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STUDY OF THE EFFECT OF THE RELATIVE HEIGHT ON THE EFFICIENCY OF A SUBMERGED HORIZONTAL PLATE TYPE WAVE ENERGY CONVERTER APPLYING CONSTRUCTAL DESIGN

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Abstract. *The large energy density available in the sea waves makes this resource an important alternative as a source of renewable energy. The submerged horizontal plate system is a structure used as a breakwater, but can be also used as a wave energy converter. The aim of this study is to maximize the theoretical device efficiency for several geometries of the submerged horizontal plate and to analyze the effect of the geometry over the flow below the plate. The model used was 2D and did not consider the presence of the hydraulic turbine. The Constructal Design method was used to define: the constraints – the total area of the wave energy converter structure and the area of the submerged horizontal plate ($\phi = 0.05$),* *the degree of freedom – h (relative height of the submerged horizontal plate), and the objective of the geometric evaluation of the plate. The total area of the wave energy converter structure was kept fixed in this study. Conservation equations of mass and momentum are solved using Ansys Fluent software which is based on the Finite Volume Method. Results showed an improvement of the device performance until 41.32 % between the worst and the best studied shape.*

Keywords: *Computational Fluid Dynamics, Constructal Design, Submerged Horizontal Plate, Volume of Fluid, Wave Energy Converter*

1 INTRODUCTION

The growth on demand for electricity production has led to the diversification of energy matrices and to the development of technologies for energy conversion from renewable sources. The high energetic potential available on the oceans stands out this source as a promising alternative energy resource (Falcão, 2010; Margheritini et al., 2012).

The energetic potential of the oceans is available in different forms, mainly: wave energy, tidal energy, ocean currents energy and ocean thermal energy (Uihlien and Magagna, 2016). However, surface waves concentrate most of this resource with an overall available power estimated at 2.11 ± 0.05 TW, a comparable value to the worldwide average annual electricity consumption (Gunn and Stock-Williams, 2012). Recent studies indicate that the available wave energy along the South-Southeastern Brazilian shelf can vary from 6.00 to 22.30 kW/m (Contestabile et al., 2015; Oleinik et al., 2016; Lisboa et al., 2017).

Another important aspect of the wave energy is the energy density, it is expected that the wave energy provides 15 to 20 times more energy, per square meter, than wind or solar energy (Vining and Muetze, 2009). Therefore, even with conservative estimates about the efficiency of wave energy converters (WECs), the good prospects have been stimulating the scientific and technological research to exploit this energy resource (Astariz et al., 2015).

Despite its energetic potential the wave energy is still very few explored, mainly due to the high cost of current technologies. In this sense, energy conversion structures that perform more than one function have been studied by the possibility of reduction in installation costs, for example, WECs associated with breakwaters: oscillating water column (OWC) onshore (Falcão and Henriques, 2016), overtopping onshore (Margheritini et al., 2009; Vicinanza et al., 2014) and the submerged horizontal plate (SHP) near-shore (Graw, 1993a; Ning et al., 2015).

There are different criteria used to classify the WECs. The two most common are the location (shoreline, near-shore, offshore) and the working principle (OWC, overtopping and oscillating bodies) (Cruz, 2008; Falcão, 2010). However, these criteria do not cover all the existing possibilities of converting the wave energy in electricity, like the multifunctional structures, which are not being completely and righly described by these criteria. Thus, other criteria it is being discussed in the literature, for example, the classification proposed by Margheritini et al. (2012).

The submerged horizontal plate (SHP) device is a type of structure used in coastal engineering, such as submerged breakwater, for coastal protection purposes and can also be used as a WEC (Graw, 1993a; Carter, 2005; Brossard et al., 2009). The use of this structure as a WEC has the main characteristic of the double functionality of the structure, since the same device used for wave energy conversion can be used as a breakwater (Ning et al., 2015). The SHP utilizes the alternating flow below the plate, which arise by the wave propagation through the structure, as propulsion for a hydraulic turbine (Graw, 1995a; Orer and Ozdamar, 2007).

