{g} \tag{6}$$

where $\vec{v}$ is the velocity vector (m/s), ρ is the density (kg/m³), t the time (s), $\vec{g}$ the gravity acceleration vector (m/s²), p the pressure (Pa) and $\overline{\overline{\tau}}$ the stress tensor (Pa), The volume fraction is modeled by adding to the system a transport equation for f such as:

$$\frac{\partial\left(f\right)}{\partial t} + \nabla.\left(f\vec{v}\right) = 0 \tag{7}$$

The physical properties in Eqs. (5-7) are assumed to be average values calculated by:

$$\rho = f\rho_{water} - \left(1-f\right)\rho_{air} \tag{8}$$

$$\mu = f\mu_{water} - \left(1-f\right)\mu_{air} \tag{9}$$

FLUENT software has been used to solve the above set of governing equations. FLUENT is a general propose Computational Fluid Dynamics (CFD) software which uses the Finite Volume method (FVM) to approximate the conservation equations. In all cases presented in this work a total time of 8s (ten times the wave period) was simulated with an integration time step of 0.0005 s.

3. RESULTS

Initially, the presented methodology was verified by direct comparison between numerical results and the analytical solution for the wave generation in a rectangular tank (Gomes et al., 2009). Subsequently, an OWC converter was added to the wave tank and new simulations were performed by Lopes et al (2011). Afterwards, it was initiated a numerical study to determine the best device geometry which maximizes the air mass flow rate that crosses inside the OWC chimney. To do so, a numerical sensor was allocated at the top of chimney in each case.

Considering that the Case 3 can be understood as a geometric variation of Case 1, it was plotted in Fig. 3 the transient behavior of the air mass flow rate for these cases.

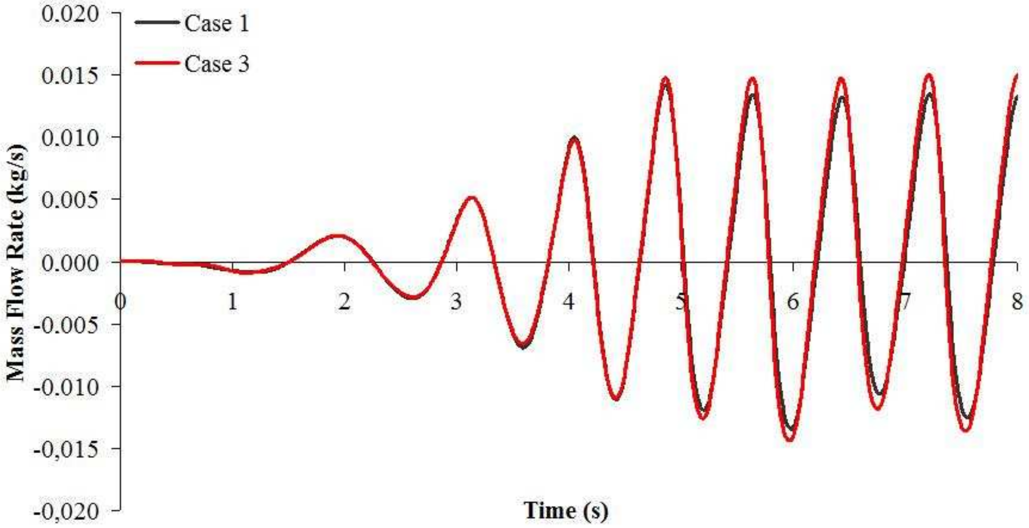


Figure 3. Transient mass flow rate of air for Cases 1 and 3.

One can note that the geometry of the hydro-pneumatic chamber of Case 3 promotes an increase in the amount of mass flow rate when compared with Case 1. This behavior was expected because conical format of the Case 3 facilitates the air flux. The same trend was observed when Cases 2 and 4 are compared, it is possible to improve the OWC behavior with a shape modification in the OWC chamber. Figure 4 illustrates this fact.

