Vol. 23, n.°3, pp. 117-140, 2024
Revista UIS Ingenierías
https://revistas.uis.edu.co/index.php/revistauisingenierias
Universidad Industrial de Santander

Design Considerations of the Resonant Chamber of an Oscillating Water

Consideraciones del diseño de la cámara de resonancia de una columna de agua oscilante

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Received: 15 January 2024. Accepted: 30 August 2024. Final version: 28 September 2024.

Abstract

One of the most promising devices for harnessing the energy of the waves is the oscillating water column (OWC). Since its creation, it has been evidenced that this device has been a subject of multiple investigations focused on improving its hydrodynamic efficiency. Several geometric factors influence the efficiency of the water resonant chamber. Among these parameters, the internal length or width, the inclination angle of the front wall, and the depth of the immersion stand out, as well as the air outlet diameter. In this regard, it is crucial to understand the importance of these factors and their interactions in the process of capturing the energy contained in a wave front for the subsequent design optimization of this type of structure. For this purpose, the response surface methodology or the surrogate models are regarded as a good option to study the sensitivity of these factors on their effect on the efficiency of the resonant chamber. In this work, the research of the main considerations for the design of an OWC resonance chamber under a wide variety of wave conditions are described.

Keywords: ANSYS; design; numerical simulation; renewable energy; wave energy.

Resumen

Uno de los dispositivos más prometedores para aprovechar la energía de las olas es la columna de agua oscilante (OWC, por sus siglas en inglés). Desde su creación, se ha puesto de manifiesto que este dispositivo ha sido objeto de múltiples investigaciones centradas en mejorar su eficiencia hidrodinámica. Existen varios factores geométricos que intervienen en la eficiencia de la cámara de resonancia de agua. Entre estos parámetros destacan la longitud o anchura interna, el ángulo de inclinación de la pared frontal y la profundidad de inmersión, así como el diámetro de salida del aire. En este sentido, resulta crucial discernir la importancia de estos factores y sus interacciones en el proceso de captación de la energía contenida en el frente de onda para la posterior optimización del diseño de este tipo de estructuras. Para ello, la metodología de superficie de respuesta o los modelos subrogados se consideran una buena opción para estudiar la sensibilidad de estos factores sobre su efecto en la eficiencia de la cámara resonante. En este trabajo, se describe el proceso investigativo sobre las principales consideraciones para el diseño de una cámara de resonancia OWC bajo una amplia variedad de condiciones de oleaje.

Palabras clave: ANSYS; diseño; simulación numérica; energía renovable; energía de las olas.

ISSN Online: 2145 - 8456

How to cite: J. Parra-Quintero, A. Rubio-Clemente, E. Chica-Arrieta, “Design Considerations of the Resonant Chamber of an Oscillating Water,” *Rev. UIS Ing.*, vol. 23, no. 3, pp. 117-140, 2024, doi: https://doi.org/10.18273/revuin.v23n3-2024010

1. Introduction

The OWC (oscillating water column) is a hollow structure that is partially submerged at its lower part (i.e., the wave resonant chamber), containing an air chamber below sea level. The incoming wave front entering the resonance chamber generates an oscillating hydrodynamic pressure distribution within the device, leading to the internal fluid oscillation [1]. The wave movement translates into pressure on the air inside the chamber, causing it to expand and compress, which actuate a Wells turbine and subsequently drives an electric generator. Unlike impulse turbines, this type of turbine has been found to be potentially more efficient [2] and has been widely implemented in studies for harnessing energy from OWC systems [2], [3]. Consequently, this high-pressure air can be used to drive a turbine connected to a power take-off (PTO) system for energy conversion [4], [5]. This energy can be harnessed to diversify the energy basket and support distributed generation, meeting the demand for electrical resources in non-interconnected zones (NIZ) of Colombia [6].

It is worth noting that nowadays, most countries worldwide aim to meet their energy demand through non-conventional renewable energy sources (NCRES) [7], [8]. According to the United Nations (UN), 90% of the global target for reducing carbon dioxide (CO_2) emissions by 2050 will depend on increased integration of renewable energies, more efficient resource utilization, and the electrification of societies and the economy [9]. The United States and China have adopted medium and long-term mitigation strategies to counteract the serious effects of greenhouse gases (GHG), reduce energy consumption, and promote development through renewable sources [10].

Colombia is not exempt from this approach; hence, as part of its national energy plan, one of the strategies to reduce the energy sector’s vulnerability is to seek diversification of the electric generation matrix across all supply chains, thereby increasing availability and reliability [11], [12]. The incorporation of NCRES into the Colombian electricity market will significantly reduce the country's CO_2 emissions and enable it to fulfill its medium and long-term commitments and policies [13]. In this regard, the country faces immense challenges, including technological development and adaptation for the utilization of NCRES, the advancement of human expertise in energy production and energy efficiency matters, as well as the exploration of funding resources for building the essential infrastructure that guarantees fairness and societal progress, all while addressing the repercussions of climate change and promoting sustainable growth [6]. Given that in Colombia, it is expected that 15% of the energy will come from NCRES by 2030 [12], [14], and with the aim of contributing to a competitive, integrated, diverse, secure, and inclusive energy basket throughout the territory (especially for NIZ), it is essential to advance towards the development, study, and inclusion of new NCRES utilization systems.

From the numerous renewable energy alternatives, marine energy offers a hopeful outlook, given that more than 70% of the Earth's surface is enveloped by oceanic waters and there is a significant potential for wave energy [15]. Waves are generated by the proliferation and movement of wind currents over the water surface, which are indirectly influenced by the sun's rays on the Earth [16]. According to the same author, about 33.33% of the total global energy comes from renewable energies, and only 0.02% of this percentage, comes from waves, not tides.

There is a wide variety of wave resonant chambers in the literature, considered as the main OWC component. Therefore, for designing an efficient OWC, it is necessary to have an in-depth understanding of this component and optimize it according to the characteristics of the local wave conditions. These unique features make the OWC an attractive proposition for small-scale electricity generation. Under this scenario, given the significance of implementing an efficient OWC for harnessing wave energy, this work presents the main advancements and design considerations of the resonant chamber of an OWC for its optimization. The operational principle and components of an OWC wave energy converter are described. Additionally, the characteristics of the wave energy resource in the coastal areas of Colombia are outlined, and various studies conducted to date concerning the air chamber of the afore mentioned device are reported.

2. Materials and methods

2.1. Data source and search strategy

Scopus is a comprehensive database for abstracts and citations that encompasses a broad array of fields of study through book chapters, conference proceedings, commercial publications, and scientific journals [17]. Moreover, it is considered one of the most widely used databases for searching scientific and academic publications [18]. In this section, a systematic search related to research articles from recent years was conducted using this database, focusing on the design and optimization considerations of the resonant chamber of an OWC.

For this purpose, three search algorithms were employed. In first algorithm, the code [TITLE-ABS-KEY (oscillating AND water AND column AND wave AND energy)] was used. For the second and third algorithms, the search criteria [TITLE-ABS-KEY (oscillating AND water AND column AND performance AND owc)] and [TITLE-ABS-KEY (water AND column AND design AND chamber AND performance)] were applied, respectively.

3. Results and discussion

The results of the search obtained through the three afore mentioned algorithms based on the information found in Scopus were analyzed, as well as the interest of the scientific community in generating and disseminating new knowledge on topics related to wave energy.

3.1. Preliminary approache

During the first search [TITLE-ABS-KEY (oscillating AND water AND column AND wave AND energy)], 1633 results were obtained from 1977 to 2022 using the first search algorithm. It was found that China, Portugal, and the United Kingdom were the countries with the highest number of publications, with 198, 183, and 172, respectively. Approximately 57.4% of the studies found in the first algorithm were scientific articles, 37.6% were conference papers, and the remaining 5% included book chapters, review articles, conference reports, and notes. Regarding the second search [TITLE-ABS-KEY (oscillating AND water AND column AND performance AND owc)], China was found to be the leading country in terms of the number of publications on the topic, with a total of 129 documents.

English, Mandarin, and Japanese were the predominant languages, accounting for 97.3%, 1.9%, and 0.5%, respectively. Under this second search, 649 documents were found, of which research articles represented the highest percentage, comprising about 63% of all publications from 1984 to 2022. Figures 1 and 2 depict the upward trend in publications reported in the scientific literature using search algorithms 1 and 2, respectively. In the final search stage [TITLE-ABS-KEY (water AND column AND design AND chamber AND performance)], which encompasses the main topic of this study (design considerations for optimizing an OWC chamber), approximately 134 documents have been published from 1984 to 2022, with 124 in English, 8 in Mandarin, and 2 in Japanese. Furthermore, it was found that 68.7% of the documents are research articles, 24.6% are conference papers, and the remaining 6.7% includes book chapters, reports, and review articles. Authors with the most significant impact were identified as Ahmed Shawki Elhanafi and Gregor J. Macfarlane, based on the H index obtained through Biblioshiny for bibliometrix®. Figure 3 illustrates the total number of documents published each year. Similar to Figure 2, this figure shows the increasing trend in research related to the topic of interest in this study, culminating in the most recent year.

