IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 28, 2022, accepted March 15, 2022, date of publication March 21, 2022, date of current version March 28, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3160713

Oscillating Water Column Geometrical Factors and System Performance: A Review

DZUL HAFEZ YACOB[1], SHAMSUL SARIP[1], HAZILAH MAD KAIDI[1], JORGE ALFREDO ARDILA-REY[2], (Member, IEEE), AND FIRDAUS MUHAMMAD-SUKKI[3]
[1]Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia, Kuala Lumpur 54100, Malaysia
[2]Department of Electrical Engineering, Universidad Técnica Federico Santa María, Santiago de Chile 8940000, Chile
[3]School of Engineering and the Built Environment, Edinburgh Napier University, Edinburgh EH10 5DT, U.K.

Corresponding authors: Dzul Hafez Yacob (hafedzul@gmail.com), Shamsul Sarip (shamsuls.kl@utm.my), and Firdaus Muhammad-Sukki (f.muhammadsukki@napier.ac.uk)

This work is partially supported by the Ministry of Higher Education Fundamental Research Grant Scheme R.K130000.7801.5F490. Firdaus Muhammad Sukki acknowledged the contribution from Edinburgh Napier University through Starter Research and Innovation Grants (Reference No REG2021/22) and the National Research and Development Agency (ANID) through the projects Fondecyt regular 1200055 and Fondef ID19I10165.

ABSTRACT Ocean waves that impact along the coast are among the most promising renewable energy sources that can be extracted from the environment. The ocean's energy can be extracted by a few methods and converted from kinetic energy into electrical energy using turbine blades and power generators installed in areas with strong waves. The best and most widely established wave energy converters use an Oscillating Water Column (OWC) conversion concept. During the past few years, numerous research projects have been conducted to ensure a continuous development of OWC technologies that could provide more systematic, consistent, and environmentally friendly electrical supply sources to the nearby communities and electric-powered facilities. OWC has distinctive techniques for every section of the energy converting process, differing from other methods. Several things need to be considered to ensure that a maximum amount of energy can be generated from the established system. This paper discusses the OWC system design characteristics and functions. This paper also summarizes the current technology developments for the OWC and their achievements.

INDEX TERMS Wave energy converter, oscillating water column, ocean energy, review, OWC design characteristics.

I. INTRODUCTION

The worldwide renewable energy industry has started to develop wave energy conversion technologies to an advanced level to ensure that available ocean energy can be fully utilized, which replace the conservative electricity generating methods for residential needs. There are several established wave energy converter methods in the industry, including oscillating water column, point absorber, attenuator, and overtopping device; each of which have individual advantages and disadvantages [1]. A typical wave energy conversion concept has been developed. The Oscillating Water Column (OWC) could be the most promising energy-producing device, and it represents 26.79% of the world's usage of energy converter concepts based on the wave energy converter deployment [2]. Wave energy converters are capable of harnessing up to MW of energy if those systems are built in the correct locations and in an exemplary configuration [3]. Research of this type of ocean energy converters is significant, corresponding to 45% of EU's funding in wave technologies [4]. Improvements have been made on the OWC air turbine equipment in the system, especially modifications regarding cost reduction in materials and manufacturing processes that reduce electricity costs per output power and that aim to continue operations under low and moderate ocean wave conditions [5]. In the acceptance study conducted by Heras-Saizarbitoria *et al.* [6] regarding ocean wave energy, specifically OWC placed at the shoreline, most of the surveyed participants were in favor of local renewable energy and of infrastructure built

The associate editor coordinating the review of this manuscript and approving it for publication was Haiyong Zheng.

in the area. The economic benefits for the local installation included the development of regional industries, promotion of regional research, development programs on renewable energy, and increased local tourism. In contrast, other surveyed respondents opposed the idea of developing the OWC, indicated their rejection on the basis of the limited yield from the system, immaturity of the OWC technology, the high development costs of the technology, the potential impact on the environment that may negatively affect marine life, and noise pollution generated by an OWC plant. The optimal absorption of a wave energy converter usually takes into account the resonance element and this indicates that the device's structural size and geometry are associated with the ocean's wavelength [7]. The ocean characteristics that play an important role are ocean depth, amplitude of the ocean wave, wavelength and frequency, the coastline, and the seabed conditions where the harnessing device is located. Maintenance cost is also an important factor to consider when seeking the most suitable device system for the specific area where wave energy is extracted [8]. The accumulated and established energy cost estimations of daily project management costs and specific cost databases are essential when formulating policy and risk assessment on a particular project. Policy preferences and possible subsidies provided by the government and other sectors are crucial in order to further promote the commercialization of marine renewable energy [9]. Currently, there is considerable research being conducted to formulate an optimal combination of different types of Energy Storage Systems (ESS). The most effective and suitable system for the specific sites to be developed will be chosen to increase the conversion system efficiency and, at the same time, reduce energy losses, development costs, environmental impacts, and health concerns [10].

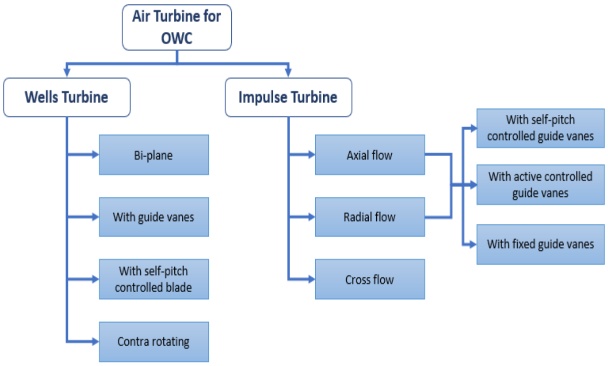

FIGURE 1. Classification of air turbine. Adapted from [11].

This paper summarizes the OWC geometrical factors and their effects on the performance of the converter system. Section 2 presents the OWC's main components and each of their functions in detail. Section 3 describes the important design aspects and how their elements produce the optimum power output. Section 4 discusses the drawbacks identified in earlier OWC developments and the improvements that were made to correct those issues. Section 5 discusses the review findings, and Section 6 focuses on the overall conclusions.

II. OSCILLATING WATER COLUMN SYSTEM DESIGN

This section offers general explanations of the main components of the OWC and their functions. An overview of the OWC plants in the industry provides a better understanding of the existing OWC harnessing technologies and their improvements to the concept of ocean wave renewable energy converter devices.

A. OSCILLATING WATER COLUMN SECTIONS AND THEIR FUNCTIONS

An OWC is comprised of two main sections: the water collecting chamber and the power generator. The submerged section is a structure that collects the waves. It has an opening to an underwater surface designed to receive ocean wave power from the oscillating movement of water levels within the chamber that is then transmitted into the air pocket. The power generator, also known as the Power Take-Off system (PTO), is a system that converts energy, transforming the ocean energy's pneumatic power into electricity. The air contained in the chamber has oscillating pressures that increase as the water column rises and decrease when the water column drops [11]. The moving air within the water column, called the air pocket, moves by the oscillating water levels and activates air flows through the turbine system, that are then released to the atmosphere. The air returns through the same turbine that self-rectified its rotation to the direction of the air flow. Figure 1 shows the classification of air turbines built for OWCs that obtain energy from ocean waves [11]. There are two types of air turbines usually used in OWC devices. Wells turbines use a lifting type of working principle, whereas Impulse turbines use a pressure type of working principle.

B. OWC PLANTS ESTABLISHED IN THE INDUSTRY

There have been 15 OWC plants built since 1989. Some have discontinued their operations while others remain in use. The Sea of Japan was the first OWC ever built, which was a wave power buoy built in 1983. This OWC plant used the Wells air turbine power generator, achieving a rated power of 40kW. Two years later, Norway built a wave energy converter in Toftestallen, Bergen, using a vertical axis Wells turbine that achieved a rated power of 500 kW. Unfortunately, it was destroyed in a storm and became inoperative.

In 1989, China started to build an OWC plant in Shanwei City, in the Guangdong region. From 1989 to 1991, the plant used an impulse turbine with a fixed waveguide and obtained a rated power of up to 100 kW, but it was damaged and was no longer operational. In 1990, Japan started to build another OWC plant at the Port of Sakata that integrated the converter system with the breakwater, obtaining a rated power of 60 kW using the Wells turbine system. India developed their first OWC plant, Trivandrum, the same year as the plant in Port of Sakata. Trivandrum used a Wells turbine in its converter system and managed to achieve a rated power of 125 kW. Trivandrum later changed the turbine to an impulse turbine. A plant was built at Vizhinjam, India, in 1990. In 1997, the Wells turbine used during the initial test stage was replaced with an impulse turbine with a guide vane attached to the turbine that automatically controlled the pitch of the vanes. Every year from April to November, the plant achieved a rated power of 75 kW, and from December to March, 25 kW.

Japan continued to develop the technology, and in 1998 they introduced their first Mighty Whale in Gokasho Bay. From 1998 to 2001, the plant used the Wells turbine with guide vanes and was able to generate power up to 110 kW from its three-chambered OWC floating structure. One year after the introduction of the Mighty Whale, Australia built a wave energy converter called Energetech. The fixed-structure device used a variable pitch control Wells turbine and managed to achieve a rated power of 500 kW. In 1999, on Pico Island in Azores, Portugal, the same design and specification of turbine system previously built and used in the Mighty Whales (a Wells turbine with guide vanes) was built and equipped in the fixed-structured OWC on Pico Island. Since then, the plant was able to achieve rated power up to 400 kW with a full-scale fixed structure OWC. It generated power continuously for 12 years before it was totally decommissioned in 2010. Japan invested again in the development of an OWC plant at its Niigata Port. The impulse turbine was employed in the plant and it managed to achieve rated power of 450 W with a maximum-recorded power of 800 W. The plant was only able to operate for four months, from June to September 2007. A floating Backward Bent Duct Buoy (BBDB) OWC, with a CORES backward duct, was built in 2008 with a scale model of 1:4 in Galway, Ireland, powered by an impulse turbine with stationary guide vanes. The highest rated power it was able to achieve was 13 kW and it operated until the year 2011.

Spain began using its Mutriku model in 2011, which remains in operation today. It uses Biplane Wells turbines with an output of 296 kW. In 2012, the LIMPET plant was built on Islay Island, Scotland, equipped with a contra-rotating Wells turbine. The plant initially generated power of up to 500 kW and the following year downgraded to 250 kW. This full-scale fixed structure OWC was able to continue operating from 2012 to 2018. REWEC3 was introduced in 2016 in the Civitavecchia harbor in Italy. This plant, which is still operational, uses a breakwater-integrated U-shaped OWC system with a Wells turbine and achieves 25 kW of rated power. Korea is conducting a sea trial on their OWC plant, built in 2017, located in Yongsoo, Jeju Island. It uses static guide vanes attached to impulse turbines to generate power of up to 500 kW.

Many new OWC plants developing in the future are likely to ensure a continuous and sustainable electrical supply to local areas. Table 1 lists the OWC plants that have been available since the technology began to operate until now. Improvements in ocean energy converter technologies are listed in chronological order, which provides a clear understanding of the optimization processes that have taken place to guarantee that they have a positive impact as a green energy option in the industry.

III. IMPORTANT ASPECTS OF AN OWC SYSTEM DESIGN AND ITS SPECIFICATION FOR PRODUCING AN OPTIMUM POWER OUTPUT

This section explains the important aspects that need to be considered when designing OWC devices. These include specifications, the initial activities which capture the actual ocean wave, characteristics where the plants should be built, processes involved in the OWC cycle, the environmental conditions surrounding the device, air compressibility, chamber design parameters, turbine specifications used in the system, airflow in the chamber and electrical controls for the converter.

A. BASIC CONSIDERATION FOR OWC SYSTEM DESIGN

A few crucial aspects need to be considered while designing the system, in order to develop an optimal and efficient OWC device. Due to the rigorous characteristics associated with the device specifications, extensive considerations are needed if an efficient product is to be built.

1) OCEAN WAVE CHARACTERISTICS

Scientifically, ocean waves usually begin as a little wave that increases in size due to the constant energy supplied by the wind blowing over the entire ocean. When the waves are fully developed and finally reach their peak, white capping is formed to balance out the energy input. A fully developed ocean wave depends both on wind speed and the distance from which the wind was blowing [12]. A swell wave condition can be described as the ocean wave that continues to travel for a very long distance even though there is no longer wind blowing over the water and no energy is lost during the time the wave travels. At this point, the wind is no longer responsible for generating the wave.

Figure 2 depicts the formation stages of ocean waves, depicting the difference between wavelength, period, frequency and height. A wavelength is the distance between points A and B, which represents the distance between two wave crests in the wave propagation direction. Wave height is the highest point of the wave's amplitude. Wave frequency is the rate of wave crests passing through Point A every second. The wave period is the time interval for the wave crest to travel from Point A to Point B, meaning the time taken for the waves to arrive.

