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Experimental & Analytical Hydrodynamic Behavior Investigation of an Onshore OWC-WEC Imposed to Caspian Sea Wave Conditions

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ABSTRACT

In this paper, the effect of the draft depth (as a dimensionless number) and characteristics of the incident wave on free surface oscillation, velocity, and the output power of an OWC has been analytically and experimentally investigated. Therefore, the governing equations of hydrodynamic performance inside the oscillating water column chamber were first presented by assuming a mathematical model based on the potential flow theory. Then, a 1:10 single chamber OWC has been experimentally investigated in a wave tank, by considering the Caspian Sea wave characteristics. Comparing the obtained results showed that there is a good agreement between the theoretical solution and experimental test data. According to the results, increasing the frequency of the incident wave increases the free surface oscillation outside the chamber, while the results inside the OWC are different. In other words, under these conditions, free-surface oscillations inside the OWC and subsequently, the velocity and flow rate of the orifice decrease. So, the power generated will decrease too. Also, the effects of draft depth have been theoretically and experimentally analyzed for three depths and turned out that increasing the depth of drafts from 5 to 25 cm and frequency from 32 to 42 rpm causes a decrease in power generation.

1. Introduction

Due to overpopulation and rising energy consumption, fossil fuel disadvantages, environmental pollution, climate changes, and greenhouse gas effects, researchers have concluded that renewable energies can be the best solution to tackle the problems which have been mentioned earlier. Therefore, different kinds of renewable energy resources have introduced, such as wind, solar, and wave energy. However, solar energy density is 0.1-0.2 kW / m, wind energy density is 0.4-0.6 kW / m but sea energy density is 2-3 kW / m [1, 2]. Because of the high density of wave energy, this type of energy could be considered as a good option for power generation. The total energy of the sea wave is estimated from 1 to 10 terawatt, which is a significant fraction of the world's energy consumption [3]. Many methods and devices have introduced to convert wave energy to electricity, which can be divided into three main categories: oscillating systems, overflows, and oscillating water columns [4]. Yoshio Masuda, who is known as the father of the modern science of wave energy technology, began his studies on oscillating water columns in the second half of the 1940s [5]. Practical studies on OWC's in Europe carried out in 1973 just after the oil crisis; also, a project was developed by the British government in 1975 to build a 2 GW ocean power plant, however, since the oil crisis has been solved the plan was not accomplished [6]. The National Laboratory of Engineering in Scotland has contributed significantly to the development of various kinds of marine wave energy converters, especially "s OWC's, and on the other hand, the UK's marine wave energy program resumed in 1982 and, then Norway attempted to install an OWC in the bay close to the Bergen [7]. Studies in Europe remained on the academic level until 1990, and their most significant achievement was a 75 kW oscillating water column, which has been built in the Isles of Scotland [8]. However, Asia has also had some accomplishments in this field of study, including 120-kW oscillating water column plants, which connected to a breakwater system off the coast of Sakata, Japan [9]. For years, combining a sea-wave energy converter system with breakwaters was just the same Japanese model. Still, this concept has been studied and developed by Spanish and Italian researchers in recent years [3]. There are generally two fashions to study the hydrodynamic behavior of the OWC; on the one hand, problems can be solved by implementing the Navier-Stokes equations and the assumption of viscous fluid flow which is generally performed by high-cost commercial software packages, on the other hand, there is another method which is applying potential function and assuming that the air and water are ideal flow. Despite its limitations and drawbacks in modeling viscosity losses and some boundary layer phenomena, the ideal flow assumption remains one of the most popular methods in the field of wave energy converters, due to its high performance, analytical capability, and reduced solution costs.

Theoretical researches on the hydrodynamic performance of the oscillating water column have made significant progress during the last two decades [10]. The uniform surface pressure distribution for any arbitrary geometry was developed by Evans in 1982 [11], and also the theory of the rigid piston is a valuable solution to the method proposed in the mid-1970s for determining the relationship between waves and floating objects [12].