The improvement of systems performance is a constant pursuit in engineering projects, which has led to the development of different methods to obtain it. Among these methods, Constructal Design (CD) has shown to be adequate for the most diverse engineering applications (Rocha et al., 2009; Isoldi et al., 2013; Goulart et al., 2015; Lorenzini et al., 2015; Brum et al., 2016; Biserni et al., 2017). This method is used for the geometric evaluation of systems subjected to some kind of flow, according to which the flow is malleable and the geometry is deduced by a principle of global performance maximization (Bejan, 1997; Gomes, 2014).

This method is based on the Constructal Theory (Bejan, 1997; 2017; Bejan and Lorente, 2008) which explains, in a general way, that the forms and structures of systems subjected to some flow can be explained by a physical principle. This principle is the Constructal Law of design and evolution which states that "for a finite-size flow system to persist in time (to live), its configuration must evolve in such a way that provides easier access to the currents that flow through it" (Bejan, 1997; 2017; Bejan and Lorente, 2008; Bejan and Zane, 2012).

The present numerical work report the Constructal Design of a SHP type WEC. The aim of this study is to maximize the theoretical device efficiency, which is given by the ratio between the average power available in the flow below the plate and the mean power of the incident wave, for several SHP geometries; and to analyze the effect of the geometry over the flow below the plate. A 2D model was used and does not consider the presence of the hydraulic turbine.

The CD was used in association with the exhaustive search method. The CD method was used to define the constraints and objective for the geometric evaluation of the plate. Thus this problem has two constraints: the total area of the wave energy converter structure and the area of the submerged horizontal plate ($\phi = 0.05$), and one degree of freedom: h (relative height of the submerged horizontal plate). The total area of the wave energy converter structure was kept fixed in this study. The model was based on the multiphase model Volume of Fluid (VOF – Hirt and Nichols, 1981; Srinivasan et al., 2011) to description of interaction between air and water. Conservation equations of mass and momentum are solved for all studied cases using the commercial code Ansys Fluent which is based on the Finite Volume Method (FVM – Patankar, 1980; Versteeg and Malalasekera, 2007).

2 SUBMERGED HORIZONTAL PLATE

The submerged horizontal plate device consists of a flat plate and horizontally submerged below the free surface of the sea. The passage of the waves through the structure causes a flow under the plate, which alternates periodically of direction, absorbing energy of the incident waves. Thus, this device can act as both a wave energy converter, taking advantage of this alternating flow of water to drive a hydraulic turbine, and as a breakwater, attenuating the energy of the waves that reach the coastal regions.

Initially the submerged plate system was studied as a submerged breakwater for coastal protection. Experiments conducted by Dick and Brebner (1968), with solid and permeable submerged blocks, presented a flow pattern around the permeable blocks, giving rise to submerged horizontal plate studies.

In experiments performed by Graw (1992), the system was described as an efficient wave filter, whose flow below the plate was considered advantageous in relation to other submerged breakwaters. In this same work, it is affirmed that this flow is quite stable, not undergoing significant changes even when the region below the plate is partially obstructed.

Graw (1993a) announced the SHP type WEC. The author proposed the use of this stable flow, which occurs under a submerged horizontal plate, as propulsion for a hydraulic turbine (according to Fig. 1) installed under the plate (Graw, 1993a; 1993b; 1994; 1995a).