A wave condition known as shoaling is another situation that can influence the performance of wave energy converters. This occurs when the wave travels into shallower water and the wave height changes significantly due to water depth differences where a wave-energy is transported. This effect is caused by the energy flux of waves, which varies both in time and space. To further understand the situation, it's similar to a heaving body situation that undergoes small amplitudes of oscillations. The buoyancy force acting in this situation is

TABLE 1. **OWC plant established in industry.**

Name of plant	Air turbine type	System specification	Output from the system built
Sea of Japan [13]	Wells turbine	Designed as power buoy	Rated power: 40 kW
Toftestallen, Bergen [14]	Vertical axis Wells turbine	The design looks like a spar buoy but fixed at the shoreline. The device was destroyed in a storm in 1988	Rated power: 500 kW
Shanwei City, Guangdong Province, China [15, 16]	Fixed guide vanes attached with impulse turbine	The fixed OWC was built at full scale, started its operations in 1989 and broke after two years.	Rated Power: 100 kW
Port of Sakata [17]	Wells turbine	The converter system integrated with breakwater	Rated power: 60 kW
Trivandrum [18]	Wells turbine	The Wells turbine has been replaced with an impulse turbine and tested	Rated power: 125 kW
Vizhinjam, India [19, 20]	Initially equipped with a Wells turbine for tests. Replaced with an impulse turbine type in 1997, attached with guide vanes that have a self-pitch controlled feature	The fixed structure device was built at full scale, started its operation in 1990 and ended in 2011	Rated Power: 75 kW (Apr.–Nov.), 25 kW (Dec.–Mar.)
Mighty Whale, Gokasho Bay, Japan [21]	A Wells turbine type was used and attached with guide vanes	It was built as a three-chambered floating-structure OWC tested from 1998–2001	Rated Power: 110 kW
Energetech [22]	The system was equipped with a Variable pitch Wells turbine	Fixed structure	Rated power: 500 kW
Pico Island, Azores, Portugal [14]	Wells turbine type attached with guide vanes	Full-scale fixed-structure OWC ready in 1999 and ended its operation in 2010	Rated Power: 400 kW
Niigata port, Japan [23, 24]	Fixed guide vanes attached to the Impulse turbine system	Small scale fixed-structured device operated from June until September 2007	Rated Power: 450 W Maximum Power: 880 W
CORES, Galway Bay, Ireland [25]	Wells turbine was used for initial tests and replaced with impulse turbine type that was attached with self-pitch controlled guide vanes	1:4 scale floating BBDB OWC operated from 2008 to 2011	Rated Power: 13 kW
Mutriku port, northern Spain [26]	Biplane Wells turbine	The converter system was integrated with Breakwater structure and has operated from 2011 until now	Rated Power: 296 kW
LIMPET, Islay Island, Scotland, UK [27]	Contra-rotating Wells turbine	Full-scale fixed-structure OWC that was commissioned in 2000 and fully ended its operation in year 2018	Rated Power: 500 kW and demoted to 250 kW in later years
REWEC3, Civitavecchia harbor, Italy [28, 29]	Wells turbine	Breakwater-integrated, U-OWC design concept Operated from 2016 until now	Rated Power: 25 kW and cumulatively nearly 2.5MW
Yongsoo, Jeju Island, South Korea [30]	Impulse turbine plus fixed guide vanes	Bottom standing fixed-structure OWC which has undergone sea trial since 2017	Rated Power: 500 kW

represented in the following Equation 1:

$$F_{hs}(t) = \rho g A z(t) \qquad \textbf{(Eq. 1)}$$

where ρ represents water density, g is the gravitational acceleration, A is the OWC chamber's cross-sectional area, and z represents the vertical displacement caused by the oscillating movement of the ocean wave. Thus, Az demonstrates the difference between the OWC's submerged volume, which is equal to the water level displacement by the oscillating body. Applying the linear wave theory is valid for small amplitude motions under the assumption of the same cross-sectional area along the vertical axis of the OWC device geometry. However, due to the variation in the cross-sectional area that can take place, the linear wave theory is not compatible with large amplitude motions. Besides, it is imperative to consider the hydrostatic force to assess the non-linear amplitude motion accurately. From the earlier explanation regarding the basic ocean wave characteristics, we can recognize the impact of those wave conditions on the OWC design approach and its performance behavior.

In order to discover which design for a floating OWC device has a higher capacity to capture width (between the BBDB and the conventional axisymmetric OWC), first, we must have essential knowledge of the dynamic relations between the waves and a rigid-body floating in an experimental basin that purposely creates pressure increases and drops, and is tested both in conditions that are open and closed to the atmosphere. Previous research investigated these two geometries seeking to test both marine vessels with moonpools or wave basin. The BBDB's capture width achieved a broader frequency response than that of the axisymmetric device [31]. The BBDB in the 5 s to 10 s wave period condition also has a better hydrodynamic performance in power production for wave energy conversion than forward bent ducts that cover the primary waves, as investigated by Sheng [32]. According to Rezanejad *et al.* [33], in both regular and random

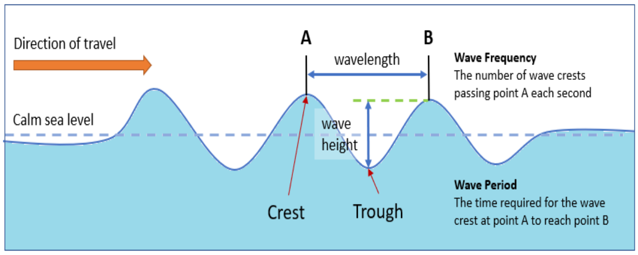

FIGURE 2. **Wave characteristics: Wavelength, wave height, wave period and wave frequency. Adapted from National Oceanic and Atmospheric Administration (NOAA) (https://www.noaa.gov/).**

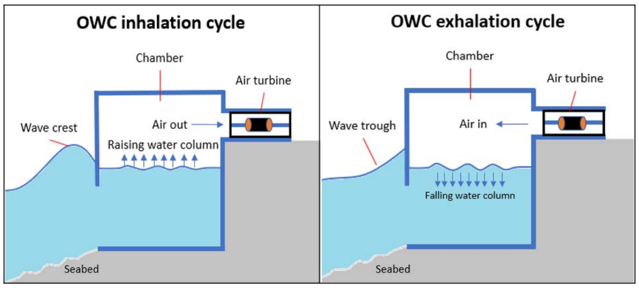

FIGURE 3. **Inhalation and exhalation cycle in OWC. Adapted from [37].**

wave conditions, the OWC device efficiency can be evaluated accurately based on a numerical approach using the frequency domain analysis, and it is applicable for investigating the wave height and period and the turbine damping effect on the converter performance. It was observed from the study that the wave height has lesser importance in the OWC's device performance than the turbine damping and wave period, which smoothen the device performance curve reflected by the variations in wave periods.

If this study were to compare a single OWC with an array of OWCs of the same dimensions, it would show that the OWC's array formation has a more significant influence on the power capture efficiency than individual devices. In addition, it demonstrates that the optimal pneumatic damping for both turbine arrangements is different even with large spacing between turbines of identical specifications [34]. 30% of the mean power improvement can be demonstrated in an array with a spacing of $L/a = 5$, confirming that the array configuration will always produce lesser power than the sum of individual OWCs in the array [35]. The finite-length wall model, introduced to act as a channel wall, produced better results than the equally spaced array model because of the closer correlation of hydrodynamic coefficients [36]. The maximum capture width under regular wave conditions was 15%, and in irregular wave conditions it was 10%, while the wall effect can amplify the channel-width-to-device-diameter 5.25 times with the same configuration.

2) INHALATION AND EXHALATION CYCLE WITHIN THE OWC CYCLE

Inhalation and exhalation are the airflow cycles that occur in the OWC water column. Inhalation is the condition where the air pocket moves towards the air turbine because of the wave force acting on the water column; exhalation is the part of the cycle in which the air retracts and moves from the pocket contained in the chamber through the air turbine in the opposite direction because the water level drops within the chamber as it returns to the sea [37]. The illustration in Figure 3 represents these two cycles. For both exhaling and inhaling processes, the PTO must be a typical air turbine that is self-rectifying so it can push the turbine in the same direction [38].

As the result of the tapered water depth, a boulder collection inside the chamber causes wave shoaling and unanticipated chamber pressure skewness, contributing to shortfalls in the turbine's performance. It can be even worse if defects in the wall produce recurrent pressure losses in the chamber. One way to overcome this situation is by adapting the passive non-return valve system to counter the chamber's pressure irregularities caused by the exhaling stroke's pneumatic over-power caused by wave shoaling. The passive valve systems could be more beneficial in the long term.

3) DUAL DIRECTION OF THE AIRFLOW

The power generating system in the OWC's air turbine operates as the air circulates through the turbine system. The water chamber and water levels increase and drop with the waves' rhythm, acting like a piston. The back and forth movements of the airflow going in and out of the turbine makes it rotate, generating the mechanical energy that is later converted into electrical energy by a power generator. Because of how the OWC operates, it should have a turbine that can adapt to the air flowing in both directions. The best turbine types are usually the ones used in Wells turbines.

The lift-type Wells turbine has a particular feature: the shape of its turbine blade is symmetrical, but the rotational direction is constantly the same even though the air flows come from both directions. The airflow going into one direction pushes the rotor blade in another direction, and because of the rotor blade's symmetry, the rotational direction remains constant even though the air flows in either direction. Therefore, the Wells turbine can continuously rotate if back-to-back airflow movements occur in the turbine system. The OWC equipped with a Wells turbine has only a few moving parts, which are not underwater, and thus, it needs no gearbox and is easy to maintain. It quickly achieves an efficiency of 40-70%. Several experiments tested the converter configuration with this type of turbine under natural conditions.

Therefore, the Wells turbine can continuously rotate if back-to-back airflow movements occur in the turbine system. The OWC equipped with a Wells turbine has only a few moving parts, which are not submerged in water, and thus, it needs no gearbox and is easy to maintain. It quickly achieves an efficiency of 40-70%. The converter configuration with this type of turbine has been tested in several experiments under real conditions.

A bi-directional turbine design in OWC wave energy converter systems is crucial since the water and air will move in two directions in the same column. Windage losses are detrimental if they occur on the inactive rotor, a central part of the machine's conception. Falcao *et al.* [39] presented a novel bidirectional air turbine and analyzed its performance in an OWC. The research consisted of a numerical simulation of four different geometries of curved-duct manifolds with five different sizes. The results demonstrated an overall efficiency peak with values of about 86% for the machine. Comparing the new and old bi-radial turbine with a sliding guide shows that the new turbine is more efficient by a margin of 8% in random waves for peak instant efficiency and maximum average efficiency. Another type of air turbine suitable for two airflow directions is the bi-radial impulse turbine, capable of producing better overall device performance than the multi-staged Wells turbine, without needing several stages and with a substantially smaller rotor diameter [40]. While axially shorter than the Wells turbine, it has a larger stator radius, typically about three times bigger than the rotor radius.

The OWC energy harnessing system employs a bidirectional air turbine to obtain energy from ocean waves. The design of the turbine blade must be aerodynamic and allow the air to flow in both directions, given the fluctuation of the ocean waves. Also, it must have turbine characteristics that are apt in particular OWC applications [41]. It also must be tested using standard testing systems with consistent results to achieve a sustainable bidirectional air turbine performance. Moisel and Carolus [42] described how they tested the bidirectional aerodynamic and aero-acoustic air turbine performance using a standard performance testing procedure at nine well-known test facilities worldwide. The testing facility with acoustic attenuators with bidirectional and steady pressurized air supply determined the turbine's aerodynamic and acoustic characteristics.

B. SEA BOTTOM SURFACE BOTTOM SURFACE OF THE OWC CHAMBER

The effect of the sea bottom's surface can be another important aspect to consider for ensuring PTO performance within the OWC system. The planning control strategies for developing OWC on a specific site can be an interesting aspect that should be taken into consideration because PTO performance can be influenced significantly by the seabed morphology. The relationship between flow rate through the turbine and pressure drops can be affected as well [43]. Energy dissipation caused by the seabed formation that usually mentioned in unit of volume can affect the performance of the OWC, and this has been proven by the lower mean efficiency obtained of 15% compared to the hypothetical case of 19% when the case involves evolved morphologies. Peak frequencies can be reduced substantially in conditions of lower bottom depths than for barrier lengths, and the same happens by increasing barrier lengths [44]. Ashlin *et al.* [45] claimed that the OWC devices have better efficiency on a circular curve profile at the bottom of the chamber than with the three other profile shapes (flat, slope 1:1, and 1:5). The curved profile at the bottom of the OWC chamber presented higher wave absorption coefficients and amplifications, higher air pressure ratio, and less reflection. However, high reflection of water flow at the OWC lip wall and its bottom profile shape may cause an OWC efficiency reduction and increasing of wave steepness to be occurred.

Ashlin *et al.* [46] conducted a study to measure the effect of wave force on OWCs with chamber design parameters of 1910 mm width, 30 mm length, 900 mm total height, front chamber water depth of 500 mm, and bottom opening of 300 mm. The experimental setup had a distance of 45 m between the OWC and the wave source. Researchers observed from their chamber design parameters that the peak wave force acting on the OWC structure could increase as an effect of wave steepness, and a higher horizontal peak wave force 2.5 to 3 times was recorded compared to the vertical component. Both peak wave force components increased with relative water depth, d/L increased up to 0.16, and the decreasing trend of wave force was noticeable for more than 0.16 of relative water depth value. Elhanafi [47] confirmed that the vertical hydrodynamic force is always lower than the horizontal force, and ratio between those two hydrodynamic force components can be clearly visible if the analysis involves with lower PTO damping, high-frequency waves, lower wave heights.

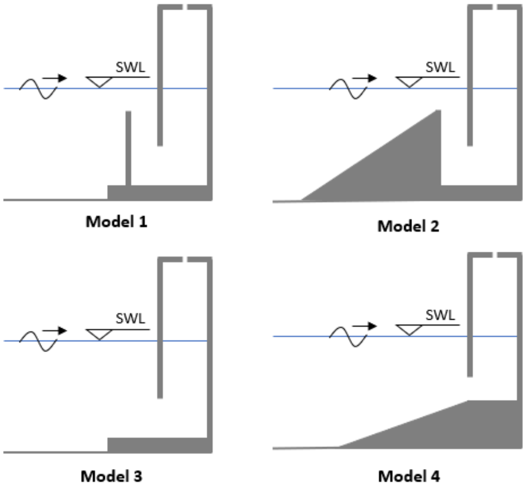

FIGURE 4. **Four lid-on devices. Adapted from [51].**

Sometimes, the OWC might experience turbine performance shortfalls due to unanticipated chamber pressure skewness that contributes to the deficit, differing from the results of the scale model testing. Wall defects in the chamber can cause accidental loss of internal pressure, due to shallow chamber water depth, this situation known as exhale stroke's pneumatic overpower. A passive non-return valve system can resolve it, like in the Pico plant study by Monk *et al.* [48]. We have to consider the durability and stability of the device to prevent any performance drop that eventually affects the system's operation and causes operation abnormalities.

