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Review

Review of the Influence of Oceanographic and Geometric Parameters on Oscillating Water Columns

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Abstract: Wave energy is one of the most powerful sources of energy on our planet, but its exploitation is difficult. Much current research on renewable energy is focused on how to harness ocean energy. However, wave energy converter (WEC) technology is still immature and how to reach high levels of efficiency is still unknown. In coming years, this field is likely to reach a high level of development, so it is important to continue research on the improvement of the performance of these devices. One of the most important wave energy converters is the oscillating water column (OWC). The main difficulty of OWCs is that they have to provide good rates of hydrodynamic efficiency for many different types of sea states (different periods, heights, wavelengths, etc.). The other big concern is the optimization of the geometric parameters of the device. This research paper is focused on these two big concerns: how oceanographic parameters affect the hydrodynamic behavior of an OWC and its geometric optimization. Different studies about how wave and geometric characteristics affect the performance of an OWC are reviewed and relationships between these and the hydrodynamic performance of an OWC are finally outlined and summed up.

Keywords: oscillating water column; hydrodynamic efficiency; geometric optimization; OWC turbines; multipurpose platforms; breakwater-integrated OWCs; dual chambers OWCs; wave climate

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1. Introduction

Since 1880, atmospheric levels of carbon dioxide (CO_2), methane (CH_4), nitrogen dioxide (NO_2) and other greenhouse gases have been increasing and this is due to anthropogenic causes. It would have taken thousands of years for nature to produce current levels of greenhouse gases, but humankind has produced them in only a few decades. Climate change is, definitely, one of the biggest threats of our century [1].

The development of new renewable energies is a key to reducing the consumption of fossil fuels and to fighting against climate change. One of the main sources of renewable power is ocean waves. While wave energy technology is still immature and is not cost efficient yet, it is very likely that in the coming decades this new source of energy will reach a high level of development [1].

Ocean wave energy is based on the power of surface gravity. Waves are formed due to the imbalance between gravitational force and the shear force produced by wind [2].

Wave energy has many advantages: it has one of the highest rates of energy density and its environmental impact is minimal. Moreover, waves will always exist, and they are a reliable and predictable source of energy that can travel huge distances without losing energy [2,3].

Despite these big advantages, there are still some issues that must be solved in order to make wave energy profitable: waves are not regular, they have different heights, periods, directions, phases, etc. This broad range of possibilities makes it very difficult to operate energy devices efficiently most of the time. In many cases, only low energy conversion efficiency levels can be reached. Moreover, the loading on the devices can be 100 times higher than the average loading in extreme weather conditions, which significantly increases the difficulty of designing the technology. A balance between money invested and structural safety is needed. The devices used to extract wave energy need a complex and expensive process of evaluation [2,3].

Furthermore, using wave energy is not affordable for all countries. Only in areas where wave activity is intense are wave energy devices cost efficient. These areas are between the latitudes of 30° and 60° in both hemispheres [3], as can be seen in Figure 1.

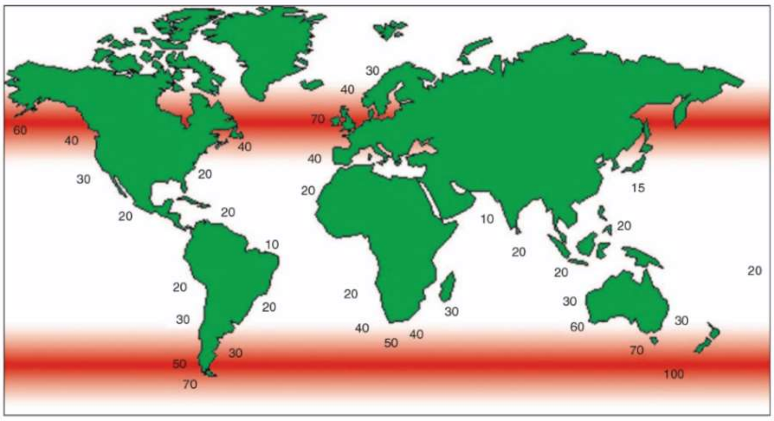

Figure 1. Global wave power distribution by kW/m of crest length (Centre for Renewable Energy Sources (CRES) [4]).

The devices used to extract wave energy are called wave energy converters (WECs). The main problem of WECs is that they have to operate efficiently with a great variability of wave parameters. Each wave is unique: there are no two waves in the ocean with the same period, length, and height and WECs have to be efficient for all of them. There are different types of WECs, but one of the most promising is the oscillating water column (OWC). The purpose of this article is to define the relationships between wave characteristics and the geometric parameters of the OWC and its performance and hydrodynamic efficiency. In order to extrapolate these relationships, some of the most relevant studies about OWCs are reviewed and analyzed.

The structure of the article is as follows: Section 2 describes the methodology; Section 3 presents the basic concepts about OWCs; Section 4 presents the relationships between wave characteristics and the performance of the OWC; Section 5 looks at the relationship between the geometric characteristics of the OWC and its hydrodynamic performance; Section 6 is on the influence of air and turbine properties; and, finally, Section 7, presents the conclusions.

2. Research Methodology

In this research paper a structured literature review based on Adebisi et al. (2019) [5] was conducted. The structured literature review had three stages: planning, review, and information synthesis. In the first stage, planning, the searching criteria and databases were defined: the publications were obtained from reputable databases, mainly Web of Science (WOS), Scopus, Google Scholar, and the MDPI search engine. The searching criteria selected was the topic of the articles. The search keywords were: *OWC classification*, *wave influence OWC*, *hydrodynamic optimization OWC*, *geometric optimization OWC*, *OWC turbines*, *air compressibility OWC*, *air humidity OWC*, *biradial turbines*, *dual-chamber OWC*, *U-shaped OWC*, *L-shaped OWC*, *V-shaped OWC*, *breakwater-integrated OWC*, and *multipurpose platforms*.

In the second stage, review, the articles were searched and filtered, excluding the ones that did not fit with the purpose of the research. A total of 133 papers were reviewed.

Finally, in the third stage, all the information of these 133 articles was analyzed and synthesized.

Once the state of the art was studied, different relationships between wave characteristics and geometric parameters and the hydrodynamic performance of the OWC were defined and summed up in tables (Tables 1–3).

Table 1. Influence of wave characteristics on the performance of OWCs.