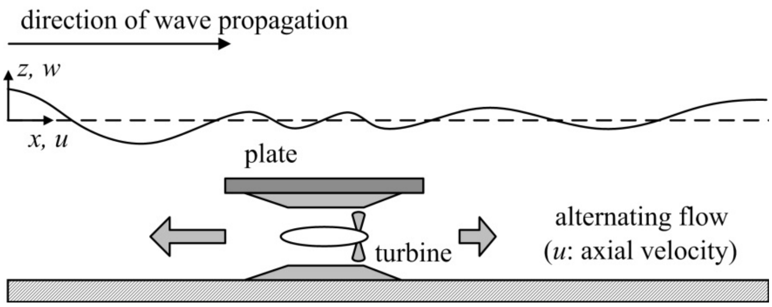

Figure 1. Sketch of the submerged horizontal plate device

Graw (1996) presented a study on the WECs feasibility associated with breakwaters including the SHP system in this context. Despite the potential of the SHP system as a dual-function device (according to Graw, 1994; 1996), much of the studies on this subject are focused on its use as a submerged breakwater (Hsu and Wu, 1998; Brossard and Chagdali, 2001; Liu et al., 2009; Lin et al., 2014; Cheng et al, 2017). These studies, however, contribute to a better understanding of the phenomena related to the flow around the SHP.

Carter (2005) studied the SHP type WEC, using a 2D numerical model with the Boundary Element Method and the linear wave theory. This study presented the velocity field of the flow under the plate, whose results evidenced the alterning behavior of the direction of this flow. Carter et al. (2006) compared this model with a model based on RANS, where they concluded that the difference between the models did not influence the arising of the characteristic flow, so that both models captured the alternating behavior of the flow under the plate.

Orer and Ozdamar (2007) presented an experimental evaluation of the SHP device efficiency as a WEC. In this study, the flow velocity under the plate was analyzed when the device, at a fixed height, is subjected to different incident waves. The authors indicated the possibility of an efficiency around 60 % for the device, in opposition to Graw (1993b) who had predicted an efficiency of only 4 %.

In Seibt et al. (2012a; 2012b) a 2D numerical model of the SHP device based on the FVM and the VOF method was used for solution and description of the water-air interface. In these works, validation of the model based on the experimental results of Orer and Ozdamar (2007) were presented, from the reproduction of a case without restrictions below the plate, as well as verification of the model based on free-surface elevation equation and velocities components equations from the 2^{nd}-order Stokes theory.

Seibt et al. (2014a) presented a numerical study about the SHP conversion efficiency at six different plate heights in relation to the bottom. Among the results, the flow velocity profiles under the plate for each case are shown, as well as the behavior of the flow field velocity vectors over a wave period, in the case of higher efficiency. The results showed an efficiency of up to 64 % for the case where the plate was positioned closest to the surface.

In another study, Seibt et al. (2014b) presented a numerical evaluation of the area reduction influence under SHP on its conversion efficiency. Configurations were analyzed with the insertion of triangular structures under the SHP, in order to reduce the area without changing the submersion height, and compared with the case without restriction. The results showed that the area reduction caused a growth of up to 300 % in the velocities magnitudes and a decrease of around 5 % in the conversion efficiency among the analyzed cases.

Seibt et al. (2015) presented an evaluation of the influence of different plate heights, with fixed length, subject to different wave periods on the equipment efficiency. The results showed that longer waves can lead to a conversion efficiency of up to 27 % among the analyzed cases.

Recently, Seibt et al. (2017a) presented a study of a real-scale model built according to a scaling factor from the model utilized by Seibt et al (2014a). In this study, the similarity between SHP numerical models based on the Froude number was analyzed. In Seibt et al. (2017b) was presented an analysis of different geometries of SHP, where they obtained efficiency up to 42 % among the evaluated cases.

In the present work the CD is applied to the SHP geometry study in order to evaluate the effect of a degree of freedom on the system efficiency. With this, it is also possible to obtain a SHP geometry that provides a better system performance for the set of considered constraints.

3 COMPUTATIONAL MODELING

The computational model used was developed with Computational Fluid Dynamics software Ansys Fluent, which was used to solve the governing equations by means of the FVM. This method allows obtaining a discrete version of Partial Differential Equations (PDEs) and is based on a physical approach of the problem represented by PDE. This method is widely used in engineering applications involving fluid dynamics, such as aerodynamics, hydrodynamics and fluid-structure interaction (Versteeg and Malalasekera, 2007).