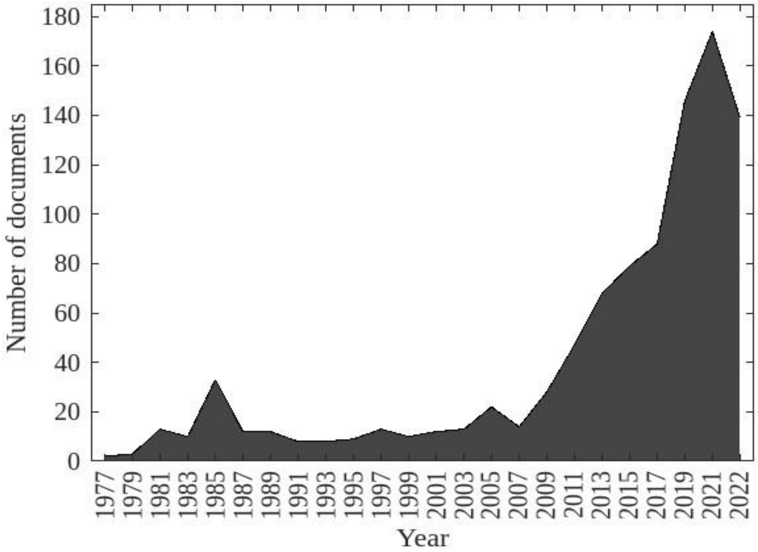


Figure 1. Documents reported from 1977 to 2022 under the search algorithm [TITLE-ABS-KEY (oscillating AND water AND column AND wave AND energy)]. Source: Scopus database.

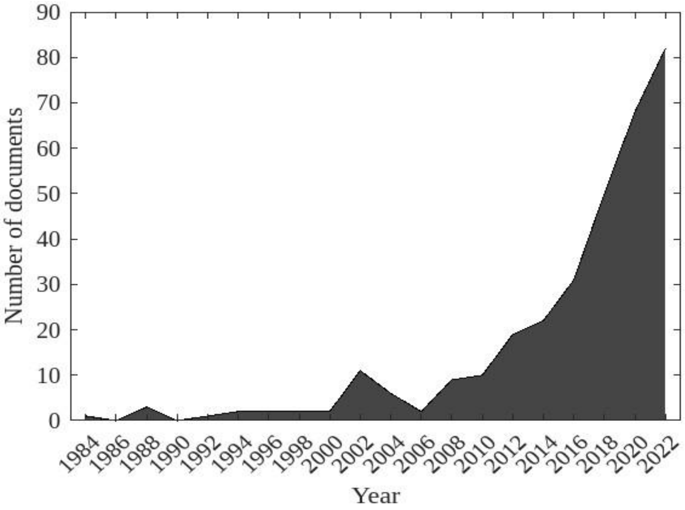


Figure 2. Documents reported from 1984 to 2022 under the search algorithm [TITLE-ABS-KEY (oscillating AND water AND column AND performance AND owc)]. Source: Scopus database.

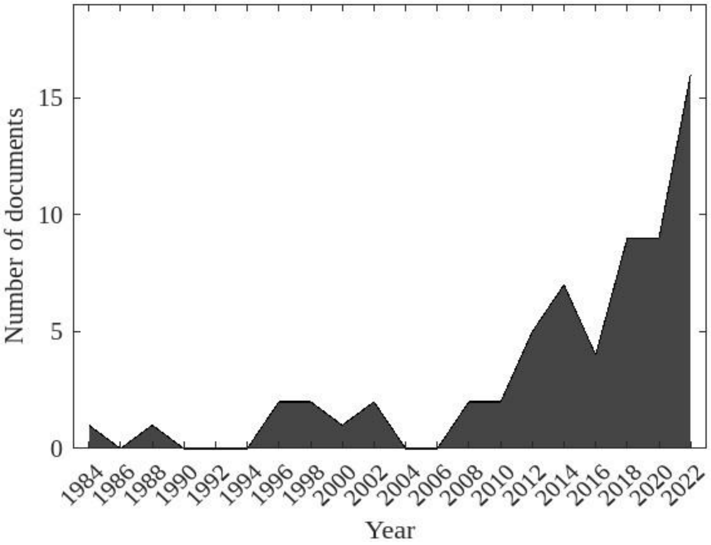
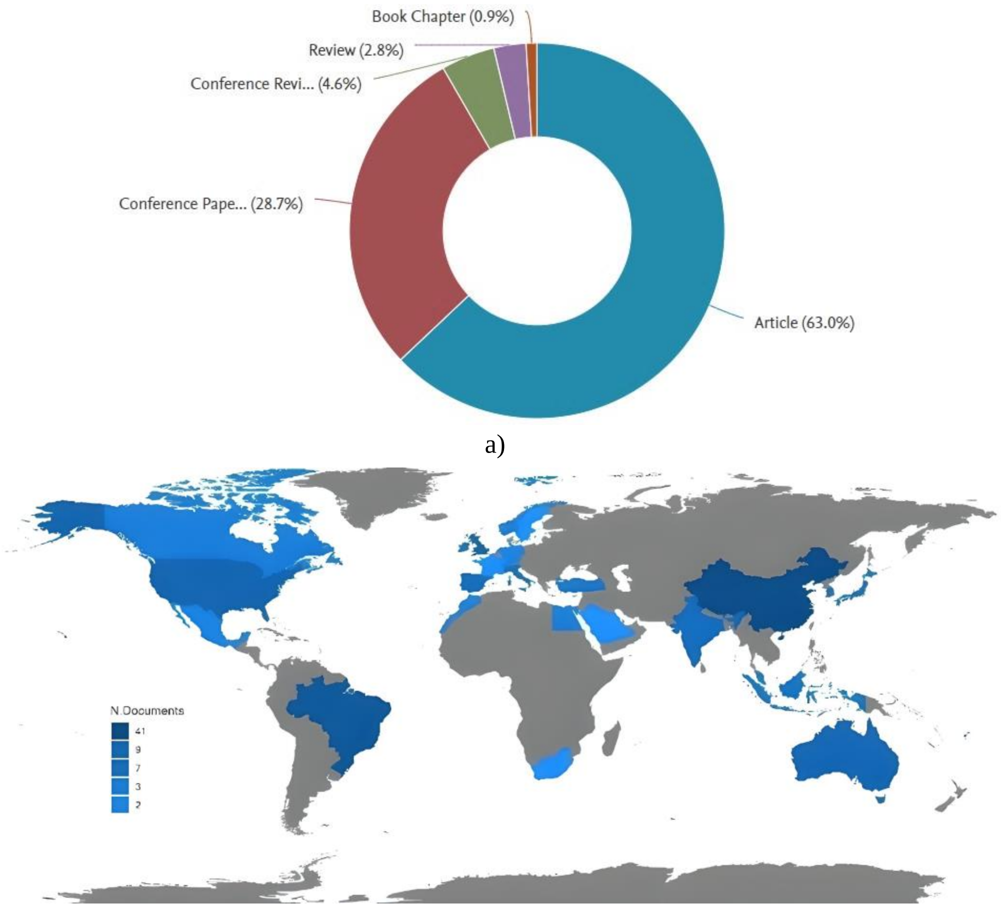


Figure 3. Documents reported from 1984 to 2022 under the search algorithm [TITLE-ABS-KEY (water AND column AND design AND chamber AND performance)]. Source: Scopus database.

In all three searches, especially in that corresponding to [TITLE-ABS-KEY (water AND column AND design AND chamber AND performance)], it has been observed that most publications are related to research articles (Figure 4). In recent years, a significant number of publications have been dedicated to the study of OWC devices (Figure 1, Figure 2, and Figure 3). There is a growing trend over the past decades in generating new knowledge and novel documentation related to wave energy and OWC devices. This suggests a strong interest within the scientific community in the study and design of these devices for optimization purposes. Furthermore, China leads in scientific production related to the topic, followed by Brazil, the United Kingdom, and the United States. This could be explained by these countries having substantial wave energy potential compared to other nations worldwide [19], [20]. Brazil is the country with the highest scientific production in this field of interest in Latin America. This can be explained by the fact that approximately 45.0% of its primary energy demand comes from renewable energy [21], and the wave energy exploration has been an opportunity to meet part of its electricity demand [22]. Hence, its growing interest in the study of devices that can capture wave energy, especially OWC.



b)

Figure 4. (a) Classification of publications according to the document type. Source: Scopus database. (b) Global distribution of publications. Source: Biblioshiny – Bibliometrix®. Search algorithm [TITLE-ABS-KEY (water AND column AND design AND chamber AND performance)].