From the thermodynamic point of view, study on air inside the chamber is a subject which plays a vital role in real-scale oscillating water columns hydrodynamic behavior, this subject was first modeled in 1985 by Sarmanto and Falcao [13] and afterward, Jeffrey and Whitaker in 1986 implemented this model to investigate the oscillating water columns performances [14].

In 2001, Weber and Thomas investigated the importance of the air chamber design on the efficiency of the oscillating water column, they have achieved the optimum design of the air chamber by considering five geometric design parameters and implementing optimization methods [15]. In 2002, Wang et al. have investigated an analytical and empirical study on the offshore OWC systems; in their research, they have illustrated that by decreasing the water depth, the peak value of the CWR diagram tends to lower frequencies [16].

Hong et al. implemented the potential function to drive equations of the OWC to predict the hydrodynamic behavior of the OWC [17]. In 2005 Soroso also studied the effect of wave height and orifice diameter on the chamber pressure experimentally, and it is turned out that decreasing orifice diameter leads to an increase in pressure inside the chamber [18]. In 2011 Nagata et al. presented a two-dimensional model and boundary element method solution for an oscillating water column, which could be able to estimate its energy efficiency [19]. In 2012 Senturk and Ozdamar investigated the effect of the draft depth on OWC performances by applying the Galerkin method and potential function [20]. In 2013 Malara and Arena solved the OWC problem by implementing the potential function, and the impact of wave height on OWC efficiency has been investigated [21]. On the other hand, it is noticeable that the experimental study on the wave tank and investigating the effect of incident wave characteristics on the OWC can play an important role in analyzing the performance of the OWC. The experimental study is often carried out to develop the hydrodynamic behavior of the oscillating water column due to estimating the power generation of the system in a wide range of ocean wave conditions [22].

In 2015, Kamath et al. carried out a two-dimensional numerical model and empirical validation, they have shown that free surface oscillation depends on the input amplitude and wavelength [23].

Ning et al. in 2016, studied the impact of the geometry and incident wave characteristics on the OWC efficiency. Results indicate that an increase in wave amplitude leads to rising in performance at first, but the efficiency decreases afterward. On the other hand, they introduced a dimensionless parameter which is called relative wavelength, and it is turned out that when it has been raised more than 100 %, the received energy by OWC tends to be zero [24].

In 2016 also Cheng et al. started and experimental and theoretical study on the effect of the wave characteristics and geometry on the performance of the OWC, and it is found that these parameters can increase efficiency by 500% [25].

In 2018, Silik and Altonkinak carried out an analytical and experimental study on OWCs; they investigated the effect of dimensionless numbers such as the ratio of the draft depth to the depth of the wave-tank on the OWC performances [26].

According to the studies carried out, most of the cases that have been experimentally and analytically studied, the size of OWC models were much smaller than the actual model; however, in this paper, in order to study the performance and real scale phenomena, a model close to the size of the prototype with a scale of 1:10 was constructed. Experimental tests of the model have also been carried out. In the analytical study, the potential theory was implemented, and the Caspian Sea wave characteristics were applied to simulate the incident wave of the wave tank. The main point that stands out in this study is investigating the hydrodynamic behavior of the proposed OWC directly by surface sensors to study the free surface oscillations inside the OWC due to changes in wave frequency and water draft depth. For this purpose, a dimensionless parameter has introduced to study the hydrodynamic behavior of the OWC; this parameter is called transmitted wave height, which is the ratio of the incident wave height to the oscillation amplitude of the water free surface inside the OWC. The effect of the wave height and wavelength on free surface oscillation inside the chamber will also be obtained.

To calculate the OWC power, the free surface displacement could be modeled in the time domain. In this regard, by determining the velocity as the derivative of the free surface displacement, it is possible to calculate the pressure and the orifice volumetric flow rate, so the power of the OWC is obtained by multiplying the pressure and the volumetric flow.

In order to ensure the accuracy of the results, uncertainty analysis carried out, and each experiment was repeated three times, and finally, 270 preliminary data obtained and analyzed.