3.1 Mathematic and Numerical Model

The conservation equations of mass and momentum for an isothermal, laminar and incompressible flow with two phases solved for the mixture of air and water are given by Eqs. (1), (2) e (3) (Schlichting and Gersten, 2000):

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\rho\frac{\partial u}{\partial t}+\rho\left[u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}\right]=-\frac{\partial p}{\partial x}+\mu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial z^2}\right] \tag{2}$$

$$\rho\frac{\partial w}{\partial t}+\rho\left[u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}\right]=-\frac{\partial p}{\partial z}+\mu\left[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial z^2}\right]+\rho g \tag{3}$$

were ρ is the density (kg/m^3), u e w are the horizontal and vertical velocity components (m/s), respectively, p is the pressure (N/m^2), ρg is the buoyancy (N/m^3) and μ is the dynamic viscosity (kg/m·s).

In order to represent the water-air interaction of the flow and to evaluate its interaction with the equipment, the VOF method is used. The VOF method is a multiphase model used for fluid flows with two or more phases. In this model, the phases are immiscible. In addition, the volume fractions (α), used to represent both phases inside the control volume, are assumed to be continuous in space and time. Therefore, in each control volume the sum of the volumetric fraction of all phases is unitary, so that there are three possible situations: i) $\alpha = 1$: characterizes a volume filled by water, ii) $\alpha = 0$: indicates a volume without water, filled only by air; iii) $0 < \alpha < 1$: identifies the position of the free surface, i.e. a transition region having water and air. Thus, the transport equation of the volumetric fraction, used to determine the volume fraction relative to the two phases in each mesh element of the computational domain, is given by Eq. (4), as (Srinivasan et al., 2011):

$$\frac{\partial(\alpha)}{\partial t}+\frac{\partial(\alpha u)}{\partial x}+\frac{\partial(\alpha w)}{\partial z}=0 \tag{4}$$

The values of density and viscosity for the mixture can be written as Eqs. (5) and (6) (Srinivasan et al., 2011):

$$\rho=\alpha\rho_{água}+(1-\alpha)\rho_{ar} \tag{5}$$

$$\mu=\alpha\mu_{água}+(1-\alpha)\mu_{ar} \tag{6}$$

Since the fluid is assumed incompressible due to the low velocity flow, the state equation is used to solve the pressure at any point in the domain, with no specific mass variation of each phase (Versteeg and Malalasekera, 2007).

The mathematical model is complemented by the boundary conditions, which are assigned as follows: time dependent velocity (v (x, z, t)) on the left border (representing the channel wavemaker) (Horko, 2007), atmospheric pressure (p_{atm}) at the upper boundary and part of the left border (represented by the dashdot line) and non-slip and impermeability condition (v (x, z, t) = 0) at the other borders, according to Fig. 2.

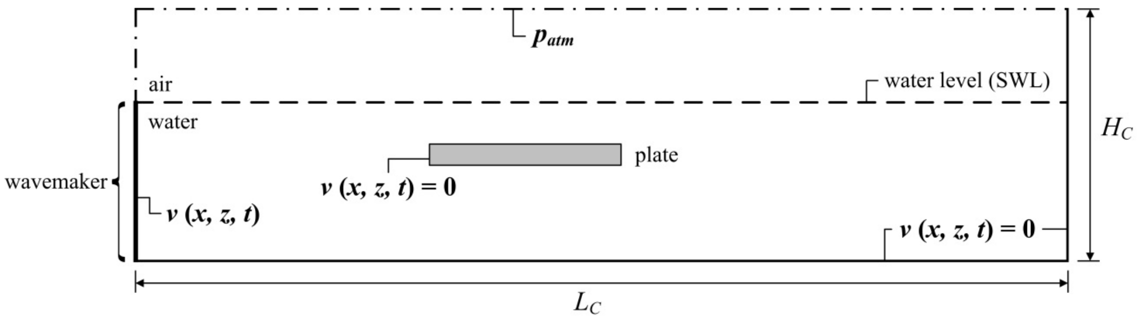

Figure 2. Computational model boundary conditions

The time dependent velocity was composed by the Eqs. (7) and (8) from the 2nd-order Stokes theory, by the wave velocity components, in the horizontal (x) and vertical (z) directions, respectively, given as (Dean and Dalrymple, 1991):