When the front wall draft increases, it could augment the viscosity of the impact of horizontal wave force where the flow separation and vortex shedding rise. This effect is greater on the seaside of the OWC front wall [49] because damping within the water column enhances because of the higher air pressure and could make the smaller opening prone to have a larger viscosity impact on the total OWC front wall horizontal wave force.

Hydrodynamic efficiency is likely the most critical parameter when evaluating OWS performance. It reflects the PTO output performance, which is measured by the Power absorbed (P_{abs}) ratio to incident wave power (P_{inc}) per meter width of the OWC [50]. In Figure 4, the conventional OWC Model 3 and 4 have lesser efficiency than the

U-OWC Models 1 and 2, under normal wave conditions. However, Model 4 turns out to be more efficient than Model 3 in irregular wave conditions, probably because it resonates in higher frequencies. Vyzikas *et al.* [51] confirmed that the presence of the ramp in front of the OWC could improve the hydrodynamic performance in terms of capture width ratio, C_w. In Figure 4, Model 2 and 4 have almost two times higher C_w than Model 1 and 3. Furthermore, the hydrodynamic efficiency variation is less in irregular wave conditions than regular waves over the many frequencies of incoming wave energy. Figure 4 also shows the four lid-on device models, representing four different sea bottom surfaces under the OWC device, might have a different effect on the hydrodynamic efficiency.

As proposed by Teixeira *et al.* [52], a promising tool for building a high-performance open chamber OWC effect based on hydrodynamic and aerodynamic characteristics is the Fluinco numerical model code.

C. AIR COMPRESSIBILITY IN AIR POCKET MOVEMENT

The air compressibility situation occurs in the water column since a contained space in the OWC chamber allows air to flow regularly in two directions. The airflow characteristics can be different in regular or irregular wave conditions. From an OWC design perspective, in order for the air turbine system to avoid suction of water under rough or unsteady sea conditions, the OWC air chamber needs a larger volume, which means that the chamber must be able to prevent water from seeping into the air turbine system. On the other hand, increasing the ratio of air chamber volume and free OWC surface area does not influence the OWC device performance, because if the ratio value increases excessively, the amplitude of oscillating air pressure could become too small and eventually reduce the converter's capability to absorb wave energy [40]. Thus, when developing a full-sized OWC converter, it is essential to consider the air compressibility that increases with the chamber volume and is prone to cause a spring-like effect. Plus, it is usually neglected for small-scale experiments and numerical simulations because it does not seem to influence the overall OWC performance, but it can diminish up to 20% of the OWC predicted efficiency for both Wells and impulse turbines, as claimed by Goncalves *et al.* [53]. However, failure to consider air compressibility may lead to an output power prediction error that depends on the wave conditions and turbine-induced damping [54]. In other research on the 1:5 model scale with a non-dimensional parameter, $\Gamma = 1.0$, the maximum overestimation on capture width ratio is 5% when considering air compressibility in large-scale simulations. Over-estimation turns out to be higher when neglecting air compressibility up to 15% for chamber pressure p_{owc} and airflow rate q_{owc}, but less than 10% for ε_{owc} [55].

D. THE OWC INLET OPENING AND OPENING LOCATION DEPTH IN WATER

When focusing specifically on the OWC geometry to obtain an optimal OWC performance, the choice of opening inlets depends on the front wall submergence depth, the chamber size, and its positioning against the flow path. Bouali and Larbi [56] have concluded that an 180° angle of the front wall in a counter flow direction turns out to be the best orientation in terms of the unit's efficiency. They also found that the optimal chamber width is around $0.8h$, and the h of the water depth should be between $0.38h$ and $0.44h$ for the front wall immersion depth. Combining these conditions in one OWC design would enhance the wave energy conversion performance. Şentürk and Özdamar [57] have suggested that an additional surface-piercing type on the front wall could improve the OWC's efficiency by having the same resonant frequency.

In terms of energy production, CFD simulations have indicated that the symmetric PTO damping could produce more output power for front and rear chambers in dual-chambered OWCs. The asymmetric damping value within the chamber design could cause an eventual improvement of up to a 138% capture width ratio, and an average value of 47% compared to single-chambered OWC was achieved [58]. The dual-chamber OWC can increase the OWC device performance in a broader range of wave periods and more realistic irregular waves. The dual-chamber OWC performance can improve more if the design combines with a stepped sea bottom condition for future OWC models. Rezanejad et al [59] reported that this combination has considerably improved device efficiency because it can cater to a wider range of frequencies as compared to other OWC. Further research conducted by Rezanejad *et al.* [59] reported that adapting one step sea bottom outside of an OWC chamber has a substantial influence on the device's efficiency, and additional steps on the sea bottom profile gave only a minimal performance improvement.

The underwater geometrical impact is one of the most common aspects that may influence OWC hydrodynamic performance. This will emphasize on the chamber lip submergence and the lip thickness. The combination of these two elements might have a far better impact on the overall hydrodynamic efficiency for wider frequency ranges and output efficiency peak values of up to 0.79, according to Elhanafi *et al.* [60]. Fixing the submergence of the chamber lip with 12% of chamber length and the front lip draught and lip thickness set at two times the wave height could achieve the expected results. The OWC amplification factor strongly makes the chamber geometry influence the existence and the outflow of the amplification factor, and the entire OWC efficiency can increase by altering the chamber geometry [61].

Another design offered in the industry is the U-shaped OWC. Its chamber does not look like a conventional OWC where the inlet lip is submerged downward. Instead, there is another inlet lip or wall (wall I) in front, positioned upwards and making a 'U' shape water path in the chamber, and it is based on the geometrical effect investigated by Ning *et al.* where a significant improvement was reported regarding the geometrical alterations. In raising the vertical duct height and making the duct's opening upper side closer to the ocean free surface results in higher hydrodynamic efficiency in the low-frequency domain and increases barrier wall thickness in a declining trend. The power output can be estimated by a linearized model, based on the mean stochastic approach in the frequency domain, as proposed by Filianoti and Camporeale [62], where for the whole range of wave height variations, it can consider a turbine non-linear characteristic curve.

The genetic algorithm (GA) and Constrained Optimization By Linear Approximations (COBYLA) are the optimization gradient-free methods available. The annual average power output is 5.9 times higher than the original result and can be maximized by optimizing U-OWC geometry by using the CIBYKA method [63]. The geometry optimization seems to be adjusted by a shorter wave period even though the natural wave climate has a more extended wave period. In finding a better solution to the problem, the GA method can identify the ratio of power to steel mass to the Leveled Cost of Electricity (LCOE). It is imperative to consider the ratio because, in the actual industry, the OWC device geometry can generate higher output power, but low in power to the steel mass ratio attained. Therefore, implementing the LCOE as the objective function during device development is highly recommended in order to produce a larger annual average power output with the lower cost of the structural component's construction.

In the BBDB, simply by lengthening the horizontal duct by 10 m, a uniformed water column could eventually increase the annual energy production (AEP) by 58% [64]. This approach has made the flows steadier because of the similar-sized water column it flows through.

Raj *et al.* [65] conducted an experimental investigation on harbor walls, which could potentially improve the OWC's performance. Designs with harbor walls achieved a 75increase than without the walls. The harbor wall's resonating length can determine the water column's natural frequency, which is not effectively determined by its inclination. In Figure 5, the harbor wall's resonant length c/b at 1.5, supposedly the most optimum and efficient hydrodynamic characteristic was much closer to the recommended range proposed by Deng *et al.* [66]. In random sea conditions, the RCW data appears to be consistent. The opening angle, q modification, is more fitting if between$5\pi/8$ and $3\pi/4$ since it is within the suggested resonant length c/b.

When comparing two commonly used OWC device designs, the U-shaped OWC and the conventional OWC, the U-OWC has more advantages than the conventional OWC because its Eigen period is more significant in swells, and it shows better performance with large waves. The performance of the U-OWC could improve by setting up the opening position higher than that of conventional OWCs under slight wind and wave conditions. The U-OWC in heavy sea circumstances can prevent sucking the air from the wave-beaten wall, but the normal OWC does not. For breakwater situations under the same weight, the U-OWC embodied breakwater has a higher safety factor than the conventional one [67]. The U-OWC design was able to maximize the energy captured by almost 66% and convert it into pneumatic power in the turbine duct but could not maximize the output power even though an Eigen period of U-OWC was close to the wave period [68].

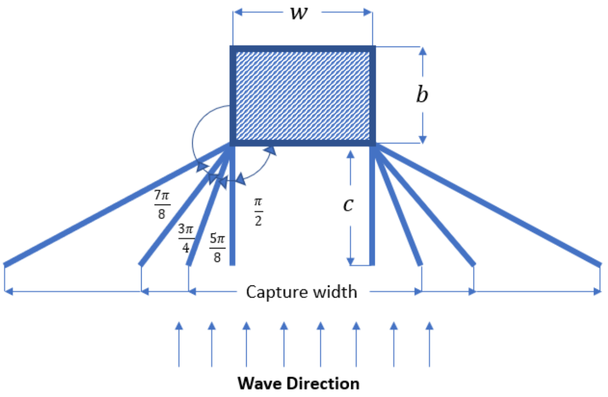

FIGURE 5. Plan view of harbor wall opening angle. Adapted from [65].

E. FLOATING AND FIXED STRUCTURE OF THE OWC

The OWC device can have a buoyancy component to float with the mooring system that anchors the device location, or it can be built upon a fixed structure placed on the ground near the shore. This section compares some aspects of the floating device and the stationary OWC structure, as displayed in Table 2. Both structural types have advantages and disadvantages. Some aspects could affect the energy harvesting efficiencies of floating OWCs, such as the pneumatic damping coefficient of the turbine, mooring elasticity coefficient, and inward wave frequency. Conversely, the fixed OWC structure only considered one resonance frequency: the chamber's natural frequency. The floating type must consider both the OWC's natural frequency and the chamber [69]. The findings presented by Luo *et al.* [69] supported the outcome researched by Sheng and Lewis [70]. For the floating OWC, the mooring spring elasticity coefficient and turbine damping coefficient can attune the high efficiency of the OWC frequency bandwidth so that the varied wave frequencies can capture and provide more energy from the ocean. The investigation concerning the hydrodynamic interactions between waves and offshore floating devices was simulated, referring to the Smoothed Particle Hydrodynamic (SPH) model presented by Crespo *et al.* [71].

F. SUITABLE TURBINE BLADE USED

OWC can use two of the turbine types that are available in the industry: the Wells turbine and the Impulse turbine. Each of them has specific advantages. For example, for the Mutriku OWC breakwater, both turbine types were analyzed in relation to their sensitivity of control parameters. Henriques *et al.* [72] claimed that the generator's control parameters affect the Wells turbine more than the bi-radial turbine. The bi-radial turbine, which offers a broader region of control parameters, comes close to achieving the maximum power output, in comparison to the smaller range allowed by the Wells turbine. Fay *et al.* [73] presented the advanced

TABLE 2. Floating and fixed structure comparison.

Aspects	Floating OWC	Fixed Structure OWC
Mooring type	Attached to mooring system to ensure device position during any sea condition. But the design might be challenging for shallow water mooring.	No need for a mooring system because the position and structure are fixed
Natural frequency response consideration	The system must consider both chamber and OWC natural frequencies.	It only considers natural chamber frequency because of the rigidity of the device's structure and position
Device structural durability against the variable sea condition	The device design can be more compliant and reliable in severe sea conditions with a long wave period.	A fixed structure may face a frequent ocean wave impact that might cause structural damage on its water column when dealing with varied and severest sea conditions.
Power capture efficiency	For the most typical waves (7 s to 13 s) floating OWCs can absorb up to 200% wave energy than the fixed type. This is because the system can adapt to varied sea conditions.	Has a lower power capture efficiency than the floating structure
Power transfer to the mainland	The power generated from the floating OWC must be transferred through an underground cable on the seabed to prevent physical interruption	The power captured can be stored and transferred to electrical supply grid
Device design	The OWC design must have a buoyancy system that ensures that the device can float during the harnessing process. The design is very convenient since it can be moved to any desired location.	The OWC is specifically designed for local wave behaviors when considering to the maximum device operating limit
Solution for achieving high-efficiency system with varied wave frequencies	The high efficiency of the OWC frequency bandwidth can be attuned by mooring spring elasticity coefficient and turbine damping coefficient	To optimize the water column design that can suit any range of sea conditions at a shallow water area

bi-radial turbine typed PTO's speed control strategies that work with the adaptive and predictive controller of induction generator. These controller combinations have produced PTO efficiency close to 60%, inducing least generator stresses and avoid generator overloads.