In the following, first, the laboratory facilities used in this study will be introduced, and then the next section will address the potential solution of the wave-tank and the oscillating water column system. In the results section, the potential solution validated, afterward the effect of wave frequency and water draft depth in the form of dimensionless numbers on transmitted wave height and wavelength has been studied. Finally, the important results of this research will be presented.

2. Experimental Study

In the following section, the experimental equipment and facilities will be introduced; furthermore, the second part shows how the experimental analysis has been carried out. Also, finally, the uncertainty analysis of the experimental study has introduced.

2.1. Experimental Setup

Experimental tests carried out in the wave-tank of the Sea-Based Energy Research Group of the Babol Noshirvani University of Technology (Figure 1). The wave-tank is capable of generating a variety of regular waves over a wide range of wave heights and periods, and it is 11 meters long, 3 meters wide and 3 meters high. Also, the wave-tank includes a flap-type wave maker (Figure 2) and able to generate and simulate deep-water waves. Figure 3 illustrates the designed and constructed OWC system; this single chamber OWC is 2.4 meters long, 1 meter wide, 2 meters high, and the area of the orifice is 0.18 m^2. The output velocity at the orifice is the prerequisites of the solution in this paper, and to measure this parameter, The GM816A velocity meter (with 5% error) has been implemented. Also, for determining the surface elevation in the wave-tank and OWC an Arduino MEGA2560 processor and ultrasonic HC-SR04 sensor have been applied, these sensors showed in Table 1.

2.2. Simulating the Wave Characteristic of the Caspian Sea

According to the design and construction of a 1:10 scale OWC wave energy converter, wave characteristics such as wave height and frequency were used to simulate the Caspian Sea wave with a ratio of 1:10 by implementing Froud scaling method.

Figure 1. Left and right side of the wave tank of the Sea-Based Energy Research Group

Figure 2. The wave maker set up

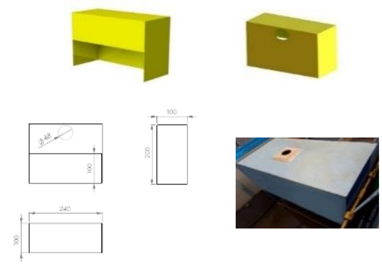


Figure 3. The oscillating water column and its size in cm

Table 1- Measurement instruments

instrument	Measurement accuracy	Image
velocity meter (GM816A)	0.1 m/s	
ultrasonic sensor (sr-04)	3 mm	

It has been analyzed that the Caspian Sea has 0.5-1 meter height, and the period is 4-6 seconds [27, 28]. By applying the Froud scaling method, the frequency and height of the required wave in the wave-tank are obtained by Eq (1) and (2).

$$\omega_{act} = \alpha_L^{-0.5} \omega_{lab} \quad (1)$$

$$H_{act} = \alpha_L H_{lab} \quad (2)$$

α_L is scaling number, lab, and act indexes refer to laboratory and actual states, respectively. The calculations showed that to simulate the frequency and the characteristics of the defined wave of the Caspian Sea, the stroke of the wavemaker must be 13 cm length, and the frequency should be 38 rpm.

In this paper, the draft depth is a variable, and to simulate the Caspian Sea wave characteristics and to prevent the sloshing phenomenon, three draft depths have selected, which are 5, 15, and 25 cm. Therefore, the OWC has imposed to 6 frequencies ranges from 32 rpm to 42 rpm, and regarding the uncertainty analysis, each test was carried out five times to achieve the most reliable data. On the other hand, dimensional analysis has carried out to determine the experimental variables; therefore, the following function has been considered

$$\eta = f(T.\rho.\lambda.g.P.H) \quad (1)$$

$$\pi_1 = \frac{\eta}{\lambda} \quad (2)$$

$$\pi_2 = \frac{H}{\lambda} \quad (3)$$

$$\pi_3 = T\frac{\sqrt{g}}{\sqrt{\lambda}} \quad (4)$$

$$\pi_4 = \frac{P}{\rho g \lambda} \quad (5)$$

$$\frac{\eta}{\lambda} = f(\frac{H}{\lambda}.T\frac{\sqrt{g}}{\sqrt{\lambda}}.\frac{P}{\rho g \lambda}) \quad (6)$$