	Forces	Efficiency	Comments
Wave period *T*	Less sensitive	-	
Wave Height *H*	Positive relationship	Positive relationship	More important near the breaking point
Wave Length *L*	Negative relationship	Positive relationship	Better to not be affected by bottom friction
Wave Steepness *H*/*L*	Positive relationship	Negative relationship	Increases nonlinearities
Relative depth *d*/*L*	Increases until 0.16 and decreases	Maximum around 0.131	
Comments	Peak horizontal force is 2.5-3 times the peak vertical force	Only vertical velocity is useful, the horizontal component is wasted	

Table 2. Influence of the geometry of OWCs on their performance.

	Efficiency	Frequency Bandwidth	Resonant Frequency	Comments
Relative Chamber Width *(Divided by water depth)*	Positive for low frequencies and long waves Negative for high frequencies and short waves	Negative Relationship	Positive relationship for long waves Negative relationship for short waves	Optimum value 0.8–1
Relative Chamber Length *(Divided by wavelength)*	Follows an U-inverted shape	Follows a concave parabolic shape	Negative relationship	More important for great values of periods and heights
Relative submergence *(Divided by water depth)*	Better behavior at resonant frequency for low values	Negative relationship	Negative relationship	Optimum value 0.3–80.44 depends on the height and period of the wave
Opening ratio	Follows an U-inverted shape	-	-	Significantly influenced by wave height
Thickness of the wall	Indifferent	Negative relationship	-	-

Table 3. Influence of geometry of dual chamber on the performance of OWCs.

	Wave Forces	Efficiency	Frequency Bandwidth	Resonant Frequency	Comments
Inner chamber draft	Positive relationship	Negative relationship	Positive relationship	Negative relationship	Must be bigger than the outer draft
Outer chamber draft	Positive relationship	Negative relationship	Negative relationship	Negative relationship	Must be smaller than the inner draft
Chamber breadth	-		Positive relationship	-	-
Thickness of the wall	-	Negative relationship for high frequencies	-	-	-
Volume of the chamber	Negative relationship	Positive relationship	Negative relationship	-	-

In these tables, a *positive relationship* means that if one variable increases, the other also does; and a *negative relationship* means that if one variable increases, the other decreases.

3. OWCs: Concept, Elements, and Classification

OWCs are a type of WEC that extracts the energy from a bidirectional air flow generated by an oscillating sea-level chamber [3,6]. They are one of the WECs that are being studied more deeply and that are likely to be highly developed in the next few years. The OWC's principle of action is presented in Figure 2.

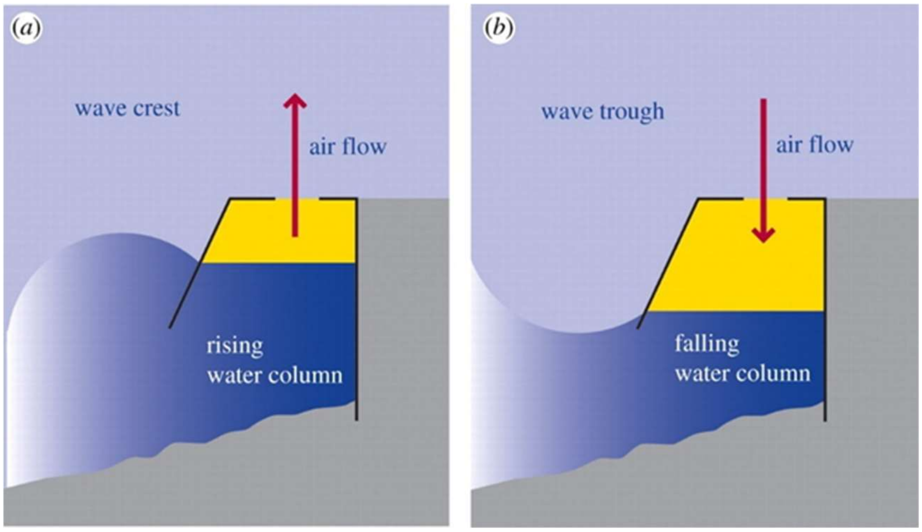

Figure 2. Principle of OWC action (Heath, T.V., 2012 [6]). (**a**) shows how the water rises pressurizing the collector and (**b**) how the water falls rarefying the collector.

OWCs are composed of two main parts that are the air chamber and the PTO, which is usually a self-rectifying axial flow air turbine. The most common ones are the Wells turbines [3,6].

OWCs have many advantages: there are not many moving parts and they have no moving parts in the water, which improves their durability and makes their maintenance cheaper and easier, and they do not have gearboxes, which also facilitates their maintenance. In addition, the concept of the OWC is versatile and can be used on the coastline, in the nearshore region or floating offshore. They are solid and secure and they use sea space efficiently [6].

3.1. OWC Elements

OWCs have two main parts: the chamber and the PTO system. As Section 5, on the influence of OWC geometry, refers to different elements of the OWC, this subsection shows a review of these elements with the aim of facilitating the understanding of the results presented.

3.1.1. OWC Chamber

The OWC chamber is formed by walls of different materials and its main geometric characteristics are the following:

The chamber length (a in Figure 3) and the chamber width, which is the dimension of the chamber in the direction perpendicular to the paper.

The front wall width or thickness (t in Figure 3)

The front lip submersion depth, also named as front wall submergence depth [7], or immersion of the front lip [8] (d in Figure 3).

The opening ratio, which is defined as the ratio of the orifice area and the cross-sectional area of the chamber [9]. The area of the orifice is determined by the parameter r in Figure 3.

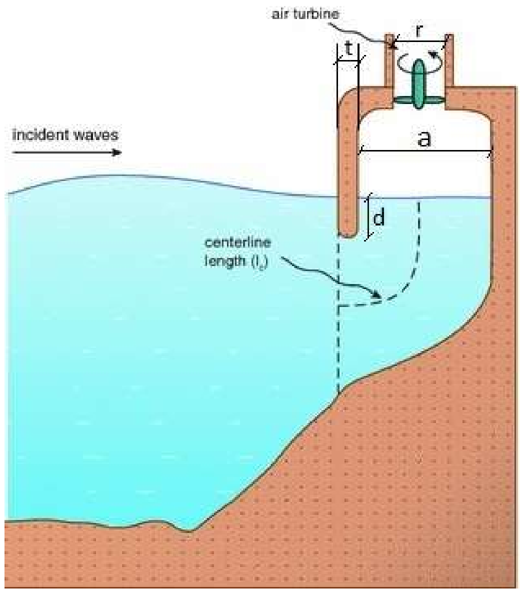

Figure 3. Sketch of the geometric parameters of an OWC. Image source: [10].

3.1.2. PTO Systems

The most common PTO systems used in OWCs are air turbines. Of the three types of air turbines (Wells turbines, impulse turbines and Denniss-Auld turbines), Wells turbines and impulse turbines are the most used turbines in OWCs [11].