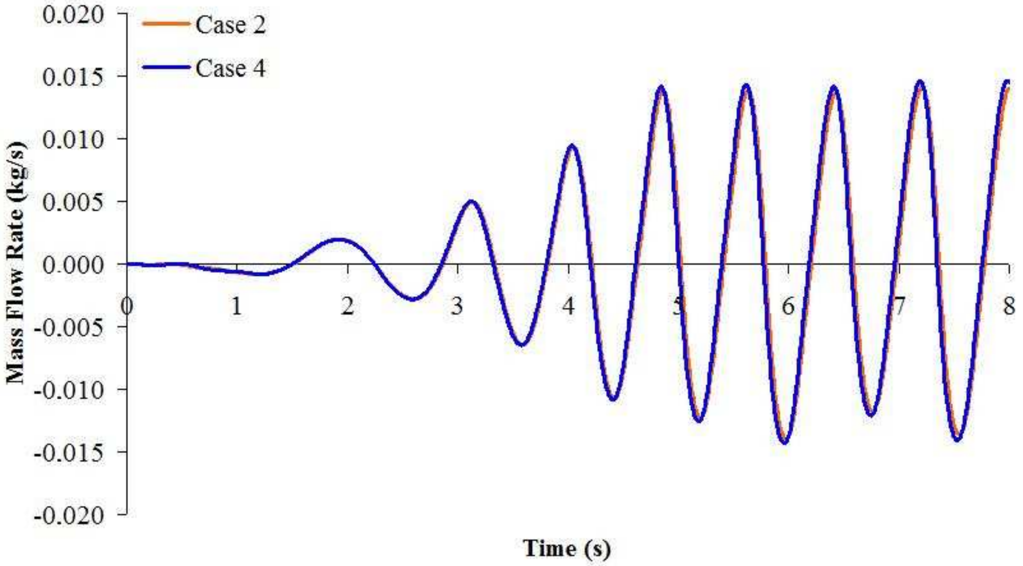


Figure 4. Transient mass flow rate of air for Cases 2 and 4.

It is worth mentioning that, for all analyzed cases, the air flux presents an oscillatory movement how can be observed in Figs. 3 and 4. This behavior is produced by the compression and decompression of the air inside the hydro-pneumatic chamber due to the piston type movement of water of the incident waves. When a wave crest reaches the device the air inside the OWC chamber is compressed and forced to pass through the chimney to the atmosphere, characterizing a positive mass flow rate. On the other hand, a negative air flux, from atmosphere to OWC chamber, crosses the chimney when a wave trough achieves the converter. For this reason, in the OWC wave energy converter is usually adopted a Wells turbine, which has the ability to maintain rotate direction independently of the air flow direction.

Concluding the comparative qualitative analysis about the behavior of the mass flow rate of air in the OWC chimney, it is possible to define that Cases 3 and 4 are the best. So, in Fig. 5 these cases have their performance compared, indicating that the best case is the Case 3.