2.3. Uncertainty Analysis

Due to the high volume of uncertainty analysis data, this section only provides surface elevation and velocity data for one experiment in 5 cm water draft depth and 32 rpm frequency; also the data in Table 2 is calculated by the Eq (3) to (6) as follows:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \quad (3)$$

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{(n-1)}} \quad (4)$$

$$u = \frac{s}{\sqrt{n}} \quad (5)$$

$$U = ku_c \quad (6)$$

In Eq (3) $\bar{x}$ is the average value, x is the considered parameter in each experiment, and n is the number of the test. In E (4), s represents the standard deviation, and in Eq (5) u is the uncertainty, finally, in Eq (6) U is the combined uncertainty by coverage factor of k which leads to 95% reliability, the derived data illustrates in Table 2.

3. Analytical Solution

In this section, Eq for solving wave-tank and determining the incident wave characteristics introduced and the Eq have derived from calculating the power of the considered wave energy converter. In the second part, the equations for the OWC are obtained by implementing the basic concepts of fluid mechanics; however, the flow considered as irrotational, non-viscous, and incompressible flow, which is known as ideal flow.

3.1. Analytical solution for wave-tank

A schematic of the size and the location of the OWC system with the size of the wave-tank are shown in Figure 4. In order to assess the wave characteristics such as height, wavelength, and angular frequency of the wave, the wave-tank equations must be solved; Therefore, due to the Caspian Sea conditions, it has been found that approximately 25% of the year the wave height is between 0.5 to 1 meter and the period of the wave is 4 to 6 seconds [29], and in this study wave frequency was derived by applying the Froud scaling which is 1:10. Then, with the wave frequency and the dispersion equation (Eq (7)), the wavenumber that can represent the wavelength was also obtained [30].

$$\omega^2 = kg \tanh(kh) \quad (7)$$

ω is the wave frequency, k wave is the number, g is the gravity acceleration, and h is the water depth. Therefore, by using the dispersion relation, water depth, and gravity acceleration, the wavenumber is determined. Then, by applying the Eq (8), the required stroke length for the wavemaker has obtained to simulate the Caspian Sea wave characteristics in the wave-tank.

$$\frac{H}{S_0} = \frac{4\sinh(kh)^2}{\sinh(2kh)+2kh}\left[1+\frac{(1-\cosh(kh))}{kh\sinh(kh)}\right] \quad (8)$$

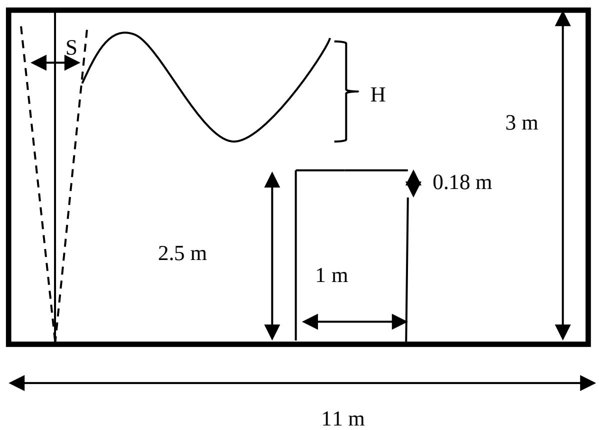


Figure 4. Location of the OWC inside the wave-tank

Table 2. uncertainty analysis of the proposed system

Value	1	2	3	4	5	Average value	Standard deviation	Average uncertainty	Uncertainty with a coverage factor
Free-surface fluctuation inside the OWC for draft depth of 5cm at 32 rpm [m]	0.09	0.1	0.09	0.1	0.09	0.094	0.005477	0.002449	0.004899
Free-surface fluctuation of the wave-tank for draft depth of 5cm at 32 rpm [m]	0.06	0.08	0.07	0.06	0.06	0.066	0.008944	0.003788	0.00758
Orifice output velocity[m/s]	2.16	2.13	2.10	2.16	2.16	2.14	0.02683	0.01199	0.02399