In the search related to the algorithm [TITLE-ABS-KEY (water AND column AND design AND chamber AND performance)], He et al. [23] are the authors with the highest number of citations up to 2022. They studied a break water performance with and without OWC and found that the inclusion of the device on the structure is a viable option to dissipate incident energy on the structure, minimizing wave reflection and smoothing the large impacts on the breakwater. They are followed by Elhanafi et al. [24] with 95 citations, who experimentally studied the onshore and offshore device and modeled the three-dimensional (3D) OWC using computational fluid dynamics (CFD) and Reynolds-Averaged Navier-Stokes-Volume of fluid (RANS-VOF) to validate the experiment with regular and irregular incident waves. Finally, there is Kamath et al. [25], who two-dimensionally (2D) simulated the OWC under waves of different wavelengths.

Since the primary focus of this work is related to the design considerations of the resonant chamber of an OWC, the documents associated with the third algorithm were used in the development of this study. From each published research, relevant information such as author, publication year, response variable, numerical simulation methods, design considerations, parameters, and optimal values were extracted in order to obtain the most important aspects regarding the optimization of the resonant chamber design of an OWC.

3.2. OWC components

WEC (wave energy converter) are used to harness the available wave energy resource. These devices can capture the ocean wave resource using various physical principles through the presence of progressive incident waves for energy extraction [26], [27]. An OWC-type device is considered a WEC [26]. Some benefits of this device compared to co-generation using steam turbines and coke ovens, fuel cells, and power plants include its simplicity in design and construction, low operating and maintenance costs and its ability to supply electrical energy to remote areas without soil contamination and health risks, maintaining this wave resource in its natural state while demonstrating long-term operation capability with high reliability and survivability [15], [28]. Figure 5 identifies the main OWC components, which consist of a resonant chamber (2), a generator (5), and a turbine (4). Essentially, the structure can be fixed or floating and is open to the sea below the water surface, allowing it to trap air inside above the internal free surface of the water that enters the chamber [11]. The incident wave action on the structure alternately compresses and decompresses the trapped air the chamber, forcing an air flow that moves forth and back through a turbine, driving a generator and producing electricity. As the water is withdrawn from the chamber, the resulting vacuum draws air through the turbine back into the chamber [26]. OWC can be installed onshore or in deeper offshore waters under extreme marine environmental conditions, which reinforces the structural design and materials quality requirements [28].

3.3. State-of-the-art related to an OWC

Ocean wave energy is considered a clean, abundant, and promising energy source worldwide. This energy can be converted into electrical energy using suitable devices that capture the energy of incident waves under different operating principles. According to Prakash et al. [29], waves can travel hundreds of kilometers with minimal energy loss. The power carried by the wave depends on its height and period and is usually given in power per unit length (W/m), representing the power per meter of wavefront. Figures 6 and 7 illustrate the distribution and global resource of energy contained in ocean waves [20], [30].

In the specific case of Colombia, the main delta morphology and the wave variability along the Colombian Pacific and Caribbean coasts have been analyzed [31]. Portilla et al. [32] studied wave conditions at Tumaco, Gorgona, Buenaventura and Bahía Solano, which are cities located in the Colombian Pacific Ocean, as shown in Figure 8. The researchers found that the significant wave height (H) and wave period (T) averages were 1.01 m and 6.14 s, 1.13 m and 7.53 s, 0.96 m and 8.21, and 1.17 m and 10.61 s, respectively.

On the other hand, Ortega et al. [33] and Osorio et al. [34] assessed the potential energy resources in the Colombian Caribbean Sea and Pacific Ocean. Their findings indicate that, in the majority of the Caribbean Sea, the most powerful waves occur in December, January, and February, irrespective of the presence of El Niño or La Niña phenomena. Figure 9 illustrates the seasonal fluctuation in the average wave power in the Caribbean Sea and the Pacific Ocean, respectively.

In the Caribbean Sea case, the peak values of average wave energy, approximately ranging from 5-7 kW/m, are observed during December through February, aligning with one of Colombia's windier summer periods. These periods also align with lower rainfall over the country, during which the water levels in rivers and reservoirs decrease.

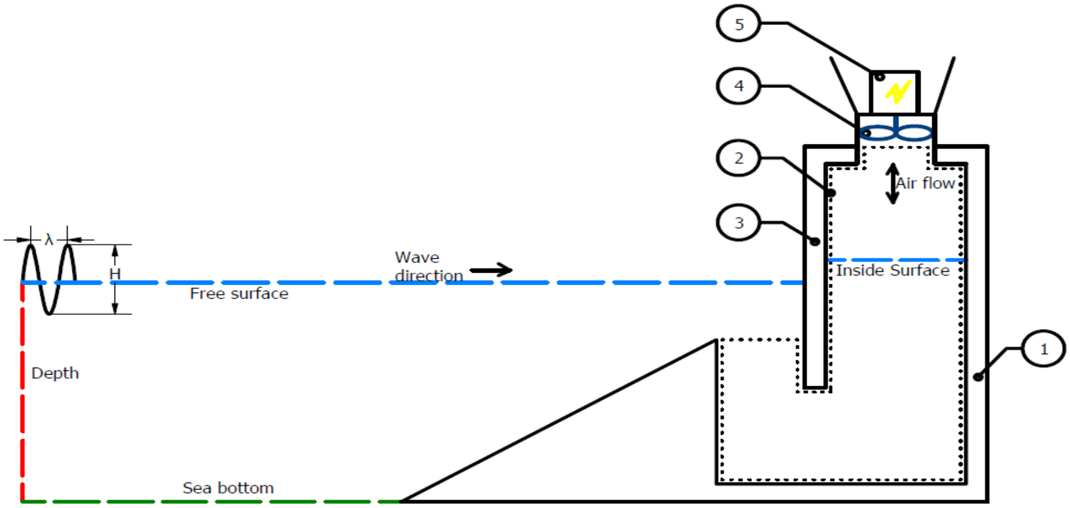


Figure 5. Oscillating Water Column (OWC) device. 1. OWC structure, 2. Resonant chamber, 3. Front chamber Wall, 4. Wells turbine, 5. Generator. Source: own elaboration.

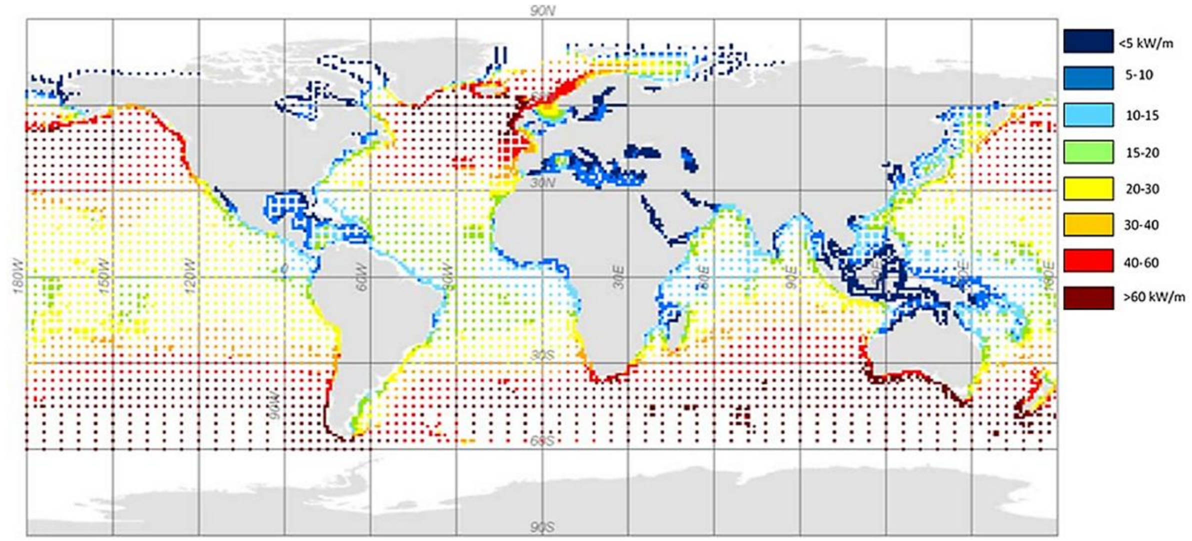


Figure 6. Wave power capacity (kW/m). Source: [20].