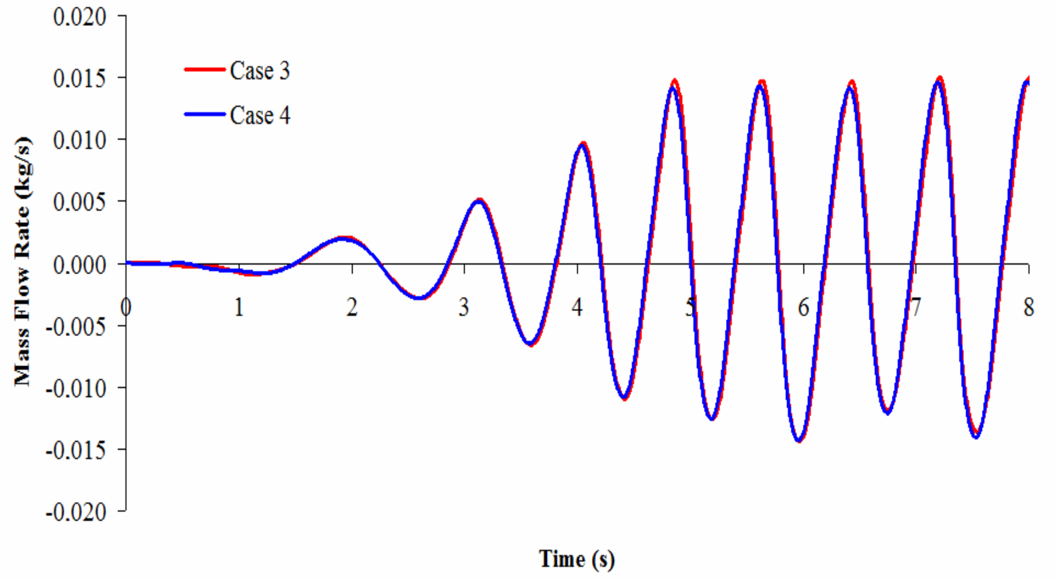


Figure 5. Transient mass flow rate of air for Cases 3 and 4.

Now, using a quantitative approach and considering that the turbine maintains the direction of rotation regardless of the air flux direction, it was made an average of the magnitude of the mass flow of air, during 8 s, for each studied case (Tab. 2). Hence, comparing these results, it is possible to quantify the difference among the performance of each hydro-pneumatic chamber shape.

Table 2. Average of the mass flow rate magnitude.

Case	Average Mass Flow Rate (kg/s)
1	0.00390
2	0.00395
3	0.00409
4	0.00407

Therefore, based on the Tab. 2, comparing Cases 1 and 3 (see Fig. 3) a difference in the average mass flow rate of 4.87% between Case 3 and Case 1 was encountered; and considering Fig. 4 an improvement of 3.04% in the air amount was obtained between Cases 4 and 2. Therefore, it is possible to note that the modifications of the chambers geometry performed between Cases 3 and 1 and Cases 4 and 2 allows a resistance reduction to the air flow. Just because of these geometric changes the Cases 3 and 4 presented better behavior of Cases 1 and 2, respectively.

Among all studied cases the best performance was reached by Case 3, as can be seen in Fig. 5 and Tab. 2, with a gain of 4.87%, 3.54% and 0.50% in the OWC air flux when compared with Cases 1, 2 and 4, respectively.

Thus, in Fig. 6 the behavior of the air/water flow velocity in vertical direction of Case 3 is showed for two specific times: 6.3s in Fig. 6(a) 6.7s in Fig. 6(b). For the same instants of time the wave incidence in the OWC converter can be observed in Fig. 7.

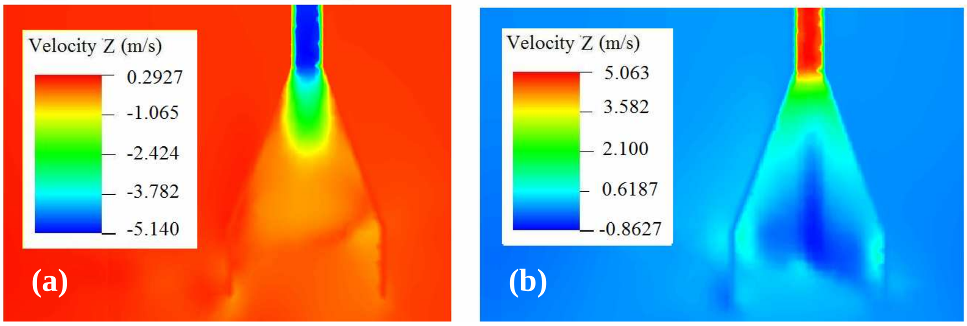


Figure 6. Instantaneous vertical air velocity (m/s) for time: (a) 6.3s and (b) 6.7s.