Wells Turbines

These were the most used turbines in OWCs until the development of biradial turbines. The most remarkable characteristic of these turbines is that they are self-rectifying turbines: they rotate in a single direction in a bidirectional flow. Although they reach only a moderately high peak efficiency as compared with conventional turbines, they can operate in reciprocating flow without the need of a rectifying valve system, which facilitates their maintenance and operation. Wells turbines have a linear pressure drop-flow rate which is well suited to energy conversion in OWCs. The type of Wells turbine most used is the multiplane turbine. Its power output operates at low flow rates and it drops sharply for flow rates above a critical value due to aerodynamic losses. Therefore, these turbines are not appropriate for very energetic seas, and if they are used, a bypass pressure-relief valve is needed [9,12]. Their main manufacturer is Voith Hydro Wavegen [13] (Figure 4).

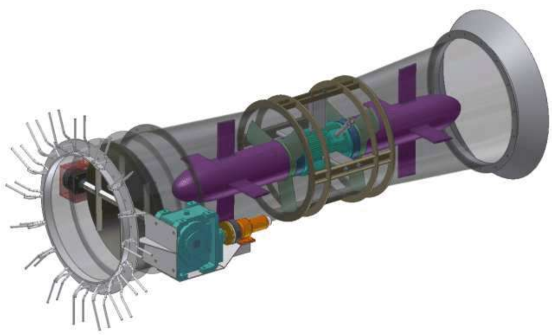

Figure 4. Wells turbine tested at LIMPET (Torre-Enciso et al. 2009 [14]).

Impulse Turbines

Impulse turbines are self-pitched, controlled turbines with guided vanes [15]. The most common types used in OWCs are the axial-flow impulse turbine and the recently patented biradial turbine [16].

- Axial-flow impulse turbines

This type of turbine is the one used in the Irish OE buoy and the Jeju island power plant [16]. The main problem of this type of turbine is the large aerodynamic losses due to the excessive incidence flow angle at the entry to the second row of guide vanes. To reduce these losses, guided vanes of variable geometry can be used. Another option is to increase the distance between the guided vane rows and the rotor blades. Although the operational flow range of the impulse turbine is wider compared with that of the Wells turbine, its peak efficiency hardly exceeds 50% [11,15].

- Biradial impulse turbines (Figure 5)

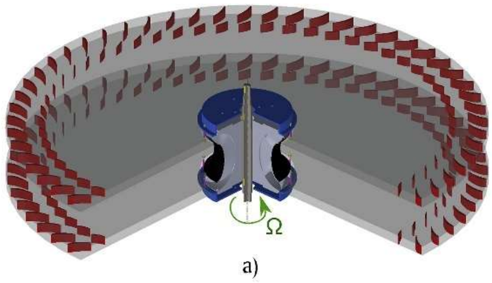

Figure 5. Biradial turbine (Carrelhas et al. 2019 [16]).

There are two types of biradial impulse turbine: those with axially-sliding guide vanes and those with fixed guide vanes. The first type was model tested and found to be the most efficient self-rectifying turbine known so far, with a peak efficiency of about 78%, but it has the disadvantage of being more complex [16].

Biradial impulse turbines are the most recent turbines developed for OWCs and they have proved to be more efficient than Wells turbines and overcome some of their main limitations [17]. Falcão et al. (2014) [18] showed that they were the best option for spar buoys and they were the turbines chosen for the MARMOK-A-5 OWC spar buoy [16].

Apart from these three most common turbines used in OWCs as PTOs, there is current research on dielectric elastomeric generators that can be implemented in OWCs [19]. The dielectric elastomeric generator (DEG) is a compliant polymeric generator that makes it possible to convert mechanical energy into electrical energy by exploiting the large deformations of elastomeric membranes, and has several advantages compared to more conventional PTOs [20].

3.2. OWC Classification

- Fixed structures
    - Separate or isolated

There are a few examples of this kind of OWC in Europe. In 1991, the European Commission decided to include wave energy in the program of renewable energy. This led to new projects and studies in this field. Two full-sized isolated fixed-structure OWC plants were built [2,11]:

- The Pico plant in Azores, Portugal (400 kW) (Figure 6) has been operating since 1999 with Wells turbines built on the sea bottom next to a vertical cliff [11,21].
- The Islay LIMPET plant in Scotland, UK (500 kW) (Figure 7). It was completed in 2000, also with Wells turbines, and is located in a recess carved into a rocky cliff [11,23].

Figure 6. Pico OWC plant (TETHYS [22]).

Figure 7. LIMPET OWC plant (Sun et al. 2018 [24]).

In Guangdong Province (China) another shoreline OWC plant (100 kW) was built in 2001 [11].

In 2015, a bottom-standing OWC (500 kW) was completed at Yongsoo, Jeju Island, South Korea [11] (Figure 8).

Figure 8. Yongsoo OWC (Curto et al. 2021 [25]).

In 2019, a similar concept was developed on King Island, Australia (200 kW) [25].

There have been other OWC projects that failed, such as the OSPREY plant (1 MW) that was located on the Scottish coast or the greenWAVE (1 MW) plant built by Oceanlinx in Port Adelaide [11].

○ Integrated in a breakwater [11,26]

When building an OWC, one option is to integrate it into a breakwater. This option is very convenient for several reasons: construction costs are shared, operation and maintenance are easier, and its efficiency is usually higher.

Some examples are the OWCs installed at the Sakata port (Japan) and in Mutriku (Spain) (Figure 9).

Figure 9. Mutriku OWC plant.

The REWEC3 is another example. It is a U-shaped OWC installed at the Port of Civitavecchia, Italy. It is a fixed oscillating OWC incorporated in upright breakwaters. The main feature of the REWEC3 is the possibility of tuning the natural period of the water column in order to match a desired wave period through the size of the U-duct [16,27].

- Floating structures

This type of structure was proposed for the first time by Masuda in 1986 [28], who developed a floating device known as a backward bent duct buoy (BBDB) that consists of an L-shaped OWC, a buoyancy caisson-type module, an air chamber, and an air turbine driving an electrical generator [11,29]. Since then, several countries in Europe, China, and the USA have studied this new concept [11,29].

Some years later, other similar systems were developed. Among these, the best known are the sloped buoy, the spar buoy, and the Mighty Whale [25].

The Mighty Whale (110 kW) was developed in Japan in 1998 [11] (Figure 10).

Figure 10. The Mighty Whale (JAMSTEC [30]).