1) TURBINE DIAMETER SELECTION

Torres *et al.* [74] has investigated the turbine diameter selection for OWCs based on the average output power under hypothetical ocean condition. The diameter selection table is a helpful reference for identifying the most suitable and optimal Wells turbine diameter for OWC designs. The research had incident wave parameters of $T = 9$ s, $H = 2$ m, and turbine diameter $D = 2.5$ m. The average output power was obtained using Reynold's Average Navier Stokes (RANS), the Turbine Diameter Optimization (TDO) model, and the Fluent model with or without the pressure control system. The reference table with the turbine diameter selection was developed based on the onshore OWC device shown in Figure 6, with the following specifications: 10 m length (B), 10 m chamber width (A), and mean water level height h_c of 6 m. The research also established some other parameters in building the reference table, such as the wall thickness, $l = 0.5$ m, the front wall submergence depth, $d = 2.5$ m, and local water depth, h of 10 m. If we wish to develop future Wells turbine designs on a small scale, we can also take the diameter value from the table and convert it into the intended scale ratio. In order to decide the best design choice, one must consider the operation and installation costs in the early development stage.

During the development of the converter system, it is necessary to examine a non-linear spring-like effect on the air compressibility within the chamber. It determines the suitable turbine induced damping for better performance of the OWC device that is built for a site-specific wave energy converter system. Lopez [75] has presented the turbine induced damping reference for researchers and developers to properly select one for their research site. The selection from the developed matrices must consider a wave-height, wave-period distribution and OWC energy absorption for variations of damping coefficient values.

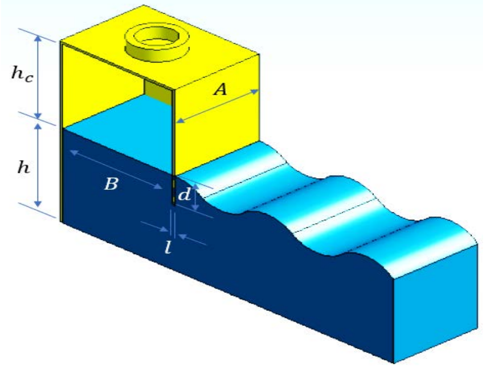

FIGURE 6. Scheme of the OWC device. Adapted from [74].

G. TURBINE DAMPING EFFECT

The wave-to-wire efficiency is the success benchmark of the OWC, where the air turbine's aerodynamic performance has one of the most significant roles. The fundamental relationship between the air flow rate and the built-up pressure in an air chamber is called a turbine damping effect, and it must be well understood when deliberating air turbine aerodynamic performance [76]. The wave-to-wire efficiency is the success benchmark of the OWC, where the air turbine's aerodynamic performance has one of the most significant roles. The fundamental relationship between the airflow rate and the built-up pressure in an air chamber is called a turbine damping effect, and it must be well understood when deliberating air turbine aerodynamic performance. To further acknowledge this fundamental relationship, it is essential to know that during the absorption of wave energy, there is a coupling between the aerodynamic process in the turbine system and the overall OWC performance that reflects on the turbine's geometry, dimensions, and rotational speed within the integrated relationship.

Brusca *et al.* [77] investigated the OWC behavior, focusing on the turbine damping characteristics with variable diameter holes, wave frequencies, and wave heights to configure the small-scale water flume simulation. This research used the Particle Image Velocimetry (PIV) method to analyze the OWC's inside and outside air velocity and wave height within the water column. A smaller damping hole diameter produced a higher time shift (of 1 Hz) when analyzing waves from inside and outside the OWC. As for the 2 Hz input wave, it obtained a constant time shift by changing the damping hole diameter. It was concluded from the research outcome that the optical measurement method conducted on a small-scale wave flume, in order to study the Wave Energy Converter systems under controlled conditions, could be appropriately used to achieve the research objective.

Liu *et al.* [30] analyzed the air chamber operating performance with a $0.428D$ orifice plate installed in a Yongsoo OWC pilot plant. It found that the turbine damping effect occurred in the OWC chamber because of the orifice size, which reduces the pneumatic energy output peak value by 30%. Lopez *et al.* [78] introduced a method that computes pneumatic power matrices over variations of validated RANS-VOF model with turbine-induced damping to improve the OWC annual energy output. This method had two purposes: measuring the OWC performance based on damping coefficient ranges for different turbines and the wave conditions and determining the optimum damping that occurred under different wave climates.

Another study conducted by Lopez *et al.* [79] on the physical OWC model investigated how efficient the OWC device is under regular and irregular wave conditions and how it can be influenced by employing turbine damping coefficients, wave heights, and wave incidence periods. A 20% increment of OWC performance was observed with the altered turbine damping value within the chamber, and it achieved optimum damping values using the numerical model for the given wave conditions.

H. AIRFLOW PERFORMANCE OF OWC CHAMBER

The air flowing through the chamber, which has undergone compressed and decompressed processes, has enough power to drive the turbine rotation even though there is low wave motion because it can produce enough airflow to sustain the turbine's rotation and generate energy as long as there are waves. Thus, the compressed and decompressed air movements within the water column guarantee the OWC's consistent airflow performance. Brusca *et al.* [80] proposed the PIV method to measure the airflow performance and analyze the turbine rotor velocity field and air chamber while assessing the air turbine.

1) FLOW CFD MODEL AT THE OWC INLET

Concerning the flow around the inlet, a vortex could form on the sidewalls during the inflow, which happens if a significant flow inside the chamber allows another flow to enter the inlet [81]. These two conditions have led to flow redistribution from the centerline during inflow and to a redistribution flow towards the sidewalls during outflow. There is also a restriction on the inflow.

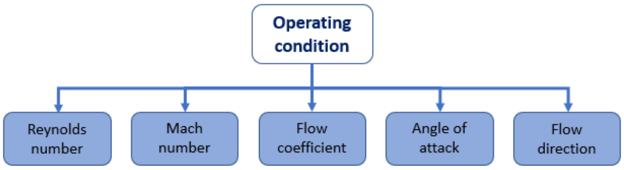

FIGURE 7. Fluid flow operating condition.

2) STEADY AND UNSTEADY SEA STATE

A steady-state flow means that the fluid properties in the system do not change over time, while the time-dependent flow means that the flow is unsteady or is a transient flow. Whether flows are steady or unsteady can depend on the chosen frame of reference. For example, a laminar flow situation over a sphere is steady in a stationary frame reference for the sphere shape, but it can be considered unsteady with the same reference for a background flow. For the oscillating flow, the harmonic components of a wave-induced flow become more important. The mean flow at the outer edge of the boundary layer was considerably weaker than the predictions studied by Mouazé *et al.* [82]. This analysis is consistent with earlier observations by Chaplin [83] that steady streaming around a circular cylinder beneath waves is weaker than expected using a boundary layer theory.

3) FLUID FLOW OPERATING CONDITION

The fluid flow through the turbine system into a closed pipeline, or ducted area, must be considered and categorized by a dimensionless number. Figure 7 shows that a few considerations are related to the airflow through the turbine's operating conditions: the Reynolds number, Mach number, flow coefficient, angle of attack, and flow direction.

From the Reynolds number, we can identify the fluid flow through the turbine system, whether laminar or turbulent flow, where ρ is the density of the fluid, (kg/m^3). v is the transit speed of the fluid into the pipeline (m/sec). The Mach number (M) is defined as the ratio of the speed of an object (or of a flow) to the speed of sound. A relative measure of device efficiency at permitting fluid flow refers to the flow coefficient, meaning that it defines the relationship between the corresponding flow rate and the pressure drop across an orifice valve or other assembly. The Angle of Attack is the wind angle when reaching an airfoil and is related to the flow direction. In the OWC air chamber, the Reynolds number usually defines the airflow conditions in the turbine system. Thus, the rotational performance of the turbine blade can be measured and observed. The angle of attack is determined to see whether there are any changes in the turbine's efficiency if the angle changes.

4) CFD MODELS FOR OWC AIR CHAMBER

The list of CFD models for OWCs is tabulated as in [84], based on recent research. The purpose of this list is to act as a reference for the development of future OWC designs. The CFD model reviewed by Cui *et al.* [84] was based on the CFD model developed by the previous authors to simulate the flow condition within the OWC chamber and through the turbine system that generates the output power with the kinetic energy received from the flow. The paper also has displayed the important parameters for CFD model such as turbulence model, Reynold number, wall function, model features and flow condition of the analysis.

I. TURBINE ROTATIONAL SPEED AND ELECTRICAL CONTROL

The selection of electrical equipment for OWC rated power significantly impacts how much energy is produced annually. The same goes for the PTO design, where the optimal rated power depends on the turbine size and electrical equipment. Thus, these two elements are responsible for optimization. A numerical simulation can be the best way to identify the relationship between instantaneous torque on the generator and the instantaneous rotational speed, in the case of a rotational speed control strategy test [85]. The algorithm can be stored in the programmable control system to ensure the OWC operates in controlled conditions. The best performance OWC device or plant is equipped with a more advanced controller, such as the reinforcement learning and the predictive control model because both controllers control turbine efficiency and generator and consider their optimization process as suggested by Fay *et al.* [86].

For the case of U-OWC, the implementation of control strategies for maximizing the device performance in a variety of environmental conditions can occur by identifying the turbine reference rotational speed that leads to conversion efficiency. Two different approaches can resolve the problem; first, establishing experimental formulations that consider the influence of substantial wave peak periods and wave height, with a formulation that involves optimal turbine reference rotational speed determined by an analytical law. Second, using a Maximum Power Point Tracking (MPPT) algorithm for the rapid dynamic conditions inside the wave-to-wave controller plant. Since the energy converter device adapts to the speed controller in the system, these two solutions have shown a consistent turbine rotational speed reference during ocean conditions, granting the system better performance. Strati *et al.* [87] concluded that the system would approach both phase and sub-optimum amplitude simultaneously when considering wind-dominated ocean conditions, and the system response will be close to resonance conditions when it approaches an optimal turbine reference speed. On the other hand, a higher turbine rotational speed in the case of long waves will maximize the wave energy converter system, and even the resonance source is far from the system.

IV. DRAWBACK OF THE EARLIER OWC DEVELOPED AND DESIGN IMPROVEMENTS

Many OWC devices developed in the industry were created to supply the nearest settlement and electric-powered facilities with electricity. The OWC harnessing concept is a promising method of utilizing the ocean wave energy and transforming it into kinetic energy for a generator to produce electrical power. This energy harnessing technique is very environmentally friendly. However, the correct and efficient OWC design can help contribute to the expected outcome. Without a thorough study of the OWC design and its suitability for local wave behavior, it will produce less energy. The initial building cost of the OWC device can be far higher than the value of the output production, reducing the return on investment for this technology.

An efficient OWC design must consider the environmental aspects to prevent noise pollution or damage to the ocean's natural beauty from building the OWC. This factor influenced most of the researchers to choose the non-fixed OWC structure in their study. The OWC device can move from one location to another, depending on the potential energy that can be captured in the target area. Initial studies of the local ocean wave behavior must ensure that the development study is profitable, thus, obtaining the proper OWC design that suits the ocean data.

For the OWC to produce the maximum energy, it is essential to consider the OWC geometrical factors for the local ocean wave behavior. The design must be able to generate power in any ocean condition and be durable under random wave behavior. Confirming the optimum power production and lifespan of the device during operations is important. A device with low efficiency will reduce the return on investment. Every OWC structural component must have an engineering consideration for its construction. Any changes in the geometry can affect the overall device performance.

A. POTENTIAL IMPROVEMENT OF THE OWC

There are several solutions to improve the OWC's efficiency. The construction design must be able to generate power from the ocean waves available on site. One of the solutions proposed by Simonetti *et al.* [88] is a tool that optimizes OWC design parameters, such as incident wave height, wave period, the chamber configuration of turbine damping, chamber width, and front wall draught, which can influence the OWC device capture width.

On the other hand, the improvement of the OWC's geometry can change the movement's direction in the event of an inclined OWC. This improvement significantly affects the OWC because the inclination could prolong the resonant period even longer compared to the vertical OWC as claimed by Lino *et al.* [89], where the simulated resonant periods with the gravitational response closely matched the high-efficiency wave periods in the water tank. Liu [90] reported that, in order to ensure a lower optimal frequency, another solution is to attach the OWC WEC with a U-tube containing

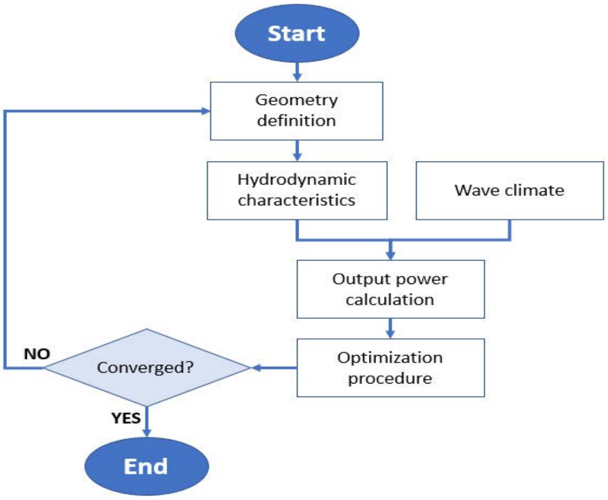

FIGURE 8. **Overview of WEC geometry optimization process. Adapted from [92].**

a viscous fluid, and the U-tube's sloped sides are beneficial for getting the desired oscillating occurrence that reaches 100% efficiency in wave energy extraction.

The OWC has proven to consistently perform as needed for a practical wave energy power plant to operate inshore. The most significant limitation of wave energy converters from a commercial point of view is the cost of obtaining the power. For the OWC converter to compete better amongst the available techniques, future research must aim to improve the energy power plants by combining the OWC harnessing concept with other concepts [91]. Figure 8 shows the optimization procedures that can potentially enhance the performance of the OWC [92]. The flow diagram explains the step-by-step procedure, starting from defining the OWC geometry, identifying the hydrodynamic characteristics and the wave climate research, and calculating the power obtained from the selected geometry. One begins to optimize the OWC geometry and observe whether the output performance converges from the initial performance obtained. If the performance is positive, thus the optimization is successfully implemented on said OWC geometry.