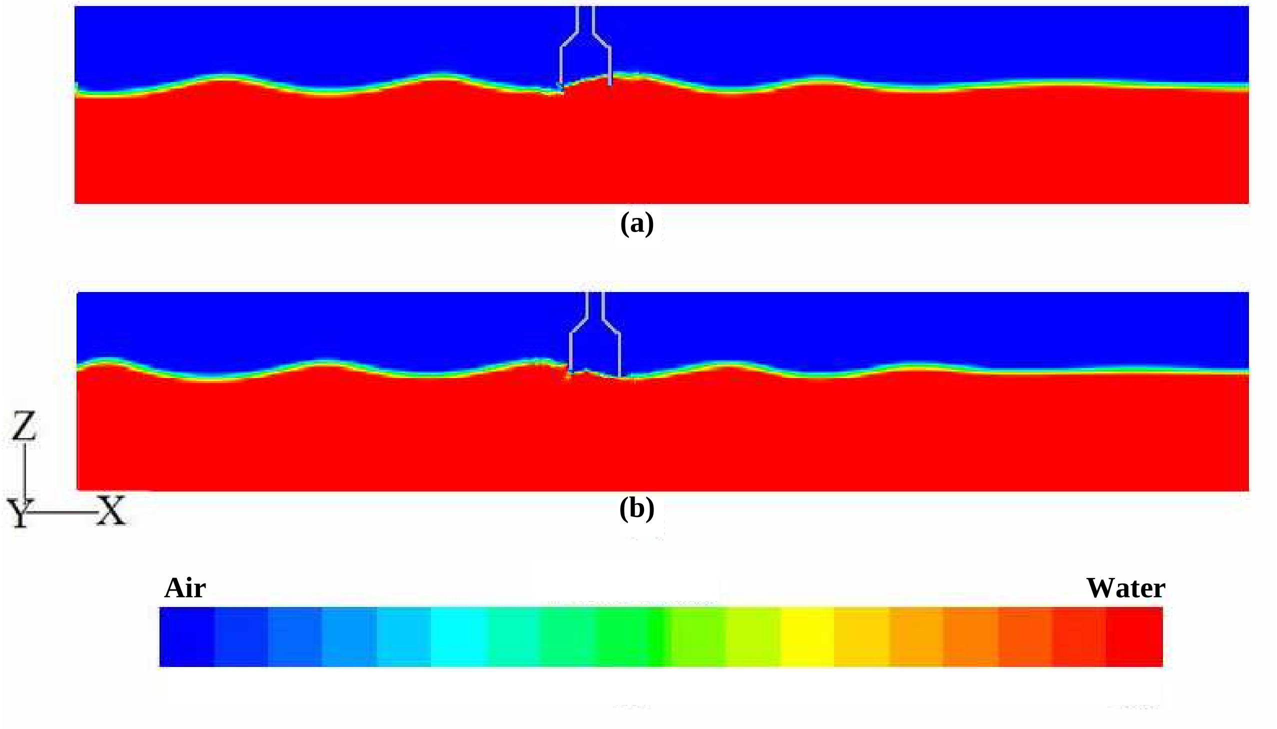


Figure 7. Wave incidence in the OWC converter for time: (a) 3 s, (b) 4.6 s e (c) 5.0 s

In Fig. 6(a) one can note a negative vertical velocity for the air crossing the OWC chimney, indicating that the external air enters in the OWC chimney due the decreasing of internal pressure in the hydro-pneumatic chamber. This air flow is caused by the presence of a wave trough acting on the device, as can be viewed in Fig. 7(a). However, in Fig. 6(b) there is a positive air flow in the OWC chimney, i.e., the air is leaving the OWC converter because a wave crest reaches the device. As already mentioned, in this condition an increasing of the chamber internal pressure is caused by the wave crest acting on the OWC converter, how can be observed in Fig. 7(b).

Therefore the alternative incidence of crests and troughs of the wave on the OWC converter produces an oscillating water column inside the OWC chamber, reproducing a piston type movement that generates an oscillating air flow in the chimney.