$$u(x,z,t)=\frac{\varepsilon}{2}\left(\frac{gk}{\omega}\right)\left[\frac{\cosh k(d+z)}{\cosh(kd)}\right]\cos(kx-\omega t)+\frac{3}{16}\left[\frac{\varepsilon^2\omega k\cosh 2k(d+z)}{\sinh^4(kd)}\right]\cos 2(kx-\omega t) \quad (7)$$

$$w(x,z,t)=\frac{\varepsilon}{2}\left(\frac{gk}{\omega}\right)\left[\frac{\sinh k(d+z)}{\cosh(kd)}\right]\sin(kx-\omega t)+\frac{3}{16}\left[\frac{\varepsilon^2\omega k\sinh 2k(d+z)}{\sinh^4(kd)}\right]\sin 2(kx-\omega t) \quad (8)$$

were ε is the wave height (m), g is the gravitational acelaration (g = 9.81 m/s²), k is the wave number given by $k = 2\pi/\lambda$ (m^{-1}), λ is the wave length (m), ω is the wave frequency given by $\omega = 2\pi/T$ (rad/s), T is the wave period (s), d is the water depth (m) and t is the time (s).

The wave length (λ) is defined, from the 2nd-order Stokes theory, by the dispersion equation – Eq. (9) – and is calculated interactively by (Dean and Dalrymple, 1991):

$$\lambda=\left(\frac{g}{2\pi}\right)T^2\tanh\left(\frac{2\pi}{\lambda}d\right) \quad (9)$$

The following solution parameters were also adopted: 1st-order UPWIND advection scheme for the advective terms; PRESTO for spatial pressure discretization; GEO-RECONSTRUCTION for the discretization of the volume fraction; PISO as pressure-velocity coupling method; sub-relaxation factors 0.3 and 0.7 for the mass and momentum, respectively. All simulations of the present work refer to a flow time of 13T, where T is the wave period, and the time step used was 0.001 s for all cases.

3.2 Numerical Domain

For the numerical simulation of the SHP device, were considered the 2D representation of a wave channel, with height $H_C = 1.00$ m, length L_C ($L_C = 6\lambda + L$) and water depth $d = 0.60$ m, with the presence of a horizontal plate below the water free surface, according to Fig. 3. It should be noted that the channel and plate widths were considered unitary since the numerical model is two-dimensional.

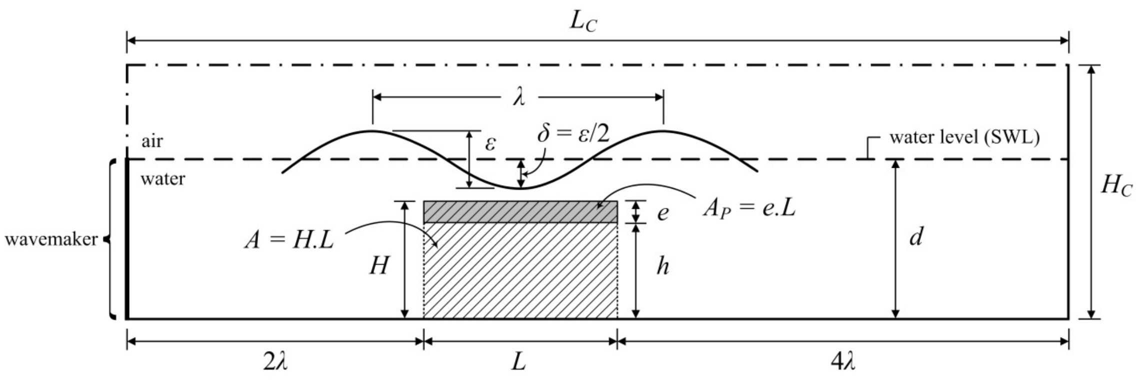

Figure 3. Computational domain sketch

For monitoring the data used in the comparative analyzes, numerical probes were inserted in the region below the plate. The main numerical probes used were the central point (*cp*) and the line (l), according to Fig. 4. These were used to monitor velocities and mass flow rate, respectively; the pressure data was monitoring by the same points of the velocities.