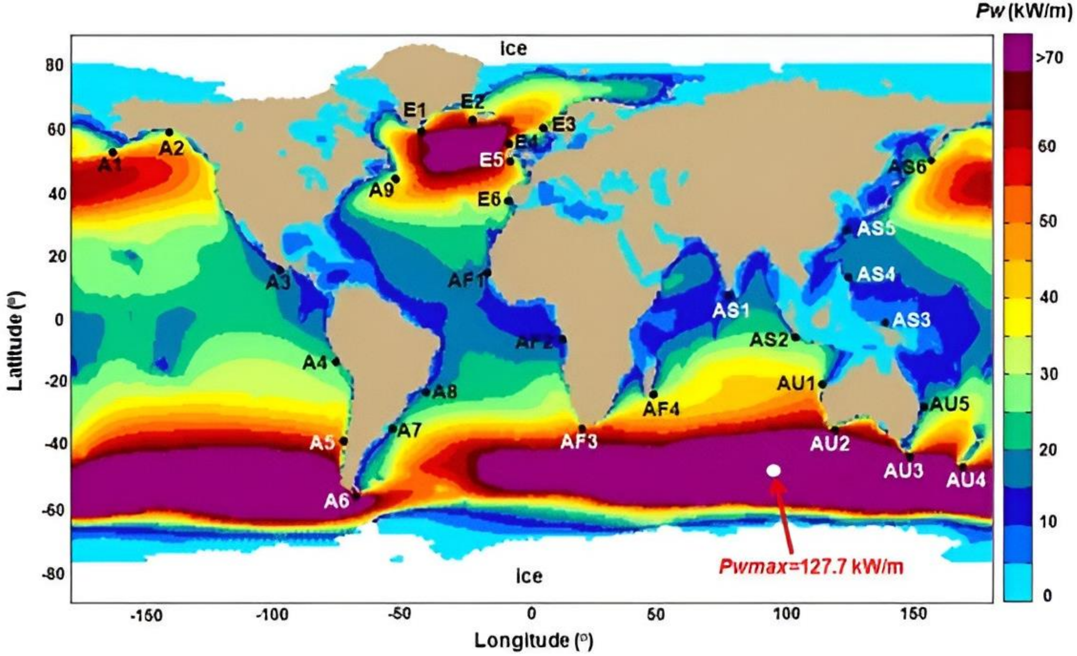
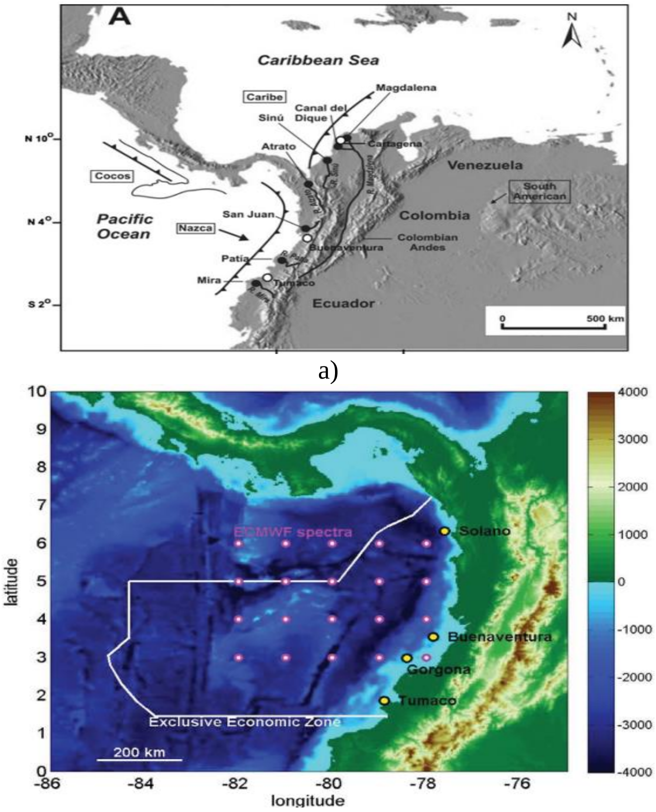


Figure 7. Global mean power map (kW/m). Source: [30].

Conversely, during the rainy season, the mean wave power only reaches around 1 kW/m. In the case of the Colombian Pacific coastline, the highest wave energy levels are roughly half of the projected energy capacity in the Caribbean Sea, measuring around 2-3 kW/m. This potential persists year-round, except for the period from June to August when the wave resource is less abundant.

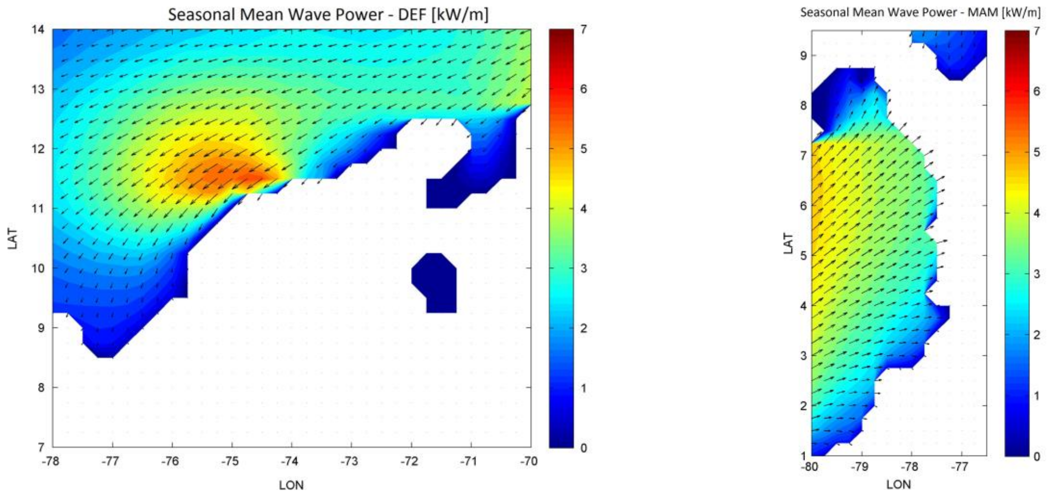
Colombia possesses a relatively modest wave energy potential when compared to other global regions. Nonetheless, this substantial available resource holds the potential to supplement the national energy grid, particularly during the summer months when reduced rainfall results in diminished hydroelectric energy generation due to lower river and reservoir levels. During such periods, thermal power plants are employed to complement the generation system, leading to elevated electricity costs and increased emissions of greenhouse gases. Wave energy also presents the opportunity to supply power to isolated regions within the country. In the event of integrating wave energy into Colombia's energy infrastructure, these installations should ideally be situated in proximity to urban centers with an accessible distribution network.



a)

b)

Figure 8. Global wave energy resource. (a) Colombian Pacific and Caribbean coast. Source: [31], (b) metrics and histograms of significant wave heights in the Colombian Pacific Zone. Source: [32].



a)

b)

Figure 9. Variation in mean wave power. (a) Wave power resource in the Caribbean Sea (kW/m), DJF (December-January-February) (b) Wave power resource in the Pacific Ocean (kW/m), MAM (March-April-May). Source: [33]

Regarding the coastal zone of the country that could be the most suitable for the installation of an OWC device, scientific literature reports that the highest wave energy capacity is found in the Caribbean Sea, near the coasts of Colombia and Venezuela, where there is a higher significant wave height [35], [36].

Most of the La Guajira coastal region has the most consistent and least year-to-year variability in wave height values for both the December to January and July to August seasons, making this area ideal for energy harnessing through an OWC

3.4. OWC worldwide

Worldwide, more than 1000 WEC have been developed and patented, including an OWC, which has been considered one of the most successful devices. This device is one of the most promising WEC globally and one of the few WEC that have reached the prototyping stage [37]. Hence, there is significant interest among researchers and companies in studying its hydrodynamic performance according to the wave conditions in regions rich in wave energy. For example, in places like Scotland, Portugal, China, Japan, Chile, and Italy, the hydrodynamics of an OWC have been extensively studied. The interest in OWC is such that even since the 20th century, structures capable of generating hundreds of kW of power have been constructed. Table 1 presents a list of some countries where significant advances in engineering and construction of such devices have been achieved.

OWC devices have been worldwide investigated using numerical, theoretical, and physical models. Since the resonance chamber is the main OWC component, to design an efficient OWC, it is necessary to thoroughly understand this component and optimize it according to the wave characteristics of the installation location. There are various types of resonance chambers in the literature, and Figure 10 shows the main models and their characteristics that have been studied the most.

Several research efforts have focused on optimizing the geometry of the resonance chamber to improve the efficiency of the OWC. Researchers aim to optimize variables such as velocity, pressure, absorption coefficient, and hydrodynamic efficiency based on the chamber's geometry. Over the years, it has been discovered that an OWC can be improved by extending the chamber structure with protruding or extruded walls in the direction of the waves, forming a port or collector [38].

Given the significant interest in studying the OWC, López et al. [39] conducted experimental research on the performance of the geometry as shown in Figure 10a. The referenced authors conducted a total of 387 tests, from which they deduced that the diameter of the outlet orifice is 15.6% of the width of the resonance chamber. In Ning et al. [40], numerical and experimental evaluations of the geometry shown in Figure 10 were conducted in a wave flume with a wave height of 1.8 m and water depth of 0.8 m. Ning and colleagues obtained favorable results, inferring that the ratios of chamber front wall immersion depth (h2) and exit hole diameter (d) to width (b2) that maximize the output variables were within the ranges of 0.2 to 0.25 and 0.0571 to 0.072, respectively.