The sloped buoy is composed of three parallel pipes installed on a floating buoy with a tilt angle of 45° [25].

The spar buoy was initially developed by McCormick (Figure 11) and it consists in an axisymmetric floating OWC open at both ends and attached to a floater [11,31].

Figure 11. Spar buoy.

Between 2008 and 2011, the OE buoy (a 1:4 scale model of a BBDB) was tested in Spiddal, in Galway Bay [11,32].

Oceanlinx also developed a floating OWC model in 2010 in Port Kembla, Australia (Figure 12). It was called the MK3 and it consisted in a floating platform with different chambers with an air turbine each [11].

Figure 12. Oceanlinx MK3 (TETHYS [33]).

The Instituto Superior Técnico (IST) is one of the most active research institutions in wave energy and has worked in the development of spar buoys and biradial turbines [34].

In 2012, it developed a prototype of a spar buoy in Narec and tested it at a scale of 1:16 [35].

In 2014, it also conducted different experiments with arrays and extreme wave conditions in Plymouth [35].

In 2016, it developed with IDOM the MARMOK-A-5 OWC, a spar buoy that was deployed at the Biscay Marine Energy Platform (BiMEP) test site [16]. It was the first WEC connected to the electricity grid in Spain and one of the first in the world [36].

- Special OWCs
    - Multi-OWCs

The Seabreath is one example of this type of device (Figure 13). It consists in a floating attenuator with a set of rectangular chambers and an open bottom [11,37].

The LEANCON is another multi-OWC device with two rows under two beams connected to each other in a V shape [11].

- Multipurpose platforms

In this group, multifunctional platforms can be included. The suitable combination of different renewable energy conversion systems on the same platform offers significant opportunities to reduce the cost of energy and can notably contribute to the sustainable exploitation of the marine natural resource [38]. There are many research projects in this field. Research on hybrid wind–wave systems has been driven primarily by a number of European research projects aimed at developing the concept of hybrid and multiplatform systems (Marina Platform, ORECCA, TROPOS, H2OCEAN, and MERMAID) [39]. Some examples of the new concepts proposed are:

- The WindWaveFloat that intends to equip the WindFloat, a semisubmersible three-column floating platform, with different types of WECS, such as OWCs and point absorbers [38,40].
- The BlueGrowthFarm, a project founded by the European Union that proposes a multifunctional platform with 10 MW wind turbines and several OWCs [41].
- The hybrid wind–wave energy converter developed by Pérez-Collado et al. in 2018 [39,42].

Figure 13. Seabreath OWC (Martinelli et al. 2013 [37]).

A scheme that sums up the classification of the OWCs is presented below (Figure 14).

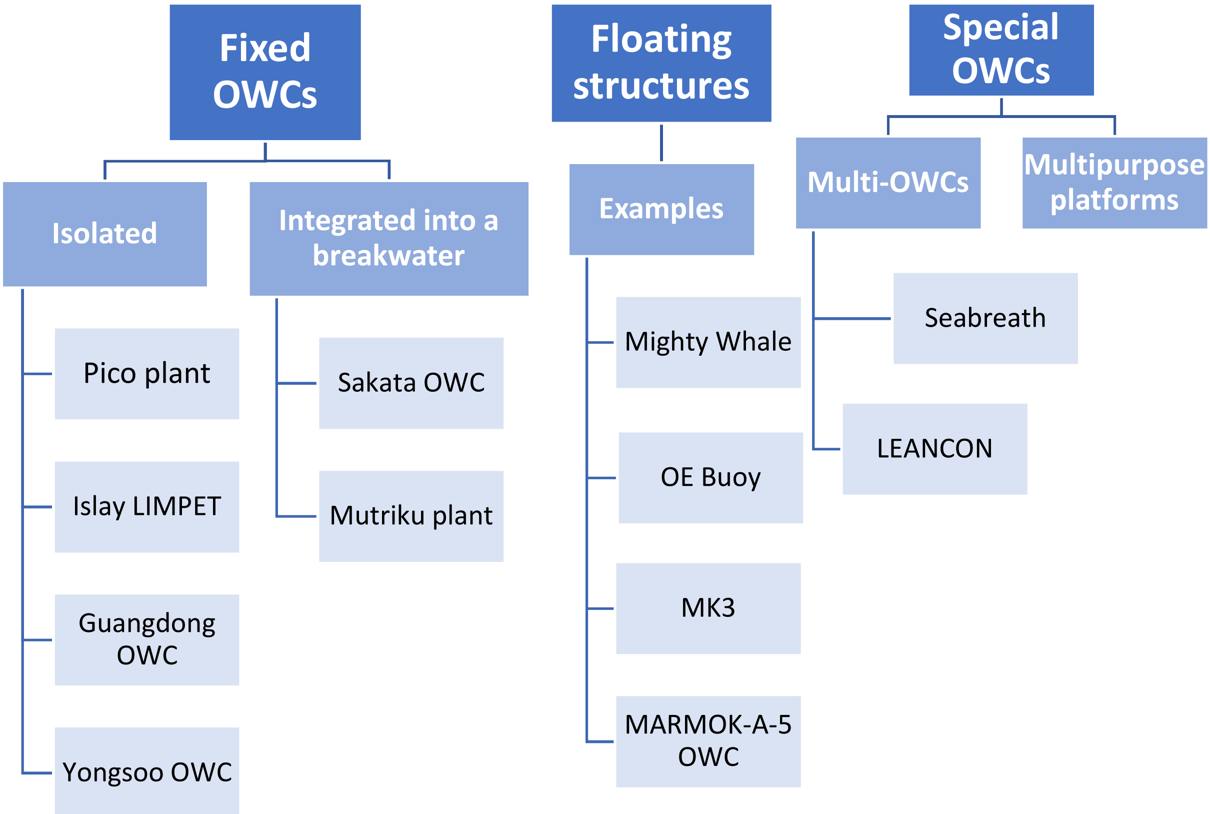

Figure 14. Scheme classification of OWCs.

4. Influence of Wave Characteristics

The performance of OWCs is mainly determined by wave characteristics and the geometric characteristics of the device [43].

The basic geometric characteristics of waves are height, length, and period.

Ning et al. (2016) showed that horizontal wave forces in OWCs increase with the wave height and decrease with the wave length [44]. Rezanejad et al. (2017) observed that the influence of the wave height on the performance of the OWC device is of lesser importance than the influence of the wave period [45], and Huang et al. (2019) reported that horizontal and vertical wave forces are less sensitive to the wave period, but increase with the wave height [46].

Apart from studying the basic characteristics of the waves, other research has been carried out to study the relationship between different monomials that characterize waves and the performance of an OWC.