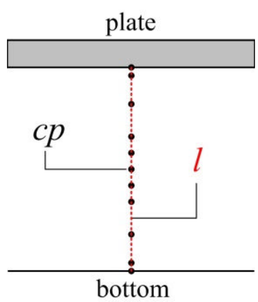

Figure 4. Location sketch of numerical probes below the plate

According to Fig. 3 some of the dimensions in the numerical domain were defined based on the characteristics of the simulated wave. These dimensions were fixed as a way to guarantee minimum conditions for the formation of the waves before reaching the plate and, also, guaranteeing a minimum number of waves incident on the plate before the reflection of the waves in the end of the channel (region downstream of the plate). Thus, allowing a sufficient amount of data to be obtained for analysis.

For discretization of the numerical domain, the recommendations of Ramalhais (2011) were adopted, which were adequate in previous studies (Seibt, 2014; Seibt et al., 2015). Thus, the cell dimensions did not exceed $\lambda/60$, in the direction of wave propagation, and $\varepsilon/20$, in the vertical direction, in the region where the wave propagates, as well as, at the bottom of the channel (Ramalhais, 2011).

3.3 Description Problem

With the Constructal Design method (CD) it is possible to analyze the configuration of flow systems based on a law of physics: Constructal Law. In this sense, the CD directs the approach and formulation of the problem in order to identify the dimensions, constraints and objective functions of the study. As well, define your degrees of freedom. (Bejan and Lorente, 2008).

The dimensions of the domain were determined from the following set of expressions. Eqs. (10) and (11) define the area of the plate (A_P) and total area of the structure (A), respectively. Already the Eq. (12) defines the total height of the plate and Eq. (13) establishes the maximum total height for the plate to remain submerged below the water level (SWL), as:

$$A_P = eL \tag{10}$$

$$A = HL \tag{11}$$

$$H = h + e \tag{12}$$

$$H < d - \delta \tag{13}$$

were e is the plate thickness and δ is the wave amplitude ($\delta = \varepsilon/2$).

The relation between the areas given by Eq. (14) defines an area constraint ϕ as:

$$\phi = \frac{A_P}{A} \tag{14}$$

The dimensionless variables, according to Eq. (15), are provided by:

$$\widetilde{H},\widetilde{L},\widetilde{e},\widetilde{h},\widetilde{d} = \frac{H,L,e,h,d}{A^{1/2}} \tag{15}$$

Substituting and rearranging the terms, are obtained the Eqs. (16), (17) and (18), as:

$$\widetilde{H} = \frac{\widetilde{h}}{(1-\phi)} \tag{16}$$

$$\widetilde{L} = \frac{1}{\widetilde{H}} \tag{17}$$

$$\widetilde{e} = \phi\widetilde{H} \tag{18}$$

Thus, knowing ϕ and $\widetilde{h}$ are determined all the dimensions of the problem. The values of d and δ are defined by the wave characteristics chosen for the study.

Based on the formulation presented, this study aimed to optimize the degree of freedom h for an area restriction $\phi = 0.05$ and a wave with the characteristics: $T = 3.00$ s, $\lambda = 6.952$ m, $d = 0.60$ m and $\varepsilon = 0.06$ m.

In addition to the restriction given by Eq. (13), two other physical constraints have been added. The first relates to the minimum thickness of the plate, such that $e > 0.005$ m, in order to avoid geometries that may be constructively impracticable. The second one concerns the relative height of the plate ($X = h/d$), such that $X \geq 20.0$ %, in view of a minimum space for installing the hydraulic turbine under the plate.

Thus, 43 simulations were performed, which some of the geometries analyzed are presented in Table 1.