B. PERFORMANCE REVIEW OF OWC GEOMETRY MODIFICATION

Geometry modifications can be one of the practical solutions to be implemented on the existing OWC designs to improve the design output and produce more electrical power. Some modifications may involve geometry alterations that change the design parameters and can produce a different output performance. Research can enhance the present OWC geometry models for power plant projects in ocean wave energy. Table 3 summarizes the performance and outcomes reviewed from the improvement conducted on the OWC system design.

Table 3 shows ten geometry modification samples and their effects on the OWC output performance. Each geometry focuses on different OWC geometry areas that significantly improve the efficiency, damping effect, hydrodynamic characteristic of the chamber, capture width ratio, and electrical power generated from the system. **Geometry 1** studies the effect of top slot size, generally known as the orifice of the chamber, and the research concluded that the narrower the top slot size, the higher the damping effect. The research also has identified that 50 mm of top slot size has a small pressure oscillation due to a small damping effect over free surface elevation. **Geometry 2** proposed an additional harbor wall, c/b of 1.5 in the OWC geometry, getting the optimum efficient resonance length, while at random ocean conditions, the capture width ratio had consistent values. A simple modification such as front and rear lip submergence and wall thickness, as depicted on **Geometry 3,** gave a different effect. Increasing the front lip thickness could reduce the transmission coefficient and improve the reflection coefficient and the overall hydrodynamic efficiency. While the deeper lip submergence into the water, the more reflection coefficient can be increased. The lip submergence increment also could reduce transmission coefficient and device maximum overall hydrodynamic efficiency.

The U-OWC introduced after establishing the conventional OWC has a different output performance and U-OWC geometry, as demonstrated in **Geometry 4,** and the U-OWC has a better performance than the conventional OWC. Because the upper opening of the vertical duct increased, bringing it closer to the free surface, the hydrodynamic increased also. Four different OWC models were analyzed to measure the hydrodynamic performance, specifically its capture width ratio. In **Geometry 5**, the adopted ramp in front of the OWC device improved the hydrodynamic performance, where Model 2 and 4 had the higher value of capture width ratio compared to Model 1 and 3. From the four models displayed in the research, Model 1 and 2 with similar U-OW and characteristic U-OWC geometries, show a substantial improvement in the capture width ratio C_w compared to Models 3 and 4 that adhere to the conventional OWC geometry, especially capture width ratios C_w almost twice as high at their peak performance. Another geometrical modification to the OWC is to adapt the long bottom plate of the chamber and the topside small opening ratio of the inlet, as shown in **Geometry 6**. These two combinations were able to improve the conversion of wave energy and inside chamber damping ability. Moreover, these two geometrical modifications are beneficial for reducing the incoming wave energy transmission and dissipating it, especially for the shortwave regime. **Geometry 7** introduced modifications to the chamber parameters, specifically to its length, width, and angle. An 80% efficiency increase was observed from the modified OWC structure compared to the conventional one. Furthermore, a 10.81% maximum efficiency increase was obtained in the modified OWC structure compared to the highest efficiency value of a conventional OWC.

Geometry 8 has five different front wall orientations, and the counter-current orientation, displayed as configuration no. 4, was estimated as the best OWC geometry for enhancing

TABLE 3. OWC Geometry modifications in a LAB scale model.

GEOMETRY MODIFICATION	MODEL SPECIFICATION AND TEST PARAMETERS	SIMULATION & EXPERIMENTAL RESULTS
GEOMETRY 1 A.Iturrioz, R.Guanchen, J.L.Lara, C.Vidal, I.J.Losada (2015) [93]	• The OWC chamber model has a distance of 5.47 m from the wave maker. • The OWC chamber has a specification of 0.30 m length and 0.68 m width combined with a front and back walls draft of 0.20m. • 0.03 to 0.08 m of wave height range and between 1.1 and 3.2 s of wave periods are tested in a regular wave series in a constant water depth of 0.60m for all experiments. • The top slot sizes are varied from 50 mm, 9 mm,4.5 mm and 2 mm. • Wave flume parameters: 20.60 m length, 0.75 m height and 0.68 m width of wave flume was set during the simulation	• The damping effect could be observed from the air pressure built within the chamber during oscillating motion and the effect is increased when the top slot narrows. • 50mm top slot size was found to have a small pressure oscillation because of a very low damping effect during free surface elevation. • The closed chamber setup with the longest periods has made the largest pressure oscillation registered within the chamber and for the closed chamber condition; the free surface oscillation was nearly imperceptible in the tests performed.
GEOMETRY 2 D. Daniel Raj, V. Sundar, S.A. Sannasiraj (2019) [65]	• The wave flume set in the study is 72.5 m in length, 2 m in width 2.5 m in depth. • The distance between wave makers to the OWC device is fixed at 36 m. • The water depth is set at 0.312 m, and the front lip wall submergence is consistently submerged at 0.12 m.	• The OWC model performance can be enhanced by the addition of harbor walls compared to that one without whereby harbor wall, c/b with the specification of 1.5 adapted, the optimum efficient resonance length can be obtained and at random sea states, the RCW appears to be consistent. • The opening angle, q can be modified within the range of $5\pi/8$ to $3\pi/4$ as long as c/b value remains around 1.5 • The OWC's natural frequency could be influenced by the inclination of harbor walls, but the harbor wall resonant length determines the frequency. • When harbor walls resonant length is increased, the pneumatic pressure resonates within the water column with respect to natural frequency and the peak value changed towards low frequency. • Whenever the natural device frequency is almost the same as the predominant wave frequency, the device energy conversion capacity remains at the optimum level.
GEOMETRY 3 Ahmed Elhanafi, Alan Fleming, Gregor Macfarlane, Zhi Leong (2017) [60]	• The research has been conducted on a fixed OWC model with the 1:50 scale purposely to identify its hydrodynamic performance based on the underwater chamber geometry effect. • The main design variables considered in this research are: a. Front (t_1) and rear (t_2) lip draught /submergence at 200 mm b. Device wall thickness (t_1 and t_2) at 12 mm c. Single wave height of 50 mm d. Eleven wave periods of T = 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8 and 2.0 s that are represented by a non-dimensional parameter range of K_b= 0.30-1.50. A slot opening size of 5 mm with 1.67% opening ratio for PTO damping.	• The deeper lip submergence into the water could increase the reflection coefficient. It also could reduce transmission coefficient, device maximum overall hydrodynamic efficiency and natural device frequency. When chamber lip draught is increased from 100mm to 300mm, the overall hydrodynamic efficiency reduction of 0.06 could have occurred. • The increasing of front lip thickness could reduce transmission coefficient and increase both reflection coefficient and improve overall hydrodynamic efficiency. The increment of the wall thickness up to the optimum thickness of 24 mm or 8% of chamber length could improve the overall hydrodynamic efficiency and later having a significant drop of efficiency of 0.10 when tested with 100 mm thickness or reaching chamber length of 33%. • In the situation of intermediate and high frequency waves, it was the more visible reduction of the overall hydrodynamic efficiency and the bandwidth maximum efficiency could be minimized with increasing front lip thickness. • Combining both effects has provided a massive overall device hydrodynamic efficiency improvement for the whole frequency range. 0.79 of peak hydrodynamic efficiency was obtained with the parameters such as lip thickness at 12% of chamber length with submergence ratio of 0.03, and front lip draught is two times higher than wave height.
GEOMETRY 4 De-zhi Ning, Bao-ming Guo, Rong-quan Wang, Thomas Vyzikas, Deborah Greaves (2020) [49]	• To identify the relationship between nonlinear waves with U-OWC device • 2D fully non-linear model using higher-order boundary element method (HOBEM) • The air pressure enacted within the chamber is determined using the inner domain source method. • The study investigated geometrical parameters effects on the U-OWC device hydrodynamic performance, specifically on the vertical duct height, width and wall thickness.	• The U-OWC has performed better than the conventional OWC due to the upper opening of the vertical duct that has been increased and makes it closer to the free surface and this has made hydrodynamic to be increased. • The greater vertical duct width in the low-frequency domain could be resulting from higher hydrodynamic efficiency, but in the high-frequency domain, the value of η_{max} and P_{max} increase at first and started to decline with the increase of vertical duct width because pressure excitation amplified at the upper opening of the horizontal spatial inhomogeneity with the decrease of wavelength. • The Wall I thickness increment could increase the hydrodynamic efficiency at a declining rate.
GEOMETRY 5 Thomas Vyzikas, Samy Deshoulieres, Matthew Barton, Olivier Giroux, Deborah Greaves, Dave Simmonds (2017) [51]	• The study performed a comparison pertaining to the OWC geometry under typical wave conditions to optimize the device design for improving OWC hydrodynamic efficiency and recommended a potential shape improvement and other design aspects. • To measure hydrodynamic efficiency of all four devices based on the calculation of recording at the center of the chamber under four regular conditions.	• The hydrodynamic performance can be improved by the adopted ramp in front of the OWC device where the higher value of Capture width ratio C_w belongs to Model 2 and 4 • Model 1 and 2 that has a characteristic of U-OWC geometry really has a substantial improvement on the capture width ratio C_w compare to Models 3 and 4 that adhere to the conventional OWC geometry especially capture width ratio C_w is almost twice as high at peak performance.
GEOMETRY 6 Zhengzhi Deng, Chen Wang, Peng Wang, Pablo Higuera, Ruoqian Wang (2019) [94]	• The research analyzed the influence of bottom plate lengths geometrical impact and different chamber opening ratios at the topside on the OWC device hydrodynamic performance. • The wave absorption efficiency, reflection and transmission coefficients, energy dissipation coefficient and wave amplification coefficient, were examined in the study as all of them are the key performance indicators of the geometry modification. • In order to complement the experimental database, numerical simulation was implemented on the impact of relative vertical opening and depth of water.	• The geometrical modification that has been done, that is, the long bottom plate and small topside opening, have improved wave energy conversion and damping ability. • The reflection coefficient is significantly influenced by the opening ratio of the topside. • A small opening ratio with the decrease of the wavelength has increased the reflection coefficient. However, a large opening ratio decreases with the reduction of wavelength. • For the short-wave regime, the geometrical configuration such as the large topside opening ratio and the long bottom plate is useful for incoming wave energy transmission reduction. • The absorption efficiency can considerably be improved with a proper relative vertical opening (ε)selection, but the further increase of the relative vertical opening ε has a negligible impact. • For short waves, energy extraction efficiency for the reflection coefficient has been noticeably influenced by the variation of water depth. For a longer wave, the tide impacts are negligible for the proposed OWC hydrodynamic performance.
GEOMETRY 7 Farrokh Mahnamfar, Abdüsselam Altunkaynak (2017) [95]	• The OWC system optimization by changing air chamber parameters such as length, width and angle to achieve maximum power system has been conducted in a wave flume. • The study purposely assesses the output air velocities measured from the experimental and numerical model using the NashSutcliffe efficiency coefficient. • It was observed that the NSE value of 0.97 is shown as a very good match for both structures between the experimental and numerical model results. • Each OWC structure's air velocities are measured from 4 different regular waves and four different water depths.	• 80% efficiency increment can be observed from the modified OWC structure compared to the conventional OWC. • 10.81% maximum efficiency increment produced by the modified OWC structure compared to the highest efficiency captured from the conventional OWC. • Approximately 36% of air percentage contained with the efficiency result and this has made the importance of dimensionless numbers in analysis to be considered. • The efficiency of 50 cm water depth and 41 cm opening size setup was found to give a better result than setup of 60 cm water depth and 51 cm opening size. The highest efficiency value was obtained with the opening height equal to $(e = y - H/2)$ for each water depth.
GEOMETRY 8	• The simulation setup is using the biphasic fluid flow that contains air and water and k-ε turbulent model in two-dimensional simulations.	• The OWC device performance can be affected significantly by the front wall orientation, chamber size and submergence depth.

TABLE 3. ***(Continued.)*** **OWC Geometry modifications in a LAB scale model.**

B. Bouali, S. Larbi (2013) [56]	• The OWC wave energy converter's hydrodynamic efficiency is determined. • Five different front wall orientations are tested during the simulation with a constant wave height and wavelength in the same progressive monochromatic wave.	• The submergence depth ranging from 0.38 to 0.44 times the water depth has produced the optimum value of the device efficiency. • The best chamber width dimension of 0.8h and h (h= water depth) has produced the best device performance. • Configuration No. 4 has become the best arrangement that produced the maximum efficiency.
GEOMETRY 9 Giulio Lorenzini, Maria Fernanda Espinel Lara, Luiz Alberto Oliveira Rocha, Mateus das Neves Gomes, Elizaldo Domingues dos Santos, Liércio André Isoldi (2015) [96]	• To analyze the influence of the ratio of height and length of the chamber (H_1/L), the ratio of height and length of the chimney (H_2/l) and submergence (H_3) in order to convert varying maximum electrical power. • The total area of the chamber and device has been fixed.	• Hydro-pneumatic power variation from 10.7 W to 190.8 W can be obtained with ratio H_1/L equal to 0.135, H_2/l equal to 6.0 and H_3 of 9.5 m and the output has been contributed by incident wave properties of 5 s wave period and 37.6 m wavelength. • Geometry rationalization is a very important aspect in order to harness renewable energy sources since using the worst shape can generate nearly 11 W of pneumatic power.
GEOMETRY 10 Jin-Seok Oh and Sung-Hun Han (2012) [97]	• This research recommended modifying the inlet geometry for the idea of increasing the vertical displacement. • Trumpet type and cylindrical type of inlet geometry are designed and undergone with an experiment in the 2D wave tank at scale model and full-scale experiment for sea condition.	• The end result obtained from the experiment showed that OWC with trumpet inlet shape was able to generate higher electrical power than the cylindrical shape inlet. • The recommended inlet geometry modification could improve the OWC device conversion efficiency and can visibly reduce the cost of maintenance energy storage systems like a battery for buoy type renewable energy systems.

the device's efficiency. The submergence depth ranging from 0.38 to 0.44 times the water depth produced an optimum value of device efficiency. The best chamber width dimension of 0.8h and h (h = water depth) produced the best device performance.