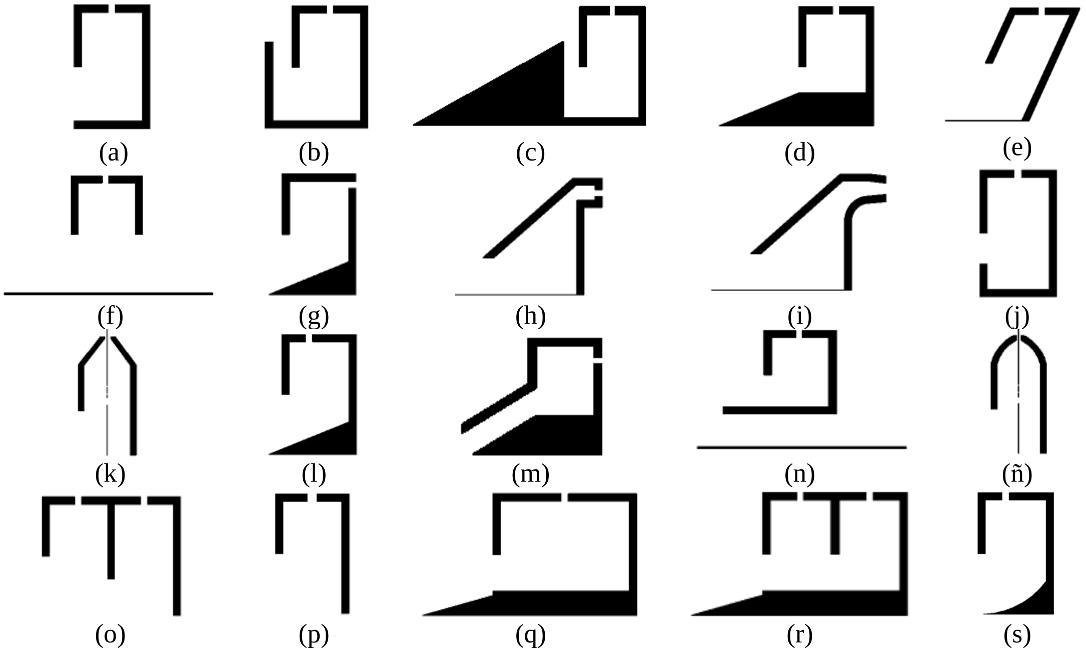


Figure 10. Designs reported in the literature. Source: own elaboration.

Vyzikas et al. [41] studied the behavior of different OWC chamber geometries, modifying some configurations of the classic designs. The authors considered models represented in Figure 10a, Figure 10b, Figure 10c, and Figure 10d as objects of study. For their research, they examined the interaction of these four models under regular and irregular waves, with each model differing from the others in terms of inclination parameters, depth, and front wall immersion distance. Although models illustrated in Figure 10b and Figure 10c showed promising results, the one represented in Figure 10c yielded better outcomes.

In Abbasi et al. [42], the device efficiency was studied through cylindrical designs of the air chamber of the model shown in Figure 10k. They claimed that, unlike the rectangular chamber, the energy losses around sharp edges and corners are minimized in the cylindrical configuration, as turbulence and splashing effects cause energy loss at the corners and edges of a chamber with a rectangular shape when interacting with waves.

Seok Jeong et al. [43] studied the geometry of the inclined OWC represented by Figure 10e, the authors analyzed the hydrodynamic characteristics of the device (pneumatic pressure and air flow rate), for that purpose they initially employed the FEM (Finite Element Method) and determined that the air flow rate and pressure change tend to decrease or increase with respect to the incoming wave height of the wave front.

Table 1. Real OWC constructions and power generation maximum capacity

Year	Site	OWC Company	Max. Capacity [kW]	Location	Reference
1983-1984	Japan	Sanze shoreline gully	40	Onshore	[38]
1985	Hébrida Island of Islay, Scotland	Wavegen-LIMPET	500	Onshore	[98], [99]
1985 - 1988	Toftestallen, Bergen, Norway	CONWEC	300 [4] 500 [26] [38]	Nearshore	[38]
1990 - 1992	Sakata, Japan	Sakata	60	Nearshore	[38] [19],[100]
1990	Trivandrum, India	Bottom-standing OW	125	Nearshore	[4], [38]
1991	Islay, Scotland	-	75	Onshore	[38], [4]
1995 < 2001	United Kingdom	OSPREY	2000	Nearshore	[38], [4]
1998 - 2000	Gokasho Bay, Mie, Japan	Mighty Whale, JAMSTEC	110	Offshore	[38], [19]
1999	Pico, Azores, Portugal	-	400	Onshore	[38], [100], [26]
2000	Islay, Scotland	LIMPET	500	Onshore	[38], [100]
2001	Guangdong, China	-	100	Onshore	[38], [4]
2007	Niigata port, Japan	-	450-880		[26]
2008	Ireland	Oe Buoy	1000	Onshore	[98], [4]
2008 - 2011	Mutriku, Basque Country, Spain	Wavegen	300	Nearshore	[4], [38], [101]
2008 - 2011	Galway Bay, Ireland	CORES	13	Offshore	[38], [26]
2010	Australia	Oceanlinx Mk3	-	Nearshore	[38]
2012 - 2016	Civitavecchia, Italy	REWEC3	25	Onshore	[38], [4], [101]
2013	Australia	Oceanlix	1000	Offshore	[98], [102]
2014	Port Adelaide, Western Australia	greenWAVE ,Oceanlinx	1000	Nearshore	[4], [102]
2015 - 2017	Yongsoo, Jeju Island, South Corea	Yongsoo WEc	500	Offshore	[38], [4], [26]

In that sense, the numerical results were verified by comparing them with scale model tests, revealing that the energy conversion efficiency shows a non-linear response dependent on the height of the incident waves.

In another study Mahnamfar and Altunkaynak [44] determined that by varying the width, angle, and length of the air chamber, an efficient OWC structure could be designed and constructed. In this regard, significant results have been reported for the chamber width. Bouali and colleagues [45] used numerical simulations and found that the ideal width of the resonant chamber should be between 0.8 and 1 times the water depth. The authors also demonstrated that there is an optimum efficiency when the immersion of the front wall is ranging from 0.38 to 0.44 times the water depth.

On the other hand, Mahnamfar and Altunkaynak [44] compared the geometry of a conventional chamber like the model shown in Figure 10h, with a modified chamber as shown in Figure 10i, using wall inclination angles of 47°, 40°, 35°, and 30°. The authors conducted their research at laboratory scale, comparing numerical results (obtained through Ansys Fluent and Flow 3D) with experimental results using a data acquisition system and wave gauges located at distances of 2.75 and 4.75 m from the OWC. It was concluded that the numerical model results closely followed the results of the experimental model (R^2 for the classic OWC = 0.9787 and R^2 for the modified OWC = 0.9889). Furthermore, the results demonstrated that the modified chamber achieved better hydrodynamic efficiency under the simultaneous combination of the following parameters: 40°, 41 cm opening height, and 91 cm front plate length, under a series of regular waves.

In another study, Howe and Nader [46], analyzed the influence of a breakwater on the OWC performance through experimental research and FEM. The results and comparison between an isolated OWC without a breakwater and non-isolated models with a breakwater or fixed structure (Figure 10m), showed a high rise in the power absorption for a device integrated into a breakwater. In conclusion, a significant increase in device extraction efficiency could be achieved by integrating an OWC into a maritime structure, including a breakwater or a harbor.

Alternatively, some researchers such as Elhanafi et al. [47] and Gomes et al. [48] studied the OWC model shown in Figure 10f. Elhanafi et al., numerical studies were carried out to analyze the effect of the ratio between the width and thickness of the offshore model. For this research, the model was compared under different geometric parameters and values, such as thickness and width. The simulation results suggested that peak efficiency was achieved when the symmetric thickness of the walls represented 12% of the chamber width, or 8% when considering only the thickness of the front wall. In contrast, Gomes et al. numerically studied the influence of the geometry of the model, above all, on the performance of the OWC device through a constructive design, adopting two degrees of freedom for the parameters to iterate. The authors considered both the hydropneumatic chamber volume and the OWC total volume as constants. In this study, all geometric possibilities were explored, and it was found that the optimal shape for the OWC chamber that maximized hydrodynamic power was achieved when the ratio of the chamber height to the air outlet diameter connecting to the turbine was four times the ratio of wave height to incident wavelength. These results provide theoretical tools related to the conceptual design of the OWC device for future research.

Recognizing the significant steps taken by N. Gomes et al., in 2020 Letzow and Lorenzini [49] published a new study. Unlike the research done by N. Gomes, they considered the geometry shown in Figure 10g and three degrees of freedom, adopting a laminar, unstable, incompressible, two-phase flow to solve the RANS equations. The design method used indicates the interaction between degrees of freedom, i.e., how changing one degree of freedom affects the sensitivity of the other two. The results are quite promising when the chamber height is set at 40% of the chamber width, and the slope of the inclined wall at the bottom of the chamber is 0.8. Considering that a resonant chamber could be vulnerable to extreme wave conditions and indirectly admit air through the front wall, some researchers considered a lower front wall, creating a new U-shape for the OWC. For example, Boccotti [50] compared the resonant chamber of a conventional OWC like the one shown in Figure 10a to a U-OWC corresponding to the model in Figure 10b, which is known to have a vertical lower wall on the wave side. The author pointed out that the model illustrated in Figure 10a is prone to aspirate air through the lower part of the front wall under extreme wave conditions. Additionally, the simulation results showed that the model represented in Figure 10b provided a higher power absorption rate, greater pressure amplitudes at the resonant chamber opening, and higher electrical power absorbed by a turbine.