4. CONCLUSIONS

In this work it was numerically studied the fluid flow behavior in a system composed by a wave tank and an OWC converter. The main objective was to investigate the influence of the hydro-pneumatic chamber geometry of an OWC device on its capacity of converting wave energy into electrical energy. To do so, four different geometries were proposed for the OWC chamber. In all simulations the cross sectional area in the bottom of chamber, the total volume of the chamber and of the chimney were kept constant, allowing a comparison among the cases.

A computational model developed in the GAMBIT and FLUENT software was used, where the OWC converter was coupled to a wave tank. The VOF method together with the 2nd order Stokes theory were employed to generates regular waves, allowing a more realistic interaction among water, air and OWC converter.

A comparative analysis for the average quantity of air flowing through the converter chimney during a period of 8 s (ten times the wave period) has been performed for the devices with different chamber formats (see Fig. 2).

The importance of the geometric optimization for the design of OWC energy converters is highlighted in the present study. Only four simple cases were studied, however an improvement around 5% in the air flow amount has already been achieved. Therefore, these results justify the continuity of the present work.

5. ACKNOWLEDGMENTS

The authors thank to FAPERGS and to CNPq for the financial support.

6. REFERENCES

Barstow, S, e Molisson, D., 2008. The wave energy resource. Ocean Wave Energy: Current Status and Future Perspectives. Bristo, Springer.

Chakrabarti, S.K., 2005. Handbook of offshore engineering. Vol. 1, Elsevier.

Conde, J.M.P e Gato, L.M.C., 2008. “Numerical study of the air-flow in an oscillating water column wave energy converter”. Renewable Energy, Vol. 33, No. 12, pp. 2637–2644.

Dean, R.G. e Dalrymple, R.A., 1991. Water wave mechanics for engineers end scientist. World Scientific, Singapura.

Echarri, L. Ciencias de la tierra y del medio ambiente. Escuela Superior de Ingenieros de San Sebastian, Universidad de Navarra. Navarra, Espanha. In: <http://www.tecnun.es/asignaturas/ecologia/hipertexto/00General/Principal.html>.

Horko, M., 2007. CFD Optimisation of an Oscillating Water Column Energy Converter. Master thesis, Western University, Australia.

FLUENT. Documentation Manual. In <http://www.fluent.com>.

Gomes, M. das N., Olinto, C.R., Rocha, L.A.O., Souza, J.A., and Isoldi, L.A., 2009. “Computational modeling of a regular wave tank”. Engenharia Térmica, Vol. 8, pp. 44-50.

Grimmler, J. do A.M, Lopes, N.R., Gomes, M. N., Souza, J.A , Santos E. D., Isoldi, L.A. and Rocha, L. A.O. 2012, “Análise Numérica da Influência da Forma da Câmara em um Dispositivo CAO para Conversão da Energia das Ondas do Mar em Energia Elétrica”. In Proceedings of NAVTEC 2012 1th International Conference on Ofsshore and Marine Technology: Science and Innovation, Rio Grande, Brazil.

Mendonça, M.J.C. and Gutierez, M.B.S. “O efeito estufa e o setor energético brasileiro”. In <http://www.ipea.gov.br/pub/td/td_2000/td0719.pdf>.

Lopes, N.R., Sant’Anna, F.S.P., Gomes, M. N., Souza, J.A., Rocha, L.A.O., dos Santos, E.D. and Isoldi, L.A., 2011. “Estudo numérico da influência da forma da câmara de um conversor de coluna de água oscilante”. In Proceedings of CILAMCE 2011 32th Iberian Latin American Congress on Computational Methods in Engineering, Ouro Preto, Brazil.

Liu, Z., Hyun B. and Hong, K., 2008. “Application of Numerical Wave Tank to OWC Air Chamber for Wave Energy Conversion”. In Proceedings of ISOPE 2008 18th International Offshore and Polar Engineering Conference, Vancouver, Canada.

Twidell, J. and Weir, T., 2006. Renewable Energy Resources. Taylor & Francis, London.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.