4.1. Relative Water Depth d/L

Sundar et al. (2014) studied the wave forces that acted on an OWC device and concluded that an OWC reaches the optimum value of its hydrodynamic efficiency when the relative water depth is around 0.131 [47].

One year later, they carried out an experimental study on a circular curve bottom profile OWC. They observed that vertical forces increased with the relative water depth up to d/L = 0.16 for all the different ranges of steepness, but that for values of d/L higher than 0.16, vertical forces decreased. Moreover, it was found that this reduction increases as the steepness of the wave decreases [48].

In addition, for d/L = 0.131, where the maximum absorption of the incident wave energy occurs, vertical forces are lower and for d/L greater than 0.15, nonlinearities dominate [48].

Referring to horizontal forces, the trend is similar to that in the behavior of vertical forces, but nonlinearities are much less important [48]. They also discovered that the peak horizontal force is more than 2.5–3 times the peak vertical force [48].

4.2. Water Steepness H/L

Thiruvenkatasamy and Neelamani (1997) found that an increase in wave steepness causes a decrease in the efficiency of the OWC [49]. Ashlin et al. (2015) discovered that wave forces acting on the OWC increase with H/L [48]. Jasron et al. (2019) showed that an increase in wave steepness leads to an increase in the maximum air pressure inside the chamber, which gives a lower hydrodynamic efficiency [43], and Zhou et al. (2020) reached the same conclusion after investigating the hydrodynamic performance of an OWC integrated into a monopile offshore wind turbine (OWT). The efficiency of the device decreases as wave steepness increases, especially next to the resonant frequency. As the wave steepness increases, nonlinearities also do, which causes a loss of energy [50].

4.3. Other Considerations

D'Aquino et al. (2018) [51] studied the correlation for two depths (4 and 11 m) between wavelength (L), wave period (T), wave height (H), and the velocity of the wave (V). Their most important findings were that:

- ○ The influence of H on the performance of the OWC becomes much more important near the breakpoint of the wave (at depth of 4 m in their study).
- ○ For a better performance of the device, it is recommended to locate the OWC where it is not affected by bottom friction.
- ○ The highest value of wave power does not necessarily correspond to the highest value of mechanical power extracted by the device. Only vertical velocity of the waves is useful and the wave power dissipated by the horizontal component of the velocity is wasted.

Considering all these studies, the relationship between the wave characteristics and the performance of an OWC are summed up in Table 1.

5. Influence of OWC Geometry

The geometry of the OWC is probably the most popular topic about OWCs due to its strong influence on the behavior of the WEC. The concept of geometry is very broad, and includes many aspects. The most significant are the dimensions and the shape of an OWC; the number of chambers; the configuration of the OWC; multi-OWCs and arrays. In this section all of them are studied.

5.1. Geometric Parameters

Optimizing the geometric parameters of an OWC is usually the main purpose of its designer. Therefore, many investigations have been carried out to obtain the best hydrodynamic performance of these devices. Malmo and Reitan (1985) proved that the natural frequency of an OWC is primarily determined by the immersion of the front lip [8]. Zheng et al. (1989) showed that flared harbor walls have better efficiency than rectangular walls [52]. Evans and Porter (1995) proved that for low values of the chamber length divided by the water depth, the water can be treated as a rigid body and that for high values of the submergence of the wall divided by the water depth, the capture width ratio (CWR) becomes narrower [53]. Thomas et al. (2007) showed that the thickness of the front wall does not have a remarkable influence on the hydrodynamic performance of the device energy conversion capacity [54]. Bouali et al. (2013) discovered that the front wall submergence depth is a key in the design of an OWC and its optimal value is between 0.38 and 0.44 times the water depth. They also proved that the width of the OWC is another important parameter and its optimum value is between 0.8 and 1 times the water depth [7]. Ashlin et al. (2015) and Sundar et al. (2014) proved that the circular bottom profile of the OWC is more efficient [47,48]. Ning et al. (2016) [44] studied the effect of the chamber width, the front wall draught, the orifice scale, and the bottom slope on the hydrodynamic efficiency of the OWC. They concluded that the water motion highly depends on the wavelength divided by the chamber width and, finally, Simonetti et al. (2017) [55] studied the geometric optimization of the OWC and the turbine damping and pointed out that the CWR of the OWC follows a concave parabolic shape with the chamber length.

Some of the most recent studies are explained in more detail below.

Tsai et al. (2018) studied the performance of a modified breakwater-integrated OWC that was supposed to be installed at Taichung Harbor, Taiwan. They obtained [56]:

- Effect of chamber width: The hydrodynamic efficiency increases as the chamber width increases for low frequencies, but it follows an opposite trend for high frequencies. In addition, the resonant frequency decreases as the chamber width increases, in line with Ning et al.'s results [44]).
- Effect of opening ratio: The hydrodynamic efficiency of the OWC increases with the opening ratio until reaching a maximum, and then decreases.

Hsien et al. (2020) analyzed different parameters of an OWC divided into three chambers by two inner walls and they obtained the following results [26]:

- Effect of relative chamber length: It is defined as the length of the chamber divided by the wavelength. As this ratio increases, the efficiency also does, until it reaches a maximum, and then decreases. It becomes more important with the period and height of the wave.
- Effect of submergence depth ratio: It is defined as the submersion depth of the OWC divided by the total depth. Its effect depends on the height and period of the wave.
- Effect of opening ratio: The results obtained were similar to the results obtained by Tsai et al. in 2018.

Medina et al. (2020) focused on the effects of the front wall thickness and the bottom profile of the OWC on its efficiency. They concluded that [57]:

- Effect of nonlinearities: Nonlinear effects can significantly change the power absorption of an OWC.
- Effect of wall thickness: The efficient bandwidth of the OWC reduces as the thickness of the front wall increases.
- Effect of the bottom of the chamber: The efficiency band slightly shifts to longer periods as the bottom of the chamber becomes steeper. Therefore, for small periods it is better to use a flat bottom. The period in which resonance occurs is almost independent of the bottom geometrical configuration and it is mostly determined by the natural frequency of the water column.

Koley et al. (2020) [58] also studied the geometric optimization of OWCs and stated that for high values of the wave length, wider chambers should be used and that for short waves, narrower chambers are more efficient, which was in line with previous studies (Evans and Porter, 1995 [53] and Rezanejad et al., 2013 [59])

Chen et al. (2021) [60] analyzed the influence of the chamber width and the submergence depth of the OWC. They showed that the efficiency of the chamber follows a concave parabolic shape with the chamber width divided by the wave length, and pointed out that the front wall draught corresponds to a unique chamber width, so that the hydrodynamic efficiency reaches the maximum value under certain wave conditions.