Likewise, various authors such as Spanos [51], Ning [52], Gurnari [53], Fonseca [54], Moretti [55] investigated the effect of implementing the U-shape of the resonant chamber. Similar to Boccotti [50], the referenced authors found that this new chamber shape is quite significant and demonstrates significant improvements in hydrodynamic efficiency and outlet velocity of the OWC device.

On the other hand, Gaspar et al. [56], examined numerically the performance of two WEC using Ansys Fluent and VOF with the model represented in Figure 10. The study found that the device had higher efficiency, greater power, and pressure when the walls were inclined at 40° relative to the horizontal plane. The findings achieved showed that the device with inclined walls had better efficiency and power because the vortices generated within the resonant chamber were smaller and dissipated less energy within the OWC.

According to Letzow and Lorenzini [49], changing the chamber height has a significant effect on the efficient energy extraction. Additionally, Kharati-Koopaee and Fathi-Kelestani [57], found that using the model represented in Figure 10, the best device efficiency for low-frequency waves was achieved with a tall chamber length. Furthermore, for high-frequency waves, the best device performance was achieved with a short chamber length. Bouali and Larvi [58], found that changing the chamber height above the water did not have a high influence on the OWC performance. Consequently, the research given by Hayati et al. [59] studied the model in Figure 10d, keeping the chamber height above the water constant during the optimization process. The authors varied some geometric factors related to the height, width, and thickness of the chamber, as well as the air outlet hole diameter and water depth. Among the results, it was found that efficiency peaked and remained within the range of 0.15 to 0.35 times the value of the ratio between the exit hole diameter and the chamber width. Moreover, the location of the air outlet hole directed toward the turbine was significant, with the conclusion that the hole just above the central part of the chamber, compared to those on the sides, achieved better performance. Hayati et al. also studied the models represented in Figure 10a, Figure 10ñ, and Figure 10k (rectangular, circular, and conical, respectively), concluding that the efficiency values for each type of configuration were 27.3%, 24.22%, and 23.9%, respectively.

Rodríguez and Ilzarbe [60] demonstrated that the OWC geometric characteristics can play an important role in device performance. For the resonant chamber model corresponding to Figure 10j, the authors inferred that increasing the front barrier thickness led to a reduction in efficiency because wave movement within the chamber decreased during short wave periods when the front barrier was thicker.

Shahabi-Nejad and Nikseresht [61], using the k-w SST turbulence model in Ansys Fluent, numerically investigated the implementation of a new land-based HWEC (hybrid wave energy converter). This device combined the OWC model illustrated in Figure 10q with a horizontal-floating cylinder (HFC) placed perpendicular to the wave propagation. The authors successfully demonstrated that an OWC could also be complemented with an HFC to improve performance. Incorporating a porous horizontal wall and an inclined barrier near the chamber in the OWC design was found to reduce wave reflections, significant forces acting on the device, and sediment entering the chamber, thereby promoting energy extraction efficiency.

3.5. Considerations for a horizontal wall

Some authors have considered the use of a horizontal-bottom plate attached to the rear wall of the air chamber [62], [63], [64]. A bottom plate can be viewed as a combination of a submerged plate-type breakwater with an asymmetric OWC device [62]. For example, Rashed and colleagues [64] analyzed the model represented in Figure 10n offshore, characterized by having a horizontal-bottom plate attached to the rear wall. To conduct the numerical study, the authors considered the k-w SST model. They determined improvements in hydrodynamic efficiency when the front wall immersion is 25% of the water depth and when the length of the horizontal plate attached to the rear wall is twice the width of the model's chamber. Similarly, Deng et al. [62] conducted experimental and numerical tests using OpenFOAM software, analyzing geometric parameters such as plate length, relative aperture, and water depth of the model illustrated in Figure 10n concerning efficiency. The results demonstrate that the optimal configuration of the structure is achieved when the length of the horizontal plate is twice the width of the air chamber.

3.6. Considerations for a perforated wall

The uncertainty surrounding the survivability of the OWC under extreme conditions is a result of the lack of rigorous designs, which unfortunately could jeopardize an OWC and its viability in terms of commercialization and investment. Ensuring high survival capabilities of the device will be a significant challenge, as it has been found that wave power during a storm can be up to five times the average power levels of up to 2000 kW/m [65]. This fact leads to a dual design consideration because, beyond structural design and high robustness, it poses an economic challenge. Building a prototype involves substantial costs driven by the need for the device to withstand extreme wave conditions [66].

Over the years, various structures have been proposed to reduce wave reflection, including porous plates, breakwaters, and mooring systems. Zhang et al. [67] studied the hydrodynamic and structural performance of the design illustrated in Figure 10a, to which they added a perforated wall that acts as a protective barrier for the front wall, receiving incident waves and dissipating wave reflection. Similarly, in a study conducted by C. Tsai et al. [68], the model from Figure 10d was compared, and they modified it by implementing a perforated wall to the structure as shown in Figure 11.

The authors performed simulations using the Flow 3D solver and demonstrated that implementing the perforated wall can not only promote energy extraction efficiency but also reduce the forces of the waves acting on the structure.

Considering that waves initially interact with the front wall of an OWC, and its design directly influences the device's performance, the effect of seafloor morphology and asymmetric pressure correction in an OWC chamber will be a crucial aspect to consider ensuring device performance. In the study developed by Çelik [69], a circular section of the lower edge of the OWC front wall is quite significant, as it allows for a higher efficiency percentage by reducing vortex shedding, thereby increasing the transported amount of incident wave energy into the chamber. The presence of vortices could have a negative impact on an OWC, as it indicates energy dissipation and the generation of turbulence phenomena [70].

For this purpose, some researchers have focused their attention on investigating and using a variety of bottom profiles for a resonant chamber [39], [40], [41], [49], [58], [60], [61], such as the one presented in Figure 12. For Rodríguez and Ilzarbe [60], the results showed that the proposed bottom profiles slightly alter the curve of efficiency, with each profile having a maximum at a certain period. The elliptical bottom profile represented a slightly more suitable option. On the other hand, Ashlin and colleagues [71] compared the bottom profiles of Figure 10a, Figure 10g, and Figure 10s; it was demonstrated that the bottom profile of the latter represented a higher energy capture rate. Rezanejad et al. [72] in their study, discovered that changes in seafloor geometry are significant, and implementing a step outside the chamber would allow for a small increase in device efficiency.

The quest to ensure the good performance of an OWC will always be a focal point. To date, a high number of studies have been focused on single-chamber devices. However, significant increases in energy extraction can be achieved from dual-chamber devices. For example, in the study conducted by Elhanafi et al. [73], the energy capture capability in a single and dual-chamber OWC was compared. Therefore, the authors investigated the performance of the models represented in Figure 10o and Figure 10p through 2D and 3D CFD using the VOF and RANS numerical analysis methods. It was found that the dual-chamber model provided greater effectiveness, and good results were obtained considering 3D effects over 2D. Haghighi et al. [74] conducted a numerical study of a dual-chamber using Ansys Fluent 2D under RANS and Airy theory.

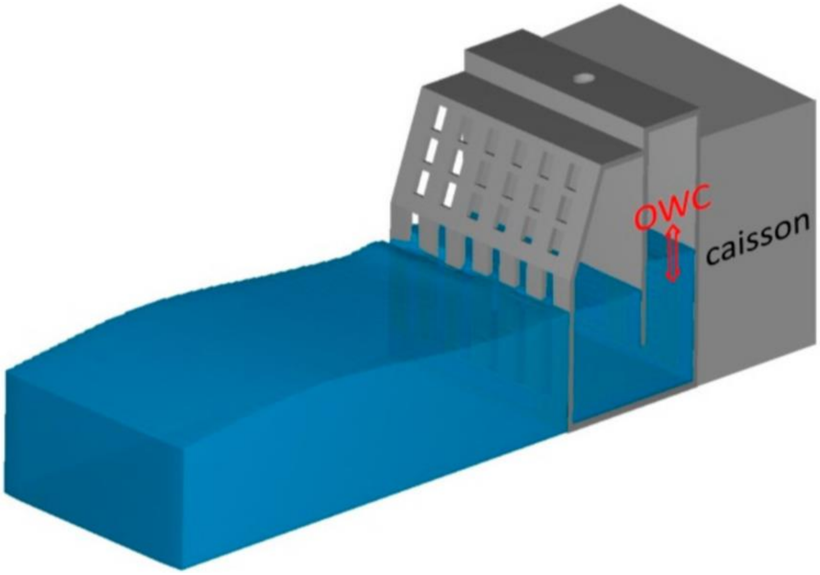


Figure 11. Perforated wall considerations in an OWC. Source: [68].

They compared the model illustrated in Figure 10q with the one in Figure 10r, and through the simulation process, it was found that the latter improved the device's energy absorption capacity.

