21th International Conference on Renewable Energies and Power Quality (ICREPQ'23)
Madrid (Spain), 24th to 26th May 2023
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.21, July 2023

# Performance of Resonant Chambers in Oscillating Water Column Devices

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## Abstract.

The utilization of marine power potential in Colombia holds a great promise, and the oscillating water column (OWC) is one option that deserves to be explored. The wave energy conversion process using an OWC typically involves two stages: the conversion of wave power to pneumatic power in an air chamber, and the conversion of pneumatic power to electricity using a self-rectifying air turbine coupled to an electric generator. In order to improve the efficiency of the primary stage, this study is aiming at determining the hydrodynamic performance of an OWC air chamber using a numerical model based on the Reynolds Averaged Navier-Stokes equations and the Volume of Fluid approach for free surface simulation. The chamber geometry was based on a U-shaped OWC. The maximum efficiency and the mean velocity of the chamber free surface were found to be 66.8% and 0.17 m/s, respectively. The numerical results for the wave height obtained through simulation were validated by comparing them to analytical expressions reported in the existing literature, and a significant level of agreement was observed. Optimizing the chamber shape parameters for the specific wave characteristics is concluded to be crucial to enhance the operating efficiency of the OWC.

**Key words**. Oscillating water column, resonant chamber, efficiency, wave energy

## 1. Introduction

Harnessing wave energy plays a significant role in the energy transition of developing countries. Wave energy is a clean, renewable and abundant source of energy that can provide a reliable and sustainable source of power. It is estimated that the power available from wave energy is several times greater than the current global energy demand [1,2]. The technology used to convert this energy is still in its early stages of development, but significant progress has been made in recent years. Developing countries, as developed ones, seek to reduce their reliance on fossil fuels; therefore, wave energy presents a viable alternative. In addition to the advantages of being renewable and abundant, wave energy has other benefits, including low operating costs, minimal land use, and a reduced carbon footprint. However, it is essential to consider the environmental aspects of wave energy. The construction and operation of wave energy devices may impact marine ecosystems, and proper environmental impact assessments and monitoring are necessary to ensure that the deployment of wave energy does not cause harm to marine life. With a careful planning and implementation, the harnessing of wave energy can contribute to a more sustainable future for developing countries [2, 3, 4].

There are several technologies that have been developed to harness wave energy, including oscillating water columns (OWCs). OWCs are attractive as they are simple, robust, and have minimal environmental impact. OWCs work by using the wave movement to compress and decompress the air in a chamber, which drives a turbine and generates electricity [1, 2]. One advantage of OWCs is that they can be located close to shore, which reduces transmission costs. Nevertheless, several challenges are ascribed to this technology, such as their susceptibility to storm damage and the high capital cost of building and deploying them. Additionally, the power output can be limited, and the need for a relatively large chamber to achieve a resonant frequency can be required [1, 5].

The components of an OWC include a chamber, a turbine and a generator [4]. The resonant chamber in an OWC is one of the most critical components of the system as it helps amplify the waves and increase the energy conversion efficiency of the device. This component serves as an interface between the incoming waves and the air turbine that generates electricity [1, 5]. In this regard, the design of the chamber is critical as it determines the resonant frequency and the efficiency of the system. For this purpose, numerical simulation can be used, allowing to optimize the chamber design and other components, as well as to understand the complex fluid dynamics involved in the energy conversion process [5, 6].

Concerning the chamber design, it is made to resonate at the same frequency as the incoming waves, which causes the water column inside the chamber to oscillate and drive the air through the turbine. The chamber geometry, volume and shape are essential parameters that determine its resonant frequency and, consequently, the device power output. Therefore, understanding the behaviour of the resonant chamber is crucial for the optimal design and operation of an OWC system. Numerical simulation of the resonant chamber can provide insights into the complex flow dynamics and aid in the optimization of its geometry and other parameters for maximum power extraction [5, 6].

Wave energy has an estimated efficiency ranging from 50% to 70%, making it one of the most efficient forms of renewable energy [1, 2]. In turn, solar energy has an efficiency range between 15% and 20%; while for wind energy an efficiency between 20% and 40% has been reported, depending on the location and technology used. However, hydropower has an estimated efficiency of 90%. Each of these renewable energy sources has advantages, with wave energy being a predictable source of energy, while solar energy is readily available in most parts of the world, and wind energy is the most cost-effective. Hydropower has the potential to provide a large amount of energy, but it is highly dependent on rainfall and water supply [7, 8, 9]. Overall, the efficiency and advantages of these renewable energy sources make them a viable alternative to traditional fossil fuels .