The three Degrees of Freedom (DOF), presented in **Geometry 9,** are the height to chamber length ratio, height to chimney length ratio, and submergence, and have a hydro-pneumatic power variation from 10.7 W to 190.8 W that can be obtained with a ratio H_1/L equal to 0.135, H_2/l equal to 6.0 and H_3 of 9.5 m. This output performance contributed to the wave parameters, 5s wave period, and 37.6m wavelength, which helped to examine the effect of configuration No. 4 with these key parameters. **Geometry 10** has modified the inlet geometry and found that the OWC with a trumpet inlet shape could generate higher electrical power obtained through the experiment than the cylindrical shape inlet.

V. DISCUSSION

Developing a good oscillating water column system with a comprehensive design is possible by considering several important elements that affect the device's performance. Device performance consists of the system's air turbine rotational speed, the OWC chamber outlet's airflow performance yield, the hydrodynamic efficiency from the wave force received by the water column, among others. This paper has outlined the optimum design elements for OWCs in order to provide a better output performance. The configuration of the OWC system described in this paper can serve as a guideline for future developments of energy converter devices. This paper's description of the most influential OWC characteristics can help improve the devices' energy harnessing principles and promote this promising electricity source for local settlements and nearby facilities.

Before discussing the geometry-related concerns that may affect the OWC device performance, we reviewed previous research on the specific site where the device will be located. First, we collected data to study the location's ocean wave characteristics and understand the wave behavior. Aspects that needed to be measured were ocean wave height, wave period, wavelength, wave frequency, and sea bottom profile. Non-wave related aspects that were necessarily considered in the research were: target residence area, the required output power, geographical conditions that could affect wave behavior, the design's turbine system, whether the OWC type should be a fixed or a floating structure, the energy storage systems, the costs of building the device opposed to the expected return in total power output. These aspects were an essential requirement in the initial development stage of the OWC, before the design stage.

When discussing the OWC output performance, the key component in the device structure is the OWC chamber. In order to develop an efficient OWC design, good knowledge of the OWC chamber's important components is necessary. The geometric characteristics of those components could affect the overall OWC system efficiency. The essential geometric parameters of the structural components that can influence the OWC output performance are the width of the air chamber, front wall thickness, sidewall draught, bottom slope, and air outlet size. The right combination of front wall submergence and thickness could provide the OWC device a better hydrodynamic efficiency, as claimed by Elhanafi *et al.* [60], with a submergence configuration at 12% of the chamber length front lip draught and the lip thickness set at twice the wave height. Thomas *et al.* [98] experimentally investigated the impact of the front wall's geometry on the OWC's efficiency, finding that the curved shape of the immersed front wall has a significantly better effect than the rectangular opening shape in improving the OWC hydrodynamic efficiency. Sheng *et al.* [64] reported that annual AEP energy production could increase by 58% with a horizontal duct length extension of 10m because it causes the water flow to pass more evenly through the duct. The maximum OWC efficiency was achieved with the $0.45h$ (where h is water depth) front wall submergence depth, as reported by Bouali and Larbi [56]. Later, Ning *et al.* [99] demonstrated that by increasing the front wall immersion depth, the hydrodynamic efficiency of an OWC in short waves might decrease.

Another geometric parameter that affects the OWC performance is the OWC bottom opening. Yaakob *et al.* [100] supported this fact in their study, which confirms that the inlet's entrance curve profile and the reflector in the bottom part of the device chamber can improve the system's efficiency compared to a typical OWC design. Amin's study [101] also agrees to this point, suggesting that the curved frontal entrance of the OWC chamber could result in a higher hydrodynamic energy extraction performance. The OWC energy conversion capacity could achieve a maximum efficiency of 94% with an opening length - water depth ratio of $H_o/h = 0.80$, as reported by Wilbert *et al.* [102]. Ashlin *et al.* [45] conducted laboratory experiments with four different chamber bottom shape configurations: a 300 mm round curve radius, a flat bottom surface, a bottom slope of 1:1 and 1:5, and finally, an experiment with the findings of the best output performance obtained, which belongs to the circular curved bottom profile, compared to the rest.

The water oscillation movement within the chamber could be affected by the inclination of the OWC chamber design, especially for the front and rear walls. By inclining the OWC's rear wall, the resonant period of the device [89] could extend. Dizadji and Ehsan [103] added that the parallel inclined assembly of the chamber's back and rear walls resulted in better output performance. Ravinesh *et al.* [104] presented a modification of the air chamber's inclination angle from 90° to 55°, thus increasing the dynamic pressure inside the OWC chamber by 200%.

The chamber's orifice size can affect the OWC's energy extraction efficiency. Ning *et al.* [99] found that the internal chamber pressure could decrease by adopting a larger orifice ratio, causing the water surface elevation inside the chamber to increase. He and Huang [105] studied the effects of different orifice sizes and learned that the reported circular shaped orifice ratio at 0.625% could achieve the maximum airflow. Ashlin *et al.* [46] also modified the top air outlet area, opening the ratio from 0.1% to 1.2%, and concluded that an opening ratio between 0.6 and 0.7% could increase the maximum efficiency by about 64%.

Increasing of chamber width of the collector chamber reduces the resonant frequency inside the chamber, and this occurs due to the broader chamber width that allows more water column mass to build up inside the OWC chamber [99]. Gomes *et al.* [106] reported that 0.84 of chamber width to height ratio would be the ideal parameter of OWC and the worst value obtained was the ratio of 0.14. Sameti and Farahi [107] found that the output power is directly proportional to wave height and chamber width. They reported that the configuration of chamber width over wavelength, B/L equal to 0.42, produced the optimum power output and 46% more efficiency. Ning *et al.* [108] presented that a maximum value of OWC device efficiency achieved at $0.92h$ of chamber width, where h referring to water depth.

When discussing the OWC efficiency, another aspect that plays a significant role in the ocean wave characteristics is the wave height because it influences the air pressure generated inside the chamber. The expected greater pneumatic power generated from the OWC chamber is due to a larger incidence of waves impacted on the device, and this produced a situation where the increase in wave steepness could reduce the air chamber efficiency. The steeper the waves, the more energy losses could occur due to turbulence, spillage, and vortex shedding [109]. López *et al.* [110] claimed that the device's capture factor decreases with high wave frequencies and vice versa.

Last but not least, it is very important to understand and consider the air compressibility that occurs inside the air chamber. Not accounting for the air compressibility factor may lead to an error in power output predictions, which is highly dependent on wave conditions and turbine-induced damping in the device's system [54]. When neglecting the air compressibility, Simonetti *et al.* [55] confirmed that it could results in an overestimation of the output performance up to 15% for the pressure inside chamber p_{owc} and airflow rate q_{owc}, but the overestimation could be less than 10% for capture width ratio, ε_{owc} when involving small scale of the OWC device.

VI. CONCLUSION

There are many types of wave energy converters established in the industry. This paper reviews one of the converter types, which is the OWC. A considerable amount of research has been conducted to develop a converter device for a specific site and generate power from the available ocean wave energy in a location. Feasibility studies can ensure the potential amount of energy that the devices can capture. Undoubtedly, the efficiency of the existing OWC devices has improved due to numerous optimizations, and eventually, their system's output power will improve. Comparing a few different types of OWC that generate power from the impact of the ocean waves suggests that there are still opportunities for future research to continue improving the current OWC technologies in the industry.

This paper discussed the main parts of the OWC devices and their functions and reviewed some of the OWC plants in the industry that utilize ocean wave energy to supply local areas with electricity. This paper also highlighted the most important aspects of an OWC design that affect output power production. This paper offers an understanding of the fundamental principles of how ocean waves develop in the open sea and which characteristics are useful for capturing wave energy to transform it into a form of kinetic energy. Two airflow cycles play a significant role in generating electricity from the inhalation and exhalation cycle system. Thus, the need for a bidirectional turbine type equipped in a power takeoff (PTO) system ensures the dual direction of the airflow.

Other aspects that may also affect the efficiency of the wave energy converter system include the sea bottom surface under the OWC device, air compressibility within the air chamber, the OWC inlet opening, and the position of the part receiving the impact of ocean waves. There should be a different performance captured by two types of OWC, the floating and fixed structure OWC. After considering all the criteria to harness wave energy, we can select the suitable turbine specifications to install in the system using the appropriate guidelines, such as those offered in this paper.

This paper also discusses the CFD models used in previous research, allowing for more precise outcomes through simulation activities. Furthermore, this paper also highlights the drawbacks identified in the existing OWC designs and offers suggestions on the most appropriate solutions for future improvements. In order to continue improving OWC technology and for the sake of its continuous betterment, further studies are necessary.

In summary, this paper confirms that two main things influence the OWC energy conversion efficiency significantly: chamber geometry and wave characteristics. Certain critical geometric aspects must be considered to improve the existing OWC designs, such as chamber width and height, orifice opening ratio, the inclination angle in the front and rear walls, and the OWC chamber's bottom profile, as per guidelines proposed in previous research. However, most of the earlier research only focused on generating power from high degrees of ocean wave energy, and few concentrated on developing a suitable OWC design for extracting energy from milder wave conditions. For countries like Malaysia, with low wave impact and mild wave conditions around their land, optimization initiatives seem essential for improving the existing OWC designs to be compatible with the local wave conditions. Since there is potential to capture energy from mild wave conditions, this study aims to provide guidelines to develop a better OWC design in the future.

ACKNOWLEDGMENT

The authors would like to thank the Razak Faculty of Technology & Informatics, Universiti Teknologi Malaysia, for its research facilities.

REFERENCES

[1] M. D. Esteban, J. López-Gutiérrez, and V. Negro, "Classification of wave energy converters," *Recent Adv. Petrochem. Sci.*, vol. 2, no. 4, pp. 2–5, Aug. 2017.

[2] I. López, J. Andreu, S. Ceballos, I. Martínez de Alegría, and I. Kortabarria, "Review of wave energy technologies and the necessary power-equipment," *Renew. Sustain. Energy Rev.*, vol. 27, pp. 413–434, Nov. 2013.

[3] L. Y. Kai, S. Sarip, H. M. Kaidi, J. A. Ardila-Rey, N. M. Samsuddin, M. N. Muhtazaruddin, F. Muhammad-Sukki, and S. A. Aziz, "Current status and possible future applications of marine current energy devices in malaysia: A review," *IEEE Access*, vol. 9, pp. 86869–86888, 2021.

[4] N. Khan, A. Kalair, N. Abas, and A. Haider, "Review of ocean tidal, wave and thermal energy technologies," *Renew. Sustain. Energy Rev.*, vol. 72, no. 10, pp. 590–604, 2017.

[5] B. Wua, T. Chena, J. Jianga, G. Lia, Y. Zhanga, and Y. Ye, "Economic assessment of wave power boat based on the performance of 'mighty whale' and BBDB," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 946–953, Jan. 2018.

[6] I. Heras-Saizarbitoria, I. Zamanillo, and I. Laskurain, "Social acceptance of ocean wave energy: A case study of an OWC shoreline plant," *Renew. Sustain. Energy Rev.*, vol. 27, pp. 515–524, Nov. 2013.

[7] F. O. de Antonio, "Wave energy utilization: A review of the technologies," *Renew. Sustain. Energy Rev.*, vol. 14, no. 3, pp. 899–918, 2010.

[8] R. Alamian, R. Shafaghat, S. J. Miri, N. Yazdanshenas, and M. Shakeri, "Evaluation of technologies for harvesting wave energy in Caspian sea," *Renew. Sustain. Energy Rev.*, vol. 32, pp. 468–476, Apr. 2014.

[9] S. Qiu, K. Liu, D. Wang, J. Ye, and F. Liang, "A comprehensive review of ocean wave energy research and development in China," *Renew. Sustain. Energy Rev.*, vol. 113, Oct. 2019, Art. no. 109271.

[10] A. R. Dehghani-Sanij, E. Tharumalingam, M. B. Dusseault, and R. Fraser, "Study of energy storage systems and environmental challenges of batteries," *Renew. Sustain. Energy Rev.*, vol. 104, pp. 192–208, Apr. 2019.

[11] T. K. Das, P. Halder, and A. Samad, "Optimal design of air turbines for oscillating water column wave energy systems: A review," *Int. J. Ocean Climate Syst.*, vol. 8, no. 1, pp. 37–49, Apr. 2017.

[12] T. S. Garrison, *Oceanography: An Invitation to Marine Science*. Belmont, CA, USA: Cengage Learning, 2012.

[13] Y. Masuda and M. E. McCormick, "Experiences in pneumatic wave energy conversion in Japan," in *Utilization of Ocean Waves—Wave to Energy Conversion*. Reston, VA, USA: American Society of Civil Engineers, 1986, pp. 1–33.

[14] A. F. O. Falcão and J. C. C. Henriques, "Oscillating-water-column wave energy converters and air turbines: A review," *Renew. Energy*, vol. 85, pp. 1391–1424, Jan. 2016.

[15] D. Zhang, W. Li, and Y. Lin, "Wave energy in China: Current status and perspectives," *Renew. Energy*, vol. 34, no. 10, pp. 2089–2092, Oct. 2009.

[16] Y. G. You, Y. H. Zhang, Y. J. Ma, Z. Yu, and N. D. Jiang, "Structural design and protective methods for the 100 kW shoreline wave power station," *China Ocean Eng*, vol. 17, no. 3, pp. 439–448, 2003.