It should be emphasized that when studying a resonant chamber, the effects of air compressibility inside should be considered. Elhanafi et al. [75] studied the effects of air compressibility and found a 12% reduction in the maximum efficiency of an OWC at the shore due to air compressibility. Monk et al. [76], considered a relief valve system to correct pressure problems and low performance of a full-scale plant built on Pico Island in the Azores archipelago, Portugal.

The authors were able to counteract the problem by integrating a passive bypass relief valve. From the perspective of designing the OWC to prevent the device from ingesting water under extreme conditions, it has been determined that a larger chamber volume could be a significant bet. Overestimation of device air pressure and flow results to be higher when air compressibility is not considered [26], [77].

3.7. Considerations of design according to location

One of the key considerations when studying an optimal OWC is to determine the approach regarding the device's location based on factors such as depth, distance from the shore, environmental and acoustic feasibility, maintenance cost, construction, and installation [26]. Due to its versatility, this device has different design variations (land-based, seabed-mounted, and floating systems) that have allowed it to be deployed on land, near the coast, and offshore [78]. Fixed systems are characterized by their resilience to extreme wave conditions and ease of maintenance, which also means that all electronics and wiring remain above water. These systems consider only one resonant frequency for the chamber [26]. Although coastal waves are less energetic than those in deep and open seas, they are less expensive to harness, and wave energy can be more naturally concentrated towards the system due to the formation of sandbanks, refraction, and diffraction [78]. On the other hand, it has been shown that offshore areas have higher available wave energy, and therefore, designing and constructing an optimal device in this zone can be quite ambitious for future research.

However, it is also important to consider that floating or offshore systems generally have anchoring or mooring systems when in deep or shallow waters. Therefore, in the design conditions, it will be necessary to ensure their reliability in extreme sea conditions. These floating devices are also characterized by having a natural frequency for both the OWC and its chamber [26]. A good consideration for designing an efficient OWC will be to include aspects such as acoustic pollution and damage to the natural beauty or diversity of the area where the device could be put into operation. Although an OWC is associated with relatively low aesthetic and environmental impacts, it could be related to negative impacts on aquatic ecosystems through low-frequency, long-duration vibrations and noise [27]. The above section also raises interest in new research that may consider the influence of perforated horizontal walls, profiles, and angles of front wall inclination simultaneously on aerodynamic performance, and the design and numerical simulation of the pneumatic chamber of an offshore OWC.

3.8. Improvement of an OWC performance considering the constructive design

Constructive design is based on a physical principle used to enhance any finite-dimensional flow system. To ensure the longevity of a system, it must evolve and be improved in accordance with constructive design principles [49]. For the geometric evaluation of a WEC in both laboratory and full-scale settings, constructive design can be employed to evaluate the geometric design efficiency on the performance of certain devices [48]. Various designs in the field of engineering have been studied using constructive design, including turbines, materials mechanics, cooling systems, fundamental heat transfer issues in cavities, fins, and renewable energies [79].

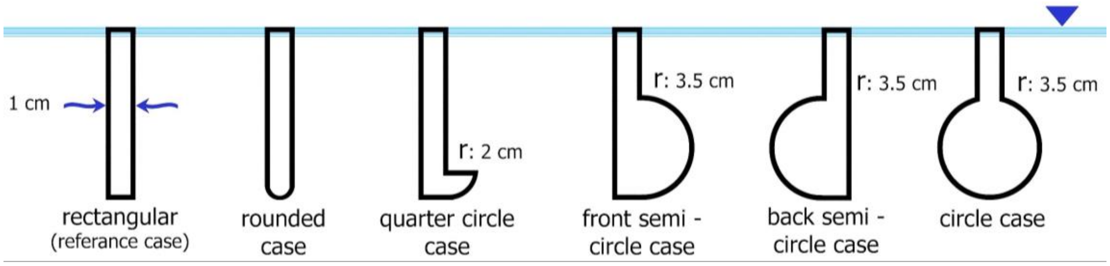


Figure 12. Considerations for a front wall profile. Source: [69].

Concerning wave energy, several studies on OWC performance have utilized this type of design [49], [79], [80], [81], [82].

3.9. Response surface methodology

RSM (response surface methodology) is used for solving multivariable problems through design of experiments (DOE). This method can effectively determine the influence of factors on the response and predict its value accurately [83]. Thus, this method allows modeling and analyzing problems in which various factors influence the variable of interest [84], [85]. Currently, RSM has been extensively used in various research endeavors, yielding favorable results [84].

Several DOE are capable of studying the effect of multiple parameters on the response variable, among them, the CCD (central composite design) has been commonly employed [83], [84], [86], [87], [88]. While considering RSM in a study is a highly effective method, there is a gap in the literature where this methodology is applied to the sensitivity study of factors and parameters concerning their impact on the efficiency of the resonant wave chamber.

3.10. Numerical simulation using CFD

CFD has been widely employed to capture and predict in detail the physical phenomena, viscosity, and turbulence of an OWC. The equations governing most CFD models are the Navier-Stokes and continuity equations [89]. Some authors have focused on the analysis of air behavior inside the resonant chamber, energy balance, wave survival, and reflection [24], [66], [67]. Over the years, the increasing demand and substantial improvement in high-performance computing and information processing have enabled researchers to quickly capture and solve the governing equations of fluid science. The effective use of CFD has allowed for numerical simulations and analyses of OWC devices as an alternative to experiments, benefiting from theories such as Stokes, Airy, and fundamental numerical methods. The geometry of an OWC's resonant chamber can be enhanced without costly construction or manufacturing tests through computational simulations with engineering considerations.

In the field of numerical simulation of an OWC by means of CFD, several models are used for the generation and absorption of the wave. Regarding wave generation, are employed directly from the software the Stokes theory, used for small to moderate amplitude waves, allowing the simulation of harmonic waves in the time domain; the Airy theory, suitable for simulating small amplitude waves, ideal for deep water conditions and commonly used in preliminary OWC studies (these two theories should be selected according to the incoming wave characteristics using the Le Mehauté theory) [58], [90]; and the random spectrum wave generator, which simulates random spectrum waves using empirical wave height and period data, allowing for a more realistic representation of sea conditions [91]. Regarding wave absorption, numerical beaches and damping boundary conditions or relaxation method are commonly used, implemented at the boundaries of the simulation domain to absorb the reflected wave energy, avoiding unwanted reflection that could affect the results [92], [93]; the VOF method, used to track the water-air interface inside the resonance chamber, being especially useful in CFD and the interaction of the wave with the OWC structure [61], [64]. The incorporation of these models in CFD simulation allows a more accurate evaluation of the hydrodynamic performance of OWC devices under various wave conditions, thus contributing to the efficient design and optimization of these systems.

It has been asserted that CFD, unlike methods such as potential theory or linear waves, is more suitable for simulating the generation of vortices near the OWC structure [70]. Linear wave analysis works well for small wave amplitudes if the chamber cross-sectional area remains constant along the axis aligned with the dominant gravity direction. In contrast to CFD software like STAR CCM+, OpenFOAM, In-house, CFX, and Flow-3D, among others, Ansys Fluent has predominantly been used to analyze the hydrodynamic behavior of OWC. This software offers advantages such as turbulence models, flexible discretization schemes, and user-defined functions suitable for simulating a wave channel [57], [63], [70], [74], [89]. Some studies have used Ansys Fluent with the VOF method to track the water-air interface, while others have implemented OpenFOAM for two-phase flow simulations. Fluent has been found to be a comprehensive computational tool, justifying its widespread use [56], [59], [61]. In order to accurately capture wave elevations, pressure differences, and OWC movements, a hybrid method was studied in [70], combining a laminar model and a realizable k-ε model for the wave generation zone and the vicinity of the resonant chamber, respectively.

Zhan et al. [70] used Ansys Fluent software and validated the mesh independence, demonstrating that the hybrid model, unlike k-ε, aligns well with experiments as it does not underestimate wave heights.

Various turbulence models such as realizable k-ε, RNG, standard k-ε, or k-w SST, k-w standard, k-w BSL have been used in OWC CFD. Due to air and water interaction on the device, it is not easy to reach a definitive conclusion about the best turbulence model since determining the optimal turbulence model solely based on geometry and flow conditions is too relative. Being proactive and critical in selecting the most suitable turbulence model for the simulation process is crucial. CFD simulations should be thoroughly verified, with mesh independence, convergence, and turbulence models being important parameters for obtaining reliable results.

A good design should be capable of harnessing wave energy resources under various ocean conditions and withstand random wave behavior [26].

In view of the significant progress made by various authors in the optimization and numerical analysis of OWC, Table 2 presents a report of some geometric relationships and their optimal values found in the literature as a result of simulation and experimentation processes to enhance the resonant chamber of the device. These reported values are referenced according to the scheme shown in Figure 13. Figure 14 presents a proposed flowchart that can be used for the optimization process of the wave resonant chamber.