Guo et al. (2021) [61] developed an analytical model to study the CWR of an OWC integrated in a breakwater and concluded that bandwidth becomes narrower as the width increases.

A table that sums up all the geometric properties and how they affect the performance of an OWC is presented below (Table 2), but it is important to say that these relationships do not have to be interpreted as fixed rules. To optimize the behavior of an OWC, each specific case should be studied in detail.

5.2. U-Shaped, L-Shaped, and V-Shaped OWCs

To improve the performance of OWCs, several design concepts diverging from the conventional OWC shape have been investigated. The most common designs proposed are the U-shaped and the L-shaped OWC [62].

Bocotti (2006) [63] was the first researcher that showed that U-shaped OWCs give better performance for both swells with large waves and small waves. This is because the natural period and the amplitude of the pressure fluctuations on the opening of a U-shaped OWC are greater than those in a conventional OWCs. Seven years later, Malara and Arena proved the same as Bocotti [64].

Vyzikas et al. (2017) [65] developed a physical model to study the performance of four three-chamber OWC models. They investigated the common U-shaped OWC, one version that resembled the U-shaped Bocotti OWC, the conventional OWC, and an adapted version of the conventional OWC. In line with previous studies, they saw that U-shaped models performed better than conventional ones, especially when they were close to the peak of their performance.

Fox et al. (2021) [62] developed a numerical model in which they studied the performance of a conventional, a U-shaped, and an L-shaped OWC and also concluded that the U-shaped gave better hydrodynamic performance.

López et al. (2021) [66] also studied the performance of different OWC configurations (conventional, stepped-bottom, U-shaped, and L-shaped) with a numerical model using the case study of Vigo port (Spain), but they found, in contrast to Fox et al., that the OWC that performed better was the L-shaped one.

5.2.1. U-Shaped OWCs

The U-shaped OWC is an OWC with an additional vertical duct at the wave-beaten side [63]. The shape modification of the U-duct induces an increase of the OWC's natural period when compared with the conventional shape, making the energy conversion more efficient for the most common wave periods [62] (Figure 15).

Ning et al. (2020) [67] developed a numerical model to study the geometrical optimization of a U-shaped OWC. They found that:

- The air pressure inside the chamber and, consequently, the hydrodynamic efficiency of the OWC increases with vertical duct height (d_1 in Figure 15). In addition, the effect of the vertical duct height on the maximum pressure increases with *kh* increasing in relatively low frequency region.
- The duct width (*b* in Figure 15) has also a great influence on the air pressure inside the chamber. A larger vertical duct width gives a larger hydrodynamic efficiency in a relatively low frequency domain. Moreover, the total hydrodynamic force exerted on the U-shaped water column almost increases linearly with the vertical duct width.
- The wall width influences the maximum air pressure and the hydrodynamic efficiency too. The higher the wall width, the higher the maximum air pressure and efficiency.

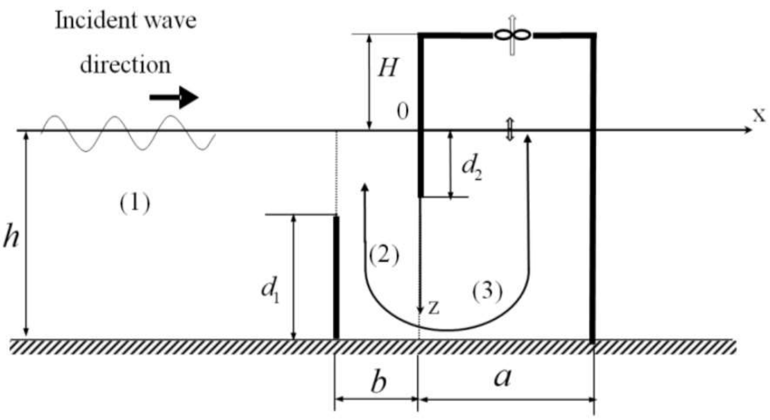

Figure 15. U-shape OWC sketch (George et al. 2021 [68]).

More recently, George et al. (2021) [68] used artificial neural networks to optimize the design of a U-shaped OWC. They developed a method using machine learning to obtain the optimal design.

5.2.2. L-Shaped OWCs

Rezanejad et al. (2019) [69] conducted an experiment in which they studied the hydrodynamic performance of an L-shaped OWC. They concluded that the amplification factor and the performance of the device are enhanced by reducing the immersion depth of the device.

López et al. (2021) [66] pointed out that:

- A wider vertical section of the chamber improves the performance of the L-shaped OWC, especially for periods different from the natural period of oscillation of the chamber.
- The greater the height of the horizontal duct of the chamber, the higher the captured energy.
- A shallower entrance enhances the efficiency of the OWC.

Samak et al. (2021) [70] studied how to improve the performance of an OWC with an L-shaped wall and concluded that the L-shaped front wall reduced the air pressure, but it enhanced the hydrodynamic efficiency of the device, especially for long waves.

5.2.3. V-shaped OWCs

The V-shape minimizes the vertical forces that act on the OWC. These devices have the highest efficiencies for the lowest wave states [71].

Kelly et al. (2013) [72] proposed a V-shape platform with 32 OWCs and highlighted the advantages of this new concept.

5.3. Use of Dual Chambers

The use of dual chambers in an OWC is very common in the design of OWCs. Rezanejad et al. (2015) [73], and later Elhanafi et al. (2018) [74] and Ning et al. (2019) [75,76], found that the capture width ratio of the OWC device was highly improved by introducing a dual chamber. Some of these studies are presented below.

Ning et al. have conducted several experiments to study the performance of dual chambers. In 2018 they developed different computational models [77] and in 2019 they studied the performance of these devices experimentally [75]. They obtained the following results:

- Efficiency: The results obtained in the models showed that the effective bandwidth of the dual chamber was about three times larger than in the single chamber. In addition, the peak efficiency was around 8% greater in the models (2018) and about 4% greater in the experiment setup (2019).
- Effect of submergence: A decrease in the outer chamber submergence causes an increase in both the maximum efficiency and the effective frequency bandwidth.
- Effect of chamber width: It increases the hydrodynamic performance of the device.
- Effect of the thickness of the shell: It was not very significant in the low-frequency domain, but in the high-frequency domain, thinner shells were better.
- Effect of the volume of the chamber: As it increases, the effective frequency bandwidth gets smaller, but the efficiency increases. An optimum chamber volume exists and it should be calculated for each case.