[17] M. Suzuki, C. Arakawa, and S. Takahashi, "Performance of wave power generating system installed in breakwater at Sakata port in Japan," in *Proc. 14th Int. Offshore Polar Eng. Conf.*, 2004, pp. 202–209.

[18] M. K. Ravindran and P. Mario, "Energy from sea waves-the Indian wave energy programme," *Current Sci.*, vol. 60, no. 12, pp. 676–680, 1991.

[19] S. Santhakumar, V. Jayashankar, M. A. Atmanand, A. G. Pathak, M. Ravindran, T. Setoguchi, M. Takao, and K. Kaneko, "Performance of an impulse turbine based wave energy plant," in *Proc. 8th Int. Offshore Polar Eng. Conf.*, 1998, pp. 75–80.

[20] K. Mala, J. Jayaraj, V. N. Jayashankar, M. A. Atmanand, T. Setoguchi, and M. Takao, "Performance comparison of power modules in the Indian wave energy plant," in *Proc. 8th ISOPE Ocean Mining Symp.*, 2009, pp. 47–51.

[21] Y. Washio, H. Osawa, and T. Ogata, "The open sea tests of the offshore floating type wave power device," in *Proc. IEEE Oceans*, vol. 1, Nov. 2001, pp. 579–585.

[22] A. Clément, P. McCullen, A. Falcão, A. Fiorentino, F. Gardner, K. Hammarlund, G. Lemonis, T. Lewis, K. Nielsen, and S. Petroncini, "Wave energy in Europe: Current status and perspectives," *Renew. Sustain. Energy Rev.*, vol. 6, no. 5, pp. 405–431, 2002.

[23] M. Takao, E. Sato, S. Nagata, K. Toyota, and T. Setoguchi, "A sea trial of wave power plant with impulse turbine," in *Proc. ASME 27th Int. Conf. Offshore Mech. Arctic Eng.*, 2008, pp. 681–688.

[24] M. Suzuki, M. Takao, E. Satoh, S. Nagata, K. Toyota, and T. Setoguchi, "Performance prediction of OWC type small size wave power device with impulse turbine," *J. Fluid Sci. Technol.*, vol. 3, no. 3, pp. 466–475, 2008.

[25] R. Alcorn, A. Blavette, M. Healy, and A. Lewis, "FP7 EU funded CORES wave energy project: A coordinators' perspective on the Galway bay sea trials," *Underwater Technol., Int. J. Soc. Underwater*, vol. 32, no. 1, pp. 51–59, Mar. 2014.

[26] Y. Torre-Enciso, I. Ortubia, L. I. De Aguileta, and J. Marqués, "Mutriku wave power plant: From the thinking out to the reality," in *Proc. 8th Eur. Wave Tidal Energy Conf.*, Uppsala, Sweden, vol. 710, 2009, pp. 319–329.

[27] T. Heath, T. J. T. Whittaker, and C. B. Boake, "The design, construction and operation of the LIMPET wave energy converter (Islay, Scotland)[land installed marine powered energy transformer]," Energicenter Danmark Teknologisk Inst., Taastrup, Denmark, Tech. Rep. NEI-DK-3963, 2001, pp. 49–55.

[28] F. Arena, V. Fiamma, R. Iannolo, V. Laface, G. Malara, A. Romolo, and F. M. Strati, "Resonant wave energy converters: Small-scale field experiments and first full-scale prototype," *Energia Ambiente Innov.*, vol. 61, no. 2, pp. 58–67, 2015.

[29] F. Arena, A. Romolo, G. Malara, and A. Ascanelli, "On design and building of a U-OWC wave energy converter in the Mediterranean Sea: A case study," in *Proc. Ocean Renew. Energy*, Jun. 2013, pp. 1–8.

[30] Z. Liu, B. Hyun, J. Jin, K. Hong, and Y. Lee, "OWC air chamber performance prediction under impulse turbine damping effects," *Sci. China Technol. Sci.*, vol. 59, no. 4, pp. 657–666, Apr. 2016.

[31] D. Bull, "An improved understanding of the natural resonances of moonpools contained within floating rigid-bodies: Theory and application to oscillating water column devices," *Ocean Eng.*, vol. 108, pp. 799–812, Nov. 2015.

[32] W. Sheng, "Motion and performance of BBDB OWC wave energy converters: I, hydrodynamics," *Renew. Energy*, vol. 138, pp. 106–120, Aug. 2019.

[33] K. Rezanejad, C. Guedes Soares, I. López, and R. Carballo, "Experimental and numerical investigation of the hydrodynamic performance of an oscillating water column wave energy converter," *Renew. Energy*, vol. 106, pp. 1–16, Jun. 2017.

[34] J.-R. Nader, S.-P. Zhu, P. Cooper, and B. Stappenbelt, "A finite-element study of the efficiency of arrays of oscillating water column wave energy converters," *Ocean Eng.*, vol. 43, pp. 72–81, Apr. 2012.

[35] G. C. Nihous, "Wave power extraction by arbitrary arrays of non-diffracting oscillating water columns," *Ocean Eng.*, vol. 51, pp. 94–105, Sep. 2012.

[36] R. P. F. Gomes, J. C. C. Henriques, L. M. C. Gato, and A. F. O. Falcão, "Wave power extraction of a heaving floating oscillating water column in a wave channel," *Renew. Energy*, vol. 99, pp. 1262–1275, Dec. 2016.

[37] Y. Cui and Z. Liu, "Effects of solidity ratio on performance of OWC impulse turbine," *Adv. Mech. Eng.*, vol. 7, no. 1, Jan. 2015, Art. no. 121373.

[38] S. R. Wang, P. Parrish, P. Dills, and T. Lee, "Multimedia learning materials for marine applications," in *Proc. OCEANS*, Sep. 2006, pp. 1–4.

[39] A. F. O. Falcão, L. M. C. Gato, J. C. C. Henriques, J. E. Borges, B. Pereiras, and F. Castro, "A novel twin-rotor radial-inflow air turbine for oscillating-water-column wave energy converters," *Energy*, vol. 93, pp. 2116–2125, Dec. 2015.

[40] A. F. O. Falcão, J. C. C. Henriques, L. M. C. Gato, and R. P. F. Gomes, "Air turbine choice and optimization for floating oscillating-water-column wave energy converter," *Ocean Eng.*, vol. 75, pp. 148–156, Jan. 2014.

[41] T. H. Carolus and C. Moisel, "Bidirectional air turbines for oscillating water column systems: Fast selection applying turbomachinery scaling laws," *Int. J. Mar. Energy*, vol. 18, pp. 65–77, Jun. 2017.

[42] C. Moisel and T. H. Carolus, "A facility for testing the aerodynamic and acoustic performance of bidirectional air turbines for ocean wave energy conversion," *Renew. Energy*, vol. 86, pp. 1340–1352, Feb. 2016.

[43] E. Medina-López, R. J. Bergillos, A. Moñino, M. Clavero, and M. Ortega-Sánchez, "Effects of seabed morphology on oscillating water column wave energy converters," *Energy*, vol. 135, pp. 659–673, Sep. 2017.

[44] K. Rezanejad, J. Bhattacharjee, and C. G. Soares, "Stepped sea bottom effects on the efficiency of nearshore oscillating water column device," *Ocean Eng.*, vol. 70, pp. 25–38, Sep. 2013.

[45] S. J. Ashlin, V. Sundar, and S. A. Sannasiraj, "Effects of bottom profile of an oscillating water column device on its hydrodynamic characteristics," *Renew. Energy*, vol. 96, pp. 341–353, Oct. 2016.

[46] S. J. Ashlin, S. A. Sannasiraj, and V. Sundar, "Wave forces on an oscillating water column device," *Proc. Eng.*, vol. 116, pp. 1019–1026, Jan. 2015.

[47] A. Elhanafi, "Prediction of regular wave loads on a fixed offshore oscillating water column-wave energy converter using CFD," *J. Ocean Eng. Sci.*, vol. 1, no. 4, pp. 268–283, Dec. 2016.

[48] K. Monk, V. Winands, and M. Lopes, "Chamber pressure skewness corrections using a passive relief valve system at the pico oscillating water column wave energy plant," *Renew. Energy*, vol. 128, pp. 230–240, Dec. 2018.

[49] D.-Z. Ning, B.-M. Guo, R.-Q. Wang, T. Vyzikas, and D. Greaves, "Geometrical investigation of a U-shaped oscillating water column wave energy device," *Appl. Ocean Res.*, vol. 97, Apr. 2020, Art. no. 102105.

[50] M. McCormick, *Ocean Wave Energy Conversion*. New York, NY, USA: Dover, 2007, ch. 4.

[51] T. Vyzikas, S. Deshoulières, M. Barton, O. Giroux, D. Greaves, and D. Simmonds, "Experimental investigation of different geometries of fixed oscillating water column devices," *Renew. Energy*, vol. 104, pp. 248–258, Apr. 2017.

[52] P. R. F. Teixeira, D. P. Davyt, E. Didier, and R. Ramalhais, "Numerical simulation of an oscillating water column device using a code based on Navier–Stokes equations," *Energy*, vol. 61, pp. 513–530, Nov. 2013.

[53] R. A. A. C. Gonçalves, P. R. F. Teixeira, E. Didier, and F. R. Torres, "Numerical analysis of the influence of air compressibility effects on an oscillating water column wave energy converter chamber," *Renew. Energy*, vol. 153, pp. 1183–1193, Jun. 2020.

[54] I. López, R. Carballo, F. Taveira-Pinto, and G. Iglesias, "Sensitivity of OWC performance to air compressibility," *Renew. Energy*, vol. 145, pp. 1334–1347, Jan. 2020.

[55] I. Simonetti, L. Cappietti, H. Elsafti, and H. Oumeraci, "Evaluation of air compressibility effects on the performance of fixed OWC wave energy converters using CFD modelling," *Renew. Energy*, vol. 119, pp. 741–753, Apr. 2018.

[56] B. Bouali and S. Larbi, "Contribution to the geometry optimization of an oscillating water column wave energy converter," *Energy Proc.*, vol. 36, pp. 565–573, Jan. 2013.

[57] U. Şentürk and A. Özdamar, "Wave energy extraction by an oscillating water column with a gap on the fully submerged front wall," *Appl. Ocean Res.*, vol. 37, pp. 174–182, Aug. 2012.

[58] A. Elhanafi, G. Macfarlane, and D. Ning, "Hydrodynamic performance of single–chamber and dual–chamber offshore–stationary oscillating water column devices using CFD," *Appl. Energy*, vol. 228, pp. 82–96, Oct. 2018.

[59] K. Rezanejad, J. Bhattacharjee, and C. Guedes Soares, "Analytical and numerical study of dual-chamber oscillating water columns on stepped bottom," *Renew. Energy*, vol. 75, pp. 272–282, Mar. 2015.

[60] A. Elhanafi, A. Fleming, G. Macfarlane, and Z. Leong, "Underwater geometrical impact on the hydrodynamic performance of an offshore oscillating water column–wave energy converter," *Renew. Energy*, vol. 105, pp. 209–231, May 2017.

[61] C.-Y. Chang, F. N.-F. Chou, Y.-Y. Chen, Y.-C. Hsieh, and C.-T. Chang, "Analytical and experimental investigation of hydrodynamic performance and chamber optimization of oscillating water column system," *Energy*, vol. 113, pp. 597–614, Oct. 2016.

[62] P. Filianoti and S. M. Camporeale, "A linearized model for estimating the performance of submerged resonant wave energy converters," *Renew. Energy*, vol. 33, no. 4, pp. 631–641, Apr. 2008.

[63] S. R. e Silva, R. P. F. Gomes, and A. F. O. Falcão, "Hydrodynamic optimization of the UGEN: Wave energy converter with U-shaped interior oscillating water column," *Int. J. Mar. Energy*, vol. 15, pp. 112–126, Sep. 2016.

[64] W. Sheng, "Power performance of BBDB OWC wave energy converters," *Renew. Energy*, vol. 132, pp. 709–722, Mar. 2019.

[65] D. D. Raj, V. Sundar, and S. A. Sannasiraj, "Enhancement of hydrodynamic performance of an oscillating water column with harbour walls," *Renew. Energy*, vol. 132, pp. 142–156, Mar. 2019.

[66] Z. Deng, Z. Huang, and A. W. K. Law, "Wave power extraction from a bottom-mounted oscillating water column converter with a V-shaped channel," *Proc. Roy. Soc. A, Math., Phys. Eng. Sci.*, vol. 470, no. 2167, Jul. 2014, Art. no. 20140074.

[67] P. Boccotti, "Comparison between a U-OWC and a conventional OWC," *Ocean Eng.*, vol. 34, nos. 5–6, pp. 799–805, Apr. 2007.

[68] P. G. F. Filianoti, L. Gurnari, M. Torresi, and S. M. Camporeale, "CFD analysis of the energy conversion process in a fixed oscillating water column (OWC) device with a wells turbine," *Energy Proc.*, vol. 148, pp. 1026–1033, Aug. 2018.

[69] Y. Luo, Z. Wang, G. Peng, Y. Xiao, L. Zhai, X. Liu, and Q. Zhang, "Numerical simulation of a heave-only floating OWC (oscillating water column) device," *Energy*, vol. 76, pp. 799–806, Nov. 2014.

[70] W. Sheng and T. Lewis, "Energy conversion: A comparison of Fix- and self-referenced wave energy converters," *Energies*, vol. 9, no. 12, p. 1056, Dec. 2016.