Table 1. Partial listing of studied cases

Caso	h (m)	H (m)	L (m)	e (m)	X (%)
1	0.12	0.126	7.917	0.006	20.0
2	0.13	0.137	7.308	0.007	21.7
3	0.14	0.147	6.786	0.007	23.3
⋮	⋮	⋮	⋮	⋮	⋮
41	0.52	0.547	1.827	0.027	86.7
42	0.53	0.558	1.793	0.028	88.3
43	0.54	0.568	1.759	0.028	90.0

3.4 Theoretical Efficiency Model

The SHP efficiency (φ) is defined, by Eq. (19), as (Graw, 1995b; Orer and Ozdamar, 2007):

$$\varphi = \frac{P_P}{P_W} \tag{19}$$

were P_P is the available power under the plate (W) and P_W is the wave power which reaches the device (W), which is obtained by the Eq. (20) as (McCormick, 1981):

$$P_W = \left(\frac{1}{16}\rho g \varepsilon^2\right)\frac{\omega}{k}\left(1+\frac{2kd}{\sinh 2kd}\right)\left[1+\frac{9}{64}\frac{\varepsilon^2}{k^4 d^6}\right] \tag{20}$$

The time-averaged available power under the plate (P_P) is calculated by the Eq. (21) as (Carter, 2005; Dizadji and Sajadian, 2011):

$$P_P = \frac{1}{T}\int_{t}^{t+T}\int_{-d}^{-d+h}\left(p+\frac{1}{2}\rho u^2\right).ubdzdt \tag{21}$$

were p is the static pressure (Pa) under the plate, the term ($\rho u^2/2$) represents the dynamic pressure (Pa) and b is the plate width which is unitary in the 2D model.

4 RESULTS AND DISCUSSION

Figure 5 shows the behavior of the axial velocity $|-u_{max}|$ under the SHP for all simulated cases. It should be noted that the degree of freedom evaluated is represented by the relative height X and the length of the plate L varies along with h, but inversely, i.e., while X increases L decreases.

In Figure 5 it is possible to observe the growth tendency of the flow velocity below the plate as the plate is closest to the surface. This behavior is observed from X = 26.67 % to 76.67 %, respectively, global minimum and global maximum of the $|-u_{max}|$ parameter. Between X = 76.67 % it is possible to observe a local minimum, at X = 80.00 %. In relation to the length L we can see that the trend of the curve is inverted, that is, the speed $|-u_{max}|$ decreases as the plate length increases.

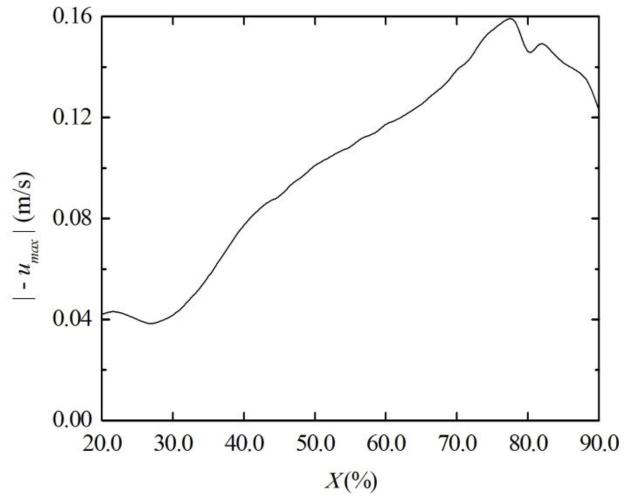

Figure 5. Velocity $|-u_{max}|$ in the *cp* under the SHP for all cases

Figure 6 shows the behavior of the mass flow rate $\dot{m}_{RMS}$ under the SHP, where it is observed the tendency of increase of the flow as the plate approaches the surface. This tendency was expected as *h* increases as the area under the plate increases allowing more fluid to pass through.