Wang et al. (2020) studied the wave loads on a land-based dual chamber OWC using a nonlinear numerical model and they reached the following conclusions [78]:

- Wave forces: They only studied the effect of horizontal forces because they are much bigger than vertical forces. The outer chamber is the chamber that suffers the highest wave loads, and these forces increase with frequency. However, forces in inner chamber increase with kh until they reach a peak, and then decrease.
- Effect of submergence: Horizontal forces in the outer chamber increase with its submergence. Increasing the curtain wall draft does not only reduce the power capture efficiency, as pointed out by Ning et al. [75,76], but also enlarges the forces on the OWC. Therefore, small curtain drafts are highly recommended.
- Effect of sub-chamber width ratio: Reducing the sub-chamber width ratio can help to reduce forces on the structure. Therefore, small sub-chamber width ratios are suggested.

5.4. Use of Arrays of OWCs

Another field of interest is how the use of multi-column and multi-OWC plants affects hydrodynamic performance, as well as what is their optimum configuration.

Hsieh et al. (2010) analyzed the use of multi-column devices and showed that they have better energy conversion effectiveness than isolated OWCs [79]. Tseng et al. (2000) reported that multi-resonant OWCs yield only 28.5% efficiency due to high energy losses [80]. Atan et al. (2019) studied the effect of arrays of OWCs on the nearshore wave climate and concluded that they do not significantly alter the nearshore climate [81], and finally, Jasron et al. (2020) studied three different arrangements of OWC devices to optimize their performance [82]: a single water column, a double water column in series arrangement perpendicular to the direction of wave propagation, and a double water column parallel to the direction of wave propagation. The results showed that the double OWC configuration operates more efficiently at deeper water depths than the single device and that the efficient frequency bandwidth is broader, especially for an arrangement in which the OWCs are in parallel, which showed a more stable behavior.

Another important fact is that when the relative depth is greater than 0.9 the effectiveness of all the devices significantly decreases due to the presence of nonlinearities.

5.5. Influence of the Integration of a Breakwater in the OWC System

One of the aspects of most interest when studying the design and construction of OWCs, and in general of WECs, is if integrating them into an existing breakwater is beneficial or not.

In the case of WECs, Zhao et al. (2019) studied the performance of a breakwater-integrated WEC system with oscillating buoys and compared it to that of an isolated WEC by studying the heave-response-amplitude operator values and wave forces on the device. They concluded that the integrated WEC system had larger HRAO (heave-response-amplitude operator) values and wave forces in the heave mode. This improves the hydrodynamic efficiency of the oscillating buoy, but should also be considered when designing the device. The presence of the breakwater amplifies the energy conversion performance of the WEC and the forces that act on it [83].

Several studies and experiments have been carried out to study the effect of breakwaters specifically on OWCs, with both single-chamber OWCs and dual chambers (Wan et al. (2020) [84]).

Falcão and Henriques (2016) pointed out that the integration of an OWC into a breakwater has many advantages, such as better access for construction and easier operation and maintenance [11].

Viviano et al. (2016) showed that integrating an OWC into a breakwater helps to reduce wave reflection and, consequently, to improve the hydrodynamic performance of the device [85].

In 2019, Reabroy et al. did a numerical model to investigate the hydrodynamic performance of an asymmetric floating device WEC. They studied two magnitudes: the RAO (response amplitude operator) and the CWR (capture width ratio). Both magnitudes were greater for the breakwater-integrated WEC system for all the wave periods studied, which means higher energy efficiency, but also higher wave loads [86]. These results are in line with Howe et al.'s (2017) [87] results.

Howe et al. (2020) [88] developed a proof-of-concept for a floating breakwater integrated with an OWC. They carried out an experiment in which they tested the performance of a bent-duct type OWC in four main aspects: device configuration, breakwater width, pneumatic damping, and structure motion influence. They concluded that device configuration, especially device spacing, really influences the performance of the OWC. They also pointed out that device integration is very beneficial and that pneumatic damping and motion influence are key aspects in the design of the OWC, while breakwater width does not play a key role in OWC performance.

Konispolaties et al. (2020) studied the configuration of different OWCs in front of a vertical breakwater. They studied three configurations: parallel to the wall, perpendicular, and rectangular arrangement. The results obtained showed that the installation of an OWC array in front of a vertical breakwater can be an effective way to improve its power absorption efficiency [89].

In 2021 they carried out another investigation studying the hydrodynamic efficiency of a WEC in front of an orthogonal breakwater, and as in the previous year, they concluded that the presence of a breakwater enhances the efficiency of WECs. However, this enhancement strongly depends on the distance between the device and the walls, the draught, the wave number, and the heading angle [90]. These findings are in line with Howe et al.'s (2020) results [88].

Wang and Zhang (2021) [91] developed a numerical in model in which they studied the performance of an OWC mounted over an immersed horizontal plate and compared it with that of an OWC breakwater integrated system. They concluded that the integration of a horizontal plate can significantly enhance the performance of an OWC, especially if the immersion depth of the plate is small, and that this system is more efficient than the common breakwater-integrated system. One year later, in 2022 [92], they proposed another novel system composed by an offshore heaving OWC device and a floating stationary breakwater with a certain length of gap between each other. They proved that the inclusion of a floating stationary breakwater is beneficial for enhancing the peak efficiency to a much higher extent, especially with a relatively larger immersed depth of the breakwater, and that the gap distance between the heaving OWC and breakwater has a dominant effect on the overall extraction efficiency.

5.6. Use of Multifunctional Platforms

Another field of interest in renewable energy resources is the design of multifunctional platforms, because their use could significantly reduce the cost and enhance the behavior of different structures. Sharing the infrastructure for different energy converters can reduce the investment and optimize their hydrodynamic efficiency.

Zhou et al. (2020) [50] studied the use of multifunctional platforms. They concluded that if an OWC is constructed next to an OWT, the forces and overturning moment acting on the monopile are lower, especially for high-frequency waves. This is due to the redistribution of the wave potential around the OWT caused by the OWC [50].

6. Influence of Air and Turbine Properties

As well as the main geometric parameters and the moisture of the air, air compressibility and turbine damping also have a great influence on the performance of an OWC.

6.1. Air Properties

When modeling the air inside the OWC, there are two main air properties that affect its performance: humidity and compressibility. Not considering these properties properly in the numerical models can lead to an overestimation of the performance of the OWC.

Referring to the humidity of the air, Medina-López et al. (2019) [93] studied it numerically and analytically and showed that the humid air model had an efficiency of 50–70% compared to the dry air model. One year later, Moñino et al. (2020) [94] showed that an increase in moisture of 45–70% in the air-water vapor mixture of the OWC induces reductions in the power input to the turbine by around 30%.