[71] A. J. C. Crespo, C. Altomare, J. M. Domínguez, J. González-Cao, and M. Gómez-Gesteira, "Towards simulating floating offshore oscillating water column converters with smoothed particle hydrodynamics," *Coastal Eng.*, vol. 126, pp. 11–26, Aug. 2017.

[72] J. C. C. Henriques, J. C. C. Portillo, W. Sheng, L. M. C. Gato, and A. F. O. Falcão, "Dynamics and control of air turbines in oscillating-water-column wave energy converters: Analyses and case study," *Renew. Sustain. Energy Rev.*, vol. 112, pp. 571–589, Sep. 2019.

[73] F.-X. Faÿ, J. C. Henriques, J. Kelly, M. Mueller, M. Abusara, W. Sheng, and M. Marcos, "Comparative assessment of control strategies for the biradial turbine in the mutriku OWC plant," *Renew. Energy*, vol. 146, pp. 2766–2784, Feb. 2020.

[74] F. R. Torres, P. R. F. Teixeira, and E. Didier, "A methodology to determine the optimal size of a wells turbine in an oscillating water column device by using coupled hydro-aerodynamic models," *Renew. Energy*, vol. 121, pp. 9–18, Jun. 2018.

[75] I. López, R. Carballo, and G. Iglesias, "Site-specific wave energy conversion performance of an oscillating water column device," *Energy Convers. Manage.*, vol. 195, pp. 457–465, Sep. 2019.

[76] A. F. O. Falcão, J. C. C. Henriques, and L. M. C. Gato, "Air turbine optimization for a bottom-standing oscillating-water-column wave energy converter," *J. Ocean Eng. Mar. Energy*, vol. 2, no. 4, pp. 459–472, Nov. 2016.

[77] S. Brusca, A. Galvagno, R. Lanzafame, A. M. Cugno Garrano, S. Mauro, and M. Messina, "On the turbine-induced damping in oscillating water column wave energy converter," *Energy Proc.*, vol. 126, pp. 581–588, Sep. 2017.

[78] I. López, B. Pereiras, F. Castro, and G. Iglesias, "Holistic performance analysis and turbine-induced damping for an OWC wave energy converter," *Renew. Energy*, vol. 85, pp. 1155–1163, Jan. 2016.

[79] I. López, B. Pereiras, F. Castro, and G. Iglesias, "Performance of OWC wave energy converters: Influence of turbine damping and tidal variability," *Int. J. Energy Res.*, vol. 39, no. 4, pp. 472–483, Mar. 2015.

[80] S. Brusca, F. Cucinotta, A. Galvagno, R. Lanzafame, S. Mauro, and M. Messina, "Oscillating water column wave energy converter by means of straight-bladed darrieus turbine," *Energy Proc.*, vol. 82, pp. 766–773, Dec. 2015.

[81] T. M. Ferguson, G. MacFarlane, A. Fleming, and I. Penesis, "PIV investigation of 3-dimensional flow within an oscillating water column," *Int. J. Mar. Energy*, vol. 11, pp. 120–131, Sep. 2015.

[82] D. Mouazé, Y. Ourmieres, and J. R. Chaplin, "Steady and unsteady flow in wave-induced boundary layers," Dept. Civil Environ. Eng., Univ. Southampton, U.K., Tech. Rep., 2002.

[83] J. R. Chaplin, "Nonlinear forces on a horizontal cylinder beneath waves," *J. Fluid Mech.*, vol. 147, pp. 449–464, Oct. 1984.

[84] Y. Cui, Z. Liu, X. Zhang, and C. Xu, "Review of CFD studies on axial-flow self-rectifying turbines for OWC wave energy conversion," *Ocean Eng.*, vol. 175, pp. 80–102, Mar. 2019.

[85] A. F. O. Falcão, J. C. C. Henriques, and L. M. C. Gato, "Rotational speed control and electrical rated power of an oscillating-water-column wave energy converter," *Energy*, vol. 120, pp. 253–261, Feb. 2017.

[86] F.-X. Faÿ, E. Robles, M. Marcos, E. Aldaiturriaga, and E. F. Camacho, "Sea trial results of a predictive algorithm at the mutriku wave power plant and controllers assessment based on a detailed plant model," *Renew. Energy*, vol. 146, pp. 1725–1745, Feb. 2020.

[87] F. M. Strati, G. Malara, and F. Arena, "Performance optimization of a U-oscillating-water-column wave energy harvester," *Renew. Energy*, vol. 99, pp. 1019–1028, Dec. 2016.

[88] I. Simonetti, L. Cappietti, and H. Oumeraci, "An empirical model as a supporting tool to optimize the main design parameters of a stationary oscillating water column wave energy converter," *Appl. Energy*, vol. 231, pp. 1205–1215, Dec. 2018.

[89] M. Iino, T. Miyazaki, H. Segawa, and M. Iida, "Effect of inclination on oscillation characteristics of an oscillating water column wave energy converter," *Ocean Eng.*, vol. 116, pp. 226–235, Apr. 2016.

[90] C. Liu, "A tunable resonant oscillating water column wave energy converter," *Ocean Eng.*, vol. 116, pp. 82–89, Apr. 2016.

[91] T. V. Heath, "A review of oscillating water columns," *Phil. Trans. Roy. Soc. A, Math., Phys. Eng. Sci.*, vol. 370, no. 1959, pp. 235–245, Jan. 2012.

[92] C. G. Soares, "Progress in renewable energies offshore," in *Proc. 2nd Int. Conf. Renew. Energies Offshore (RENEW)*, Lisbon, Portugal: CRC Press, Oct. 2016, pp. 24–26.

[93] A. Iturrioz, R. Guanche, J. L. Lara, C. Vidal, and I. J. Losada, "Validation of OpenFOAM for oscillating water column three-dimensional modeling," *Ocean Eng.*, vol. 107, pp. 222–236, Oct. 2015.

[94] Z. Deng, C. Wang, P. Wang, P. Higuera, and R. Wang, "Hydrodynamic performance of an offshore-stationary OWC device with a horizontal bottom plate: Experimental and numerical study," *Energy*, vol. 187, Nov. 2019, Art. no. 115941.

[95] F. Mahnamfar and A. Altunkaynak, "Comparison of numerical and experimental analyses for optimizing the geometry of OWC systems," *Ocean Eng.*, vol. 130, pp. 10–24, Jan. 2017.

[96] G. Lorenzini, M. Lara, L. Rocha, M. Gomes, E. Santos, and L. Isoldi, "Constructal design applied to the study of the geometry and submergence of an oscillating water column," *Int. J. Heat Technol.*, vol. 33, no. 2, pp. 31–38, Jun. 2015.

[97] J.-S. Oh and S.-H. Han, "Inlet geometry effect of wave energy conversion system," *J. Mech. Sci. Technol.*, vol. 26, no. 9, pp. 2793–2798, Sep. 2012.

[98] M. T. Morris-Thomas, R. J. Irvin, and K. P. Thiagarajan, "An investigation into the hydrodynamic efficiency of an oscillating water column," *J. Offshore Mech. Arctic Eng.*, vol. 129, no. 4, pp. 273–278, Nov. 2007.

[99] D.-Z. Ning, R.-Q. Wang, Q.-P. Zou, and B. Teng, "An experimental investigation of hydrodynamics of a fixed OWC wave energy converter," *Appl. Energy*, vol. 168, pp. 636–648, Apr. 2016.

[100] O. B. Yaakob, M. Yasser, M. N. B. Mazlan, K. E. Jaafar, and R. M. R. Muda, "Model testing of an ocean wave energy system for Malaysian sea," *World Appl. Sci. J.*, vol. 22, no. 5, pp. 667–671, 2013.

[101] I. Amin, "Numerical study of an oscillating water column chamber with internal wall," in *Proc. 2nd Int. Conf. Maritime Technol. Eng. (MARTECH)*, Oct. 2015, pp. 1271–1278.

[102] R. Wilbert, V. Sundar, and S. A. Sannasiraj, "Wave interaction with a double chamber oscillating water column device," *Int. J. Ocean Climate Syst.*, vol. 4, no. 1, pp. 21–39, Mar. 2013.

[103] N. Dizadji and S. E. Sajadian, "Modeling and optimization of the chamber of OWC system," *Energy*, vol. 36, no. 5, pp. 2360–2366, May 2011.

[104] K. R. Ram, M. R. Ahmed, M. A. Zullah, and Y.-H. Lee, "Experimental studies on the flow characteristics in an inclined bend-free OWC device," *J. Ocean Eng. Sci.*, vol. 1, no. 1, pp. 77–83, Jan. 2016.

[105] F. He and Z. Huang, "Hydrodynamic performance of pile-supported OWC-type structures as breakwaters: An experimental study," *Ocean Eng.*, vol. 88, pp. 618–626, Sep. 2014.

[106] M. N. Gomes, C. D. Nascimento, B. L. Bonafini, E. D. Santos, L. A. Isoldi, and L. A. O. Rocha, "Two-dimensional geometric optimization of an oscillating water column converter in laboratory scale," *Revista Engenharia Térmica*, vol. 11, nos. 1–2, pp. 30–36, 2012.

[107] M. Sameti and E. Farahi, "Output power for an oscillating water column wave energy convertion device," *Ocean Environ. Fluid Res.*, vol. 1, no. 2, pp. 27–34, 2014.

[108] D.-Z. Ning, J. Shi, Q.-P. Zou, and B. Teng, "Investigation of hydrodynamic performance of an OWC (oscillating water column) wave energy device using a fully nonlinear HOBEM (higher-order boundary element method)," *Energy*, vol. 83, pp. 177–188, Apr. 2015.

[109] K. Thiruvenkatasamy and S. Neelamani, "On the efficiency of wave energy caissons in array," *Appl. Ocean Res.*, vol. 19, no. 1, pp. 61–72, Feb. 1997.

[110] I. López and G. Iglesias, "Efficiency of OWC wave energy converters: A virtual laboratory," *Appl. Ocean Res.*, vol. 44, pp. 63–70, Jan. 2014.

DZUL HAFEZ YACOB received the Bachelor of Mechanical Engineering degree from the University Tun Hussein Onn Malaysia (UTHM), in 2008, and the master's degree in science engineering design from the Universiti Teknologi Malaysia (UTM), in 2018. He is currently a Ph.D. Researcher in aerodynamic of marine renewable energy system at UTM. He is also holding a position of an Assistant Manager with the Technical Field Service Department, PROTON. He is an Expert in powertrain system (engine and transmission) and regularly assigned as a company representative for powertrain troubleshooting related matters for Proton Domestic and Export market. He is a Certified Lead Assessor/Auditor in QMS IATF16949:2016 for automotive industry by Robere & Associates (Thailand) Ltd., and a Certified Internal Quality Auditor ISO9001:2015 by SIRIM STS Sdn Bhd. He has been appointed as a Lead Auditor with the Company and Product Quality Improvement Team, Proton.

SHAMSUL SARIP received the Diploma of Mechanical Engineering, Bachelor of Mechanical Engineering, and Master of Mechanical Engineering degrees from the Universiti Teknologi Malaysia, Kuala Lumpur, in 1995, 1998, and 2002, respectively, and the Ph.D. degree in mechanical engineering from the University of Bradford, U.K., in 2012. He is currently an Associate Professor with the Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia. He has been involved in engineering design, including lightweight disc brake, micro hydro turbine, ram pump, marine current turbine, and product development. He also involved in university motor sport activities which required him to expand the knowledge to finite element analysis, heat transfer, computational fluid dynamics, and structure analysis.

HAZILAH MAD KAIDI received the B.Eng. degree (Hons.) in electrical engineering in telecommunication from the Universiti Teknologi Malaysia, the M.Sc. degree in telecommunication and information engineering from the Universiti Teknologi MARA Malaysia, and the Ph.D. degree from the Universiti Teknologi Malaysia. She is currently a Senior Lecturer with the Razak Faculty of Technology and Informatics. Her research interests include mobile and wireless communications, error control coding, relay networks, cooperative communications, hybrid ARQ, cross-layer design, the Internet of Things, and green technology.

JORGE ALFREDO ARDILA-REY (Member, IEEE) was born in Santander, Colombia, in 1984. He received the B.Sc. degree in mechatronic engineering from the Universidad de Pamplona, Pamplona, Colombia, in 2007, the Specialist Officer degree in naval engineering from the Escuela Naval Almirante Padilla, Cartagena, Colombia, in 2008, and the M.Sc. and Ph.D. degrees in electrical engineering from the Universidad Carlos III de Madrid (UC3M), in 2012 and 2014, respectively. He was an Automatic Control Engineer of ARC Almirante Padilla, from 2008 to 2010. From 2010 to 2014, he worked with the High-Voltage Research and Test Laboratory (LINEALT), Department of Electrical Engineering, UC3M. He is currently working as a Professor at the Department of Electrical Engineering, Universidad Técnica Federico Santa María, Santiago, Chile. His research interests include partial discharges, insulation systems diagnosis, and instrumentation and measurement techniques for high frequency currents.

FIRDAUS MUHAMMAD-SUKKI has been an Active Researcher. He is currently a Lecturer at Edinburgh Napier University, U.K. He is an Expert in designing optical concentrators, which can be used in many applications, including creating a low cost solar photovoltaic system, illumination, heating and cooling of buildings, energy harvesting, desalination, medical devices, and waste water treatment. On top of that, he carried out a number of non-technical research, including market trend and financial analysis related to renewable technologies. He has excellent track record in collaborating with research universities around the world. He has published numerous articles in high impact factor journals as well as presenting in various conferences related to his area. Prior to joining the academia, he was a Communication Engineer in Malaysia's largest telecommunication company. He was in charge of the leased line servers for Malaysia's network and was involved in major projects related to the telecommunication while holding the post. His research interests include renewable energy technology and policies and sustainable resources.

• • •