3.11. Resonance Resonance chambers in the Colombian context

The interest in offshore and nearshore industries has significantly grown in recent years. Colombia, in accordance with Law 1715 of 2014 [94] and Law 2099 of 2021 [95], also known as the Energy Transition Law, aims to promote the participation of renewable energy sources by energizing the electrical market through the implementation, progress, and promotion of NCRE, providing greater involvement of both public and private companies in new auctions, strengthening energy efficiency [95].

Table 2. Geometric parameters and their optimal values for a resonance chamber

Reference	Approach	Variable	H_1/b_2	d/b_2	e/b_2	h/h_1	f/a	h_2/a	Θ (°)	α (°)
[52]	Numerical	v, p, η_{hyd}	-	-	-	-	0.73	-	-	-
[41]	Experimental	η_{hyd}	-	0.05	-	-	-	-	21.8	90
[48]	Numerical	v,p	0.10	0.05	-	3.4	-	-	-	90
[49]	Numerical	v,p	0.40	-	-	-	-	-	38.6	90
[59]	Numerical	Q	-	0.02	0.15	-	0.65	-	30	90
[60]	Numerical	η_{hyd}	-	-	0.01		0.62	0.12	-	-
[42]	Numerical	η_{hyd}	-	-	-	-	-	0.35	-	-
[103]	Numerical	Q	-	-	0.12	0.57	-	-	-	-
[39]	Experimental	η_{hyd}	-	0.15	-	-	-	-	-	-
[45]	Numerical	P, η_{hyd}	-	-	-	-	-	0.38	-	-
[40]	Numerical experimental	P, η_{hyd}	-	0.05	-	-	-	-	30	-
[44]	Numerical Experimental	v	-	0.13	-	-	-	-	-	35

Resonance chamber height (h), vertical distance of the front wall in the air zone (h_1), vertical distance of the openwork front wall in the water zone (h_2), width of the OWC (b), horizontal distance between the upper front wall and the inclined ramp (b_1), width of the chamber (b_2), wall thickness (e), damping diameter (d), water depth (a), sloped ramp height (f), front wall slope angle (α), sloped bottom ramp slope angle (Θ), wavelength (L), wave height (H), wave amplitude (A).

* Where v is velocity, p is pneumatic pressure, η_{hyd} is hydrodynamic efficiency, Q is volumetric flow and P is power.

Source: own elaboration.

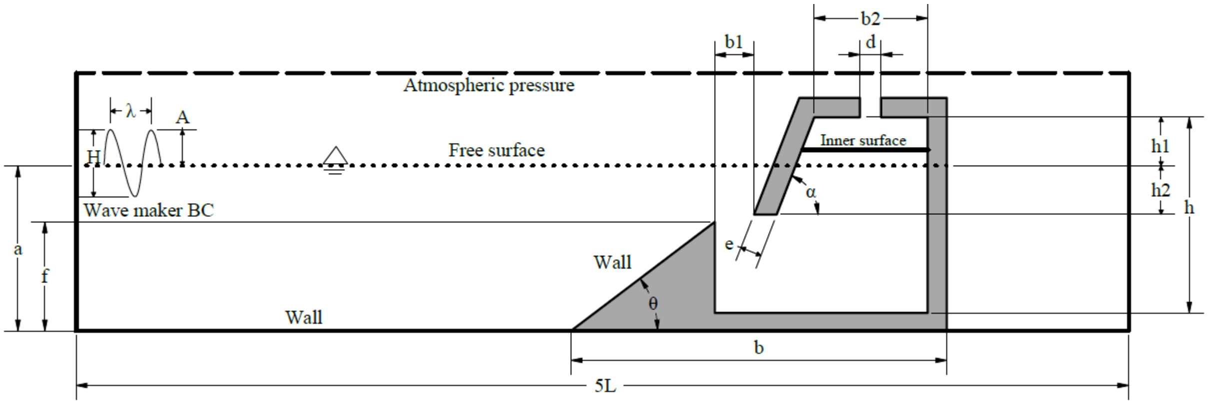


Figure 13. Parametric scheme for Table 2. Source: own elaboration.

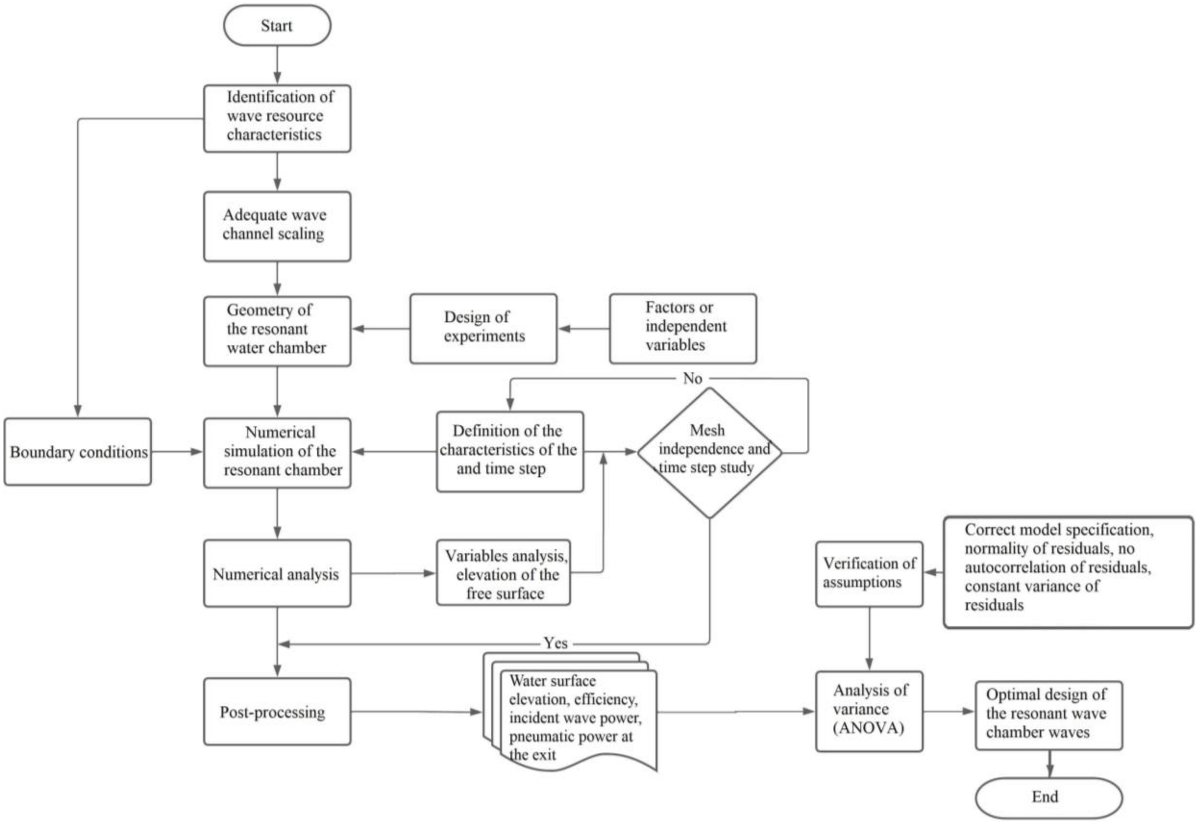


Figure 14. Flowchart of the wave resonant chamber optimization process. Source: own elaboration.

In the country, to the knowledge of the authors, there are few to almost no research studies related to the analysis of the resonant chamber of an OWC; only a few authors have focused their attention on studying some WEC and, in turn, the wave energy potential in regions of the Pacific Ocean [32], [96], the Caribbean Sea [11], [97], and the San Andrés Archipelago [11], [32]. Given the above, it will be of crucial importance for new research and development of energy systems to supply local areas with a continuous, secure, and sustainable electrical supply.

4. Conclusions

From the study conducted regarding the design considerations to optimize the resonant chamber of an OWC and the current advances in research, it has been found factors such as geometric factors, wave characteristics, location, and layout of this structure must be considered to optimize the resonant chamber, along with its environmental, economic, and structural feasibility. The wave resource under any ocean condition should be harnessed through a well-designed and durable chamber under random wave behavior.

Although the information presented in this document provides design considerations and substantial improvements for an OWC chamber, it is evident that there are parameters that need to be studied in greater depth. To enable an OWC to capture more energy, it is essential to consider geometric factors, manufacturing materials, location, and the characteristics of the study area, as well as the strategic feasibility of generation and return on investment.

Ultimately, capturing the current state of design considerations for optimizing the resonant chamber of an OWC, as well as the foundations of a design pathway are targeted to establish a consensus on the parameter values that optimize the performance of such devices.

Funding acquisition

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).

Autor Contributions

J. Parra-Quintero: Methodology, Investigation, Modelling, Validation, Formal Analysis, Visualization,

Writing-original draft. A. Rubio-Clemente: Methodology, Investigation, Modelling, Validation, Formal Analysis, Visualization, Writing-original draft. E. Chica-Arrieta: Conceptualization, Methodology, Investigation, Software, Modelling, Validation, Formal Analysis, Visualization, Writing-original draft, Writing - review & editing, Supervision.

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data availability

The data files are available on request.

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