With respect to air compressibility, many numerical models assume the incompressibility of the air. However, this assumption is not real and, as happens with air moisture, it can lead to an overestimation of the performance of the OWC. Thakker et al. (2003) [95] were one of the first to study this effect in OWCs with impulse turbines and proved that not considering air compressibility can result in overestimation of the capture width ratio (CWR) of the device. Teixeira et al. (2013) [96] studied it with Wells turbines and reached the same conclusion. More recently, Gonçalves et al. (2020) [97] studied this compressibility effect in both Wells and impulse turbines, and concluded that not considering the compressibility of the air can result in overestimation of hydrodynamic efficiency of the OWC by 16–20% in both cases. In addition, this overestimation increases with the flow rate of the turbine.

6.2. Turbine Properties

One of the most important characteristics to consider when designing an OWC is the coupling between the OWC and the PTO [98]. To obtain good rates of efficiency it is necessary to use a turbine damping that fits the damping of the chamber. López et al. (2014) [99] proved that a correct selection of the damping supposes an increment of the capture factor of more than 10 points, independently of the incident wave conditions. Therefore, although the damping of the chamber varies with wave properties, studying the damping of the chamber is essential for an efficient performance of the OWC.

Among others, Pereiras et al. (2015) [98] developed a methodology to obtain the best impulse turbine for a given OWC. It consisted in obtaining the optimum damping of the chamber and once it was obtained, selecting the best turbine for this damping.

López et al. (2016) [100] also developed a methodology to obtain the optimum turbine for a given OWC and sea state. They also proved that to get the maximum pneumatic energy, turbine-induced damping should be close to the optimum chamber damping.

Simonetti et al. (2017) [55] studied the damping of the OWC and its relationship with the geometry of the chamber. They concluded the following remarkable points:

- The effect of the damping of the OWC CWR mainly depends on the chamber length and its relative water depth.
- Near the resonant condition the effect of the optimal damping of the OWC is insensitive to the chamber geometry.
- For other frequencies, higher values of optimal damping are found for decreasing chamber length.
- The optimal damping is minimal for the resonant condition and increases for the remaining values of relative water depth.
- Underdamping (damping coefficient lower than the optimal) reduces the device performance at a higher rate than overdamping.

Bouali et al. (2017) [101] also studied this problem and stated that for each size of the OWC chamber there is an optimal value of the PTO damping, and there is only one pair, chamber size and corresponding damping, that obtains the maximum energy conversion for given wave conditions.

7. Conclusions

After analyzing research on the performance of OWCs, some general patterns can be remarked:

- Wave characteristics
    - Horizontal wave forces increase with the wave height and decrease with the wave length.
    - The peak horizontal force is more than 2.5–3 times the peak vertical force.
    - The maximum absorption of wave energy occurs when the relative water depth is around 0.131.
    - An increase in wave steepness means an increase in the nonlinearities of the waves, which gives lower efficiencies of the OWC and larger forces.
    - OWCs should be located where the bottom friction does not affect their performance.
    - Neither the wave height nor the wave period may totally represent the nature of a wave; a design based on wave energy is recommended for OWCs.
    - A large amount of wave energy does not always imply a good conversion efficiency.
- Geometric parameters
    - Natural frequency of an OWC mainly depends on its chamber width and it is influenced by the front lip depth.
    - Wider chambers should be used for longer waves and narrower chambers for shorter waves.
    - For high values of the relative submergence of the lip wall, the CWR becomes narrower.
    - Hydrodynamic efficiency increases as the breadth increases for low frequencies, but it follows an opposite trend for high frequencies.
    - The CWR mainly depends on the bottom slope and it shifts to longer periods, as the bottom of the chamber becomes steeper. The CWR of the OWC reduces as the thickness of the front barrier wall is increased.
    - As the chamber length–water depth ratio decreases, the period of maximum hydrodynamic efficiency becomes shorter.
    - Circular bottom profile of the OWC is more efficient in terms of hydrodynamic performance.
- U-shaped, L-shaped, and V-shaped OWCs
    - They usually perform better than conventional OWCs.

    - Most studies point out the U-shaped OWC is the most efficient model. Its efficiency increases with the duct height and width and the wall width.
- Dual chambers
    - They usually give higher peak efficiencies and a much larger CWR than single chambers.
    - The outer shell draft should be smaller than the inner one.
    - Thinner shells are recommended because they have a better performance in the high-frequency region. However, the design of a dual chamber needs a balance between strength and hydrodynamic performance.
    - The seaside wall is the wall that suffers the highest forces. Therefore, it should be built with the best materials.
    - A smaller sub-chamber width ratio is suggested.
- Breakwater-integrated OWCs
    - These have better access for construction, and easier operation and maintenance.
    - It helps to reduce wave reflection.
    - The presence of the breakwater enhances the energy conversion performance of the OWC, but also amplifies the forces, which should be considered in the design process.
    - It increases the CWR of the OWC.
    - There are current research lines on new innovative systems.
- Multifunctional platforms
    - These can reduce the investment, forces that act on the OWC and optimize its hydrodynamic efficiency.
    - They are very convenient solutions.
    - Research is currently being carried out in this field.
- Air and turbine properties
    - Not considering air compressibility and humidity can lead to overestimating the hydrodynamic performance of the OWC.
    - There is only one pair, chamber size, and corresponding damping that allows obtaining the maximum energy conversion for given wave conditions.
    - The effect of the damping of the OWC CWR mainly depends on the chamber length and its relative water depth. At the resonant point it is insensitive to geometric characteristics and the value of the optimum damping is minimal.
    - Overdamping is better than underdamping.

Although these general patterns give an idea of the performance of an OWC, it is important to say that a universal formula that could be applied in every kind of OWC would be very difficult, if not impossible, to obtain. Similar types of OWC wave energy conversion systems may have some design guidelines in common, but there are some uncertainties, such as sea bottom conditions, slopes in the way of incident waves, and other environmental variables that can make them work completely differently.

Therefore, future research should still focus on the process of optimization of OWC devices, on the question of how all these parameters affect the hydrodynamic performance of OWCs, and on how to make OWCs efficient for a broad range of parameters. Special efforts must be made to improve the most promising and innovative systems, which are multipurpose platforms, breakwater-integrated OWCs, U- and L-shaped OWCs, and biradial turbines. Although in recent years many advances have been made, OWC technology is still immature and great developments are needed to make it profitable and cost efficient.

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