Phenomenological research plays a crucial role in improving the efficiency of renewable energy utilization technologies for electricity generation. By conducting in-depth studies and analyses of the physical phenomena that govern the behaviour of renewable energy sources and their interactions with energy conversion systems, researchers can identify opportunities for optimization and innovation. For example, the effects of different parameters such as weather conditions, geographic location and system design on energy production and efficiency can be explored. This information can then be used to develop new technologies or to refine existing ones to maximize energy output and reduce waste. Therefore, investing in phenomenological research is critical to achieving a more sustainable and reliable energy future.

Under this scenario, the focus of this research is on conducting a numerical simulation of the OWC chamber in order to investigate the effect of the geometry on the OWC efficiency. For this purpose, a two-dimensional (2D) numerical simulation was carried out using the ANSYs Fluent software. The response variable was the efficiency of the OWC resonant chamber.

## 2. Material and methods

An OWC is a highly efficient device for capturing and extracting the wave energy with many advantages ascribed. It is a simple structure and easy to be manufactured. In addition, the generation of greenhouse gases or significant waste during its operation is limited [5, 6]. The basic design of an OWC consists of a partially submerged structure with a hollow bottom (wave resonant chamber) and an air chamber below the sea level. The movement of the waves creates pressure on the air inside the chamber, which in turn drives a Wells turbine that generates electricity [5, 6]. To optimize the OWC design and efficiency, it is essential to consider the wave characteristics of the installation site. The proposed geometry of the OWC wave resonant chamber (Fig. 1a) is less vulnerable to extreme wave conditions and has a front ramp that facilitates wave entry while decreasing sediment intrusion [5, 6]. A 2D computational domain was used to perform a fluid dynamic analysis of the resonant wave chamber behaviour. The computational domain boundary conditions are defined in Fig. 1b. To evaluate the chamber efficiency (ε), the water surface elevation and the chamber efficiency are monitored.

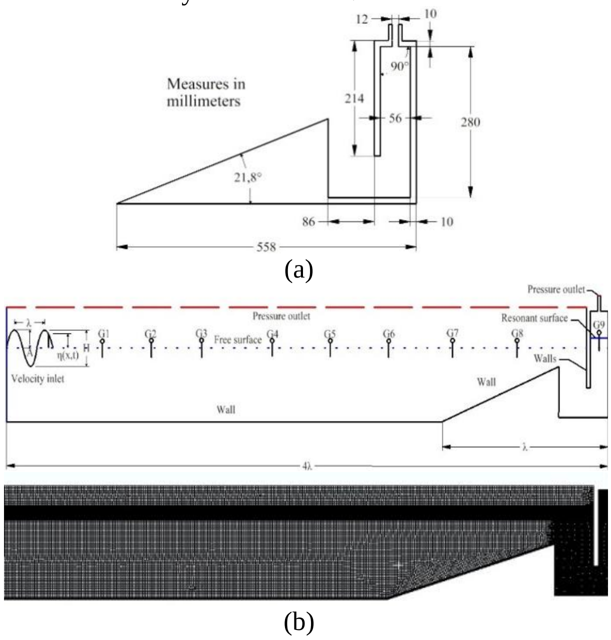


Figure 1. a) Geometry of the resonant chamber, b) computational domain

In order to assess how the resonant chamber is effectively performing, the water surface elevation (η) was carefully monitored, and ε was calculated. The monitoring of the elevation was carried out through the utilization of defined points $G_1$, $G_2$, ..., $G_9$. Various parameters are used to characterize the waves that enter the resonant chamber, such as the wave height (H), period (T), length (λ), amplitude (A), free water surface elevation (η), and the depth (h), in which the waves propagate [10]. The literature offers analytical expressions that relate the horizontal distance (x) and the time instant (t) to η, allowing for a thorough analysis of the resonant chamber performance.

Equation (1) correlates the water surface elevation (η) with the horizontal distance (x) and time (t), which are derived from the analytical wave theory developed by Airy [11].

$$\eta(x,t) = \frac{H}{2}\cos(kx - \omega t) \tag{1}$$

where k and ω are the wave number and the angular frequency, and are calculated as 2π/λ and 2π/T, respectively. To simulate the hydrodynamic behavior of the waves in a laboratory-scale channel, the wave characteristics of the Colombian Pacific Ocean under swell conditions were considered, as reported by Portilla et al [12]. The simulation process used wave front characteristics, such as H=0.02 m, λ=1.47 m and h=0.225 m [12]. The chamber efficiency (ε) can be evaluated using Equation (2), which relates the incident wave power ($P_{in}$) to the average pneumatic power obtained at the output of the device ($P_{out}$), as defined by the literature [11].

$$\varepsilon = \frac{P_{out}}{P_{in}} \tag{2}$$

Equation (3) provides the value of $P_{in}$ over a period of T, which can be expressed as a function of the total energy per period (E) and the group velocity ($C_g$), as given by Equations (4) and (5), respectively.