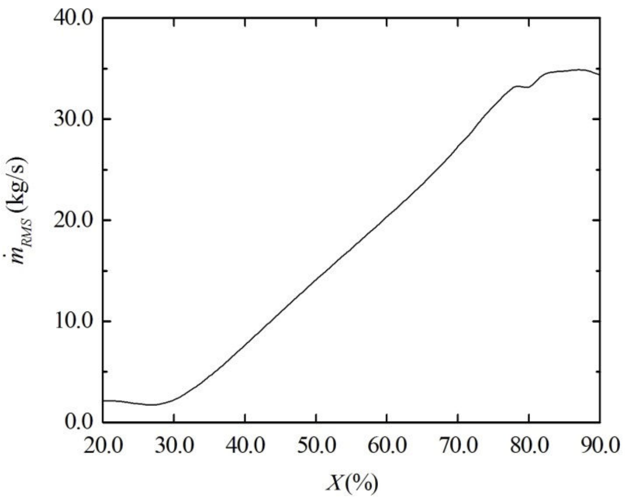

Figure 6. Mass flow rate ($\dot{m}_{RMS}$) under the SHP for all cases

Figure 6 shows the occurrence of an overall maximum for $X = 86.67$ % and an overall minimum for $X = 26.67$ %. Again, a local minimum for X between 70.00 and 90.00 %, similar to that observed in Fig. 5, also occurs at $X = 80.00$ %. It is possible to observe that the general tendency of the mass flow rate is decreasing with the increase of the plate length.

The results of the device efficiency φ variation with the degree of freedom h are shown in Fig. 7. Similar to that observed in Figs. 5 and 6, the device efficiency also exhibits a general upward trend as the plate is closest to the surface.

However, in Fig. 7, the global maximum is observed in the limit value of the range of heights h considered, $X = 90.00$ %. The overall minimum value occurs at $X = 26.67$ %, as expected, considering the minimums found in Figs. 5 and 6. In relation to the length L the greater device efficiency is found for smaller plate length. In turn, the longer plate lengths led to lower efficiency.

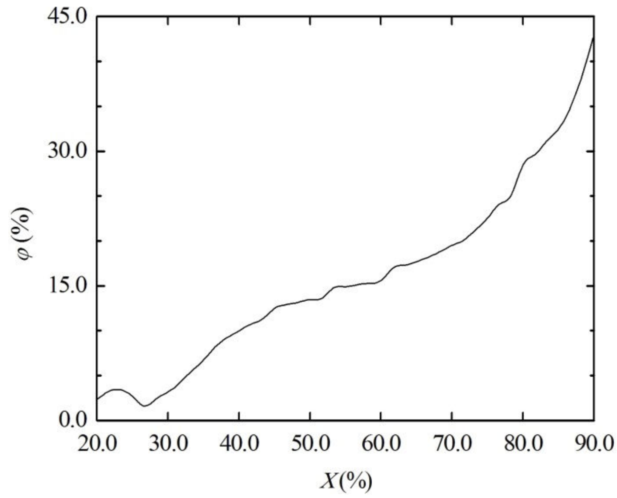

Figure 7. Theorethical SHP efficiency (φ) for all cases

5 CONCLUSIONS

This study allowed to evaluate the effects of the degree of freedom h, expressed in terms of the relative height (X), of a converter type SHP in relation to the theoretical efficiency of the converter. It was considered an incident wave with period $T = 3.00$ s, depth $d = 0.60$ m and height $H = 0.06$ m and an area restriction of $\phi = 0.05$ for a range of relative heights between 20.00 and 90.00 %.

Based on the analysis of the results, the higher performance of the SHP type WEC was achieved with the configuration of higher plate height $X = 90.00$ % and lower length $L/\lambda = 0.253$, among the considered values. The maximum efficiency found with this configuration was $\varphi = 42.91$ %. The minimum efficiency found was $\varphi = 1.59$ %, which represents an improvement of 41.32 % in the performance of the device, for the conditions analyzed. Thus, indicating the relevance of geometric optimization studies using the CD.

In future studies, it is intended to extend the analysis of this degree of freedom to other area restrictions, as well as to other incident wave characteristics in order to obtain a more efficient geometry for the SHP type WEC device.

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