$$P_{in} = EC_g \tag{3}$$

$$E = \frac{1}{2}\rho g\left(\frac{H}{2}\right)^2 \tag{4}$$

$$C_g = \frac{1}{2}\frac{\omega}{k}\left(1 + \frac{2kh}{\sin(2kh)}\right) \tag{5}$$

Equation (6) can be used to compute the average pneumatic power for regular waves by integrating the product of the instantaneous pressure drop inside the chamber (ΔP) and the volumetric flow rate (Q(t)) over time from an initial to a final T during the simulation. For a 2D geometry, Q(t) is expressed as $S_{chamber}$*$V_{fs}$, where $S_{chamber}$ is the area of the water plane of the resonant wave chamber, defined as b*w with b=0.056 m and w=1 (perpendicular to the wave propagation plane). $V_{fs}$ is the free water surface velocity in the vertical direction (m/s).

$$P_{out} = \frac{1}{T_{end} - T_{ini}}\int_{T_{ini}}^{T_{end}} \Delta P\, S_{schamber}\, V_{fs}\, dt \tag{6}$$

$V_{fs}$ refers to the velocity of the free water surface, and it can be determined by utilizing the third-order approximation reported by [10] and [11], which involves taking the first-time derivative of η within the resonant chamber. Alternatively, Equation (7) can also be employed to estimate $V_{fs}$, which is the approach taken in this particular study.

$$V_{fs} = \frac{\mathrm{d}[\,\eta(x,t)\,]}{\mathrm{dt}} \tag{7}$$

To simulate the interface between water and air, the Volume of Fluid method was employed with a time-step of 0.001 and a maximum iteration limit of 35, using a convergence criterion of residuals of $10^{-6}$ [13]. The surface points were set to f=0.5. The regular wave generation was conducted at the left side boundary of the channel, with a wave H of 0.02 m and a λ of 1.47 m. Pressure outlet conditions at the top of the channel and at the air outlet in the resonant wave chamber were set to 0 Pa. The no-slip condition was applied to the bottom of the channel and the walls of the OWC to capture the boundary layer developed between them. The power take-off (PTO) system was modelled using a rectangular hole drilled in the top of the device, and the mesh was generated using ANSYs Fluent meshing solver, with refinements made to the free water surface area, channel walls, and resonant wave chamber. Figure 1b depicts the mesh used in the simulations. An independence analysis was performed to ensure the mesh size and time step used were suitable for the simulation. The simulation began with the assumption that the fluids were at rest at t=0 s.

## 3. Results and discussion

Fig. 2 displays the results of comparing the numerical and analytical assessments of the elevation of the unconfined water surface. The analytical solution was computed using Equation (1) [13].

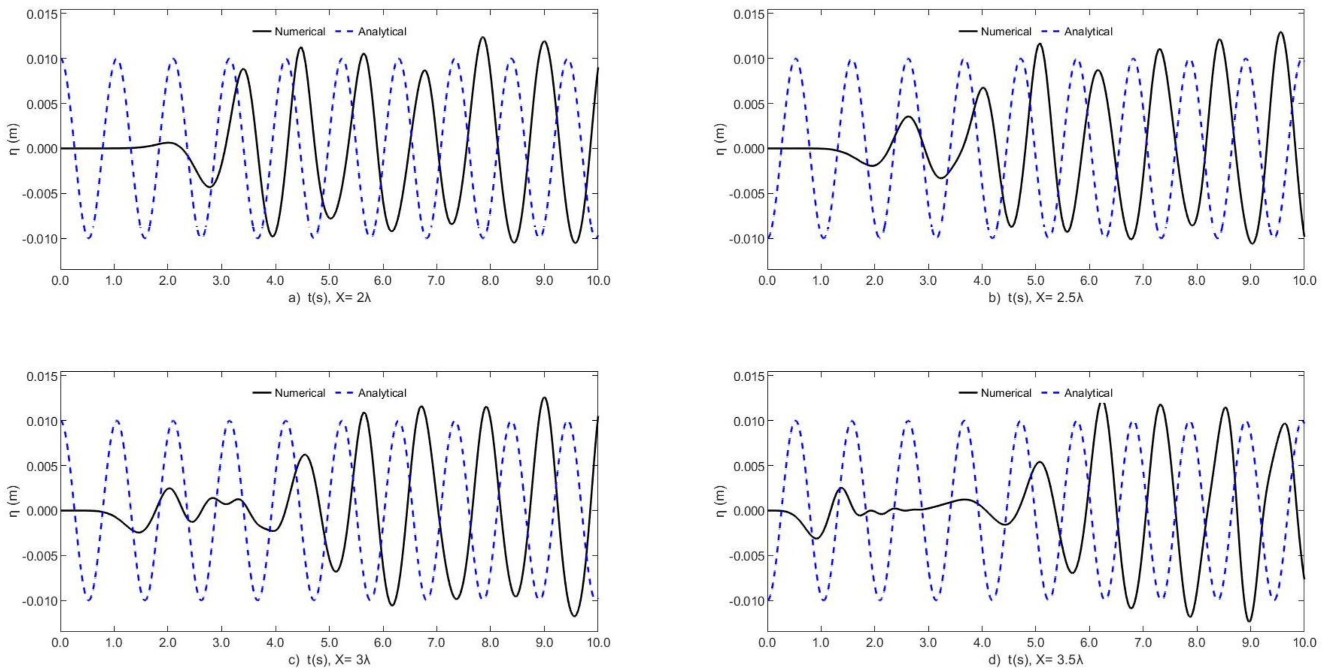


Fig. 2. Comparison between the numerical and analytical results to validate the wave for a height (H) of 0.02 m at several distances from the wave generator, including a) X= λ, b) X=1.5λ, c) X=2λ, d) X=2.5λ, e) X=3λ, and f) X=3.5λ

The simulation results at t=15.34 s is presented in Fig. 3. In the figure, the phase contour is illustrated in blue and red colours representing air and water, respectively. The plot highlights the flow characteristics and behaviour of the resonant chamber.

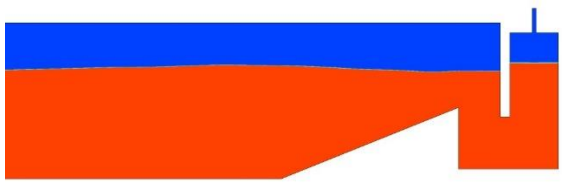

Fig. 3. a) Phase contour at t= 15.34s

The numerical and analytical results exhibit a high level of consistency. To confirm the wave propagation and generation in the channel, the elevation of the free water surface at various distances from the wave generator was examined using computational fluid dynamics (CFD) and an analytical solution from Equation (1), as illustrated in Fig. 3. Equations (2), (3), and (6) were employed to calculate the efficiency of the wave resonant chamber, which required computing the $V_{fs}$ and $\Delta P$. To determine the OWC $\varepsilon$, it was necessary to quantify the incident wave power utilizing Equation (3). Under the wave conditions studied here, $P_{in}$ was determined to be 0.504 W. Similarly, Equation (6) was employed to compute the pneumatic output power, requiring the numerical determination of $\Delta P$ and $V_{fs}$ during a steady time period ranging from 7.61 to 8.7 s, corresponding to a T of 1.09 s. To obtain the area under the curve, numerical methods were used with a $\Delta t$ of 0.001 s. The resulting $P_{out}$ was 0.337 W, leading to a $\varepsilon$ value of 66.8%.

The hydrodynamic performance ($\varepsilon$) of an OWC resonant chamber can be optimized by considering four key factors in the design illustrated in Fig. 4. These include h1/h, b2/h, d/b2, and $\alpha$, where h represents the depth of the water, h1 is the vertical length of the front wall, b2 is the width of the chamber resonant, d is the width of the air outlet, and $\alpha$ is the angle of inclination of the front wall. By using the response surface methodology (RSM) through a design of experiment, it is possible to achieve the optimal $\varepsilon$ for the resonant chamber. By carefully considering these geometric design parameters, the hydrodynamic performance of the OWC can be enhanced, which can lead to a greater energy efficiency and overall system effectiveness.

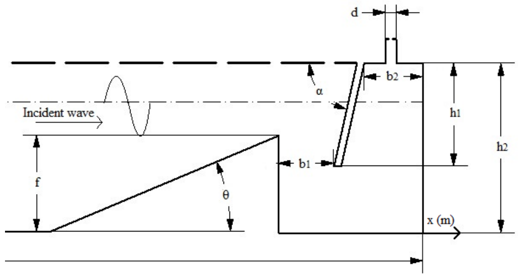


Fig. 4. Geometric factors of the resonant chamber of a water column that can be considered for optimization

## 4. Conclusion

An analysis of the performance of a resonant wave chamber designed to harness the wave energy in the Pacific Ocean of Colombia was presented. The numerical simulation, which utilized the Volume of Fluid method in ANSYs Fluent CFD software, yielded a relatively low chamber efficiency ($\varepsilon$) of 66.8%. To improve this efficiency, an optimization study of the key geometric factors of the resonant chamber is necessary. These factors include the length, inner width, immersion depth, and angle of inclination of the front wall, as well as the diameter of the air outlet. Understanding the significance of these parameters and their interactions in capturing the energy of a wave front is crucial, and response surface or surrogate model methodologies could be considered as tools of utmost importance.

## Acknowledgement

The authors gratefully acknowledge the financial support provided by the announcement No. 890 de 2020 “Convocatoria para el fortalecimiento de CTeI en Instituciones de Educación Superior (IES) Públicas 2020 (Contract No. 2022-0452).

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