3.2. Analytical Solution for OWC

The parameters related to the proposed OWC are illustrated in Figure 5. The air is considered as an incompressible fluid, and the rigid piston theory was implemented. The oscillating wave surface elevation inside the OWC chamber is the main factor that plays an essential role in the available chamber power transfers to the turbines. Since the free surface fluctuations are related to the incident wave characteristics, water depth, chamber size, chamber air pressure, and the turbine inlet air pressure, etc, It is assumed that surface elevation inside the chamber can be expressed as [31]:

$$\eta_1 = \frac{H_1}{2}\sin(\frac{2\pi}{T}t) \tag{9}$$

$$V_1 = \frac{d\eta_1}{dt} = \omega\frac{H_1}{2}\cos(\frac{2\pi}{T}t) \tag{10}$$

η_1 is the equation of the free surface elevation and V_1 is the vertical velocity of the water-free surface inside the chamber and, on the other hand, the velocity at the orifice can be calculated by implementing the continuity equation [31]:

$$Q = A_1 V_1 = A_2 V_2 \tag{11}$$

$$V_2 = \frac{A_1}{A_2}V_1 = \frac{A_1}{A_2}\omega\frac{H_1}{2}\cos(\frac{2\pi}{T}t) \tag{12}$$

In Eq (11) and (12), Q represents the volumetric flow rate. Also, the output power of the system can be obtained by using the Eq (13) to (16), and to obtain the pressure at the orifice, the Bernoulli equation should be applied.

$$P_t = (P_2 - P_1)Q \tag{13}$$

$$P_2 = p_1 + \frac{1}{2}\rho(V_1{}^2 - V_2{}^2) + \rho\frac{\partial}{\partial t}(\varphi_1 - \varphi_2) \tag{14}$$

$$\varphi_1 = V_1\eta_1 - V_0\eta \cong V_1\eta_1 = \frac{\omega H_1{}^2}{4}\sin(\omega t)\cos(\omega t) \tag{15}$$

$$\varphi_2 = \frac{A_1}{A_2}\varphi_1 \tag{16}$$

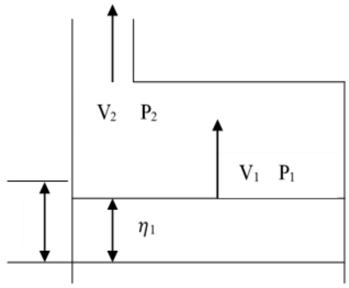


Figure 5- Oscillating water column model and parameters

In Eq (13) to (16) φ_1 and φ_2, are the velocity potentials and p1 and p2 are the pressure at points 1 and 2, respectively [32].

$$\frac{\partial\varphi_1}{\partial t} = \frac{\omega^2 H_1{}^2}{4}(2\cos(\omega t)^2 - 1) \tag{17}$$

$$P_2 - P_0 = \rho\frac{A_1}{A_2}\frac{\partial\varphi_1}{\partial t} - \rho\frac{Q}{A_2(V_2 - V_1)} \tag{18}$$

$$P_t = \left[\rho\frac{A_1}{A_2}\frac{\partial\varphi_1}{\partial t} - \rho\frac{Q}{A_2}(V_2 - V_1)\right]Q \tag{19}$$

$$P_t = \begin{bmatrix} -\rho\frac{A_1}{A_2}\frac{\omega H_1{}^2}{4}(2\cos(\omega t)^2 - 1) \\ -\rho\frac{Q}{A_2}(V_2 - V_1) \end{bmatrix} Q \tag{20}$$

In Eq (19) Pt is the output power at the orifice, and the Betz coefficient of 0.25 is applied to obtain the output power of the OWC [33]. In this study, the output velocity of the orifice was measured experimentally. Eq (21) to (24) introduce the dimensionless parameters which are considered in the study

$$Kh = \frac{\omega^2}{g} h = kh \tanh(kh) \quad (21)$$

$$\beta = \frac{y}{h} \quad (22)$$

$$\delta = \frac{L}{\lambda} \quad (23)$$

$$\mu = \frac{d}{H} \quad (24)$$

In Eq (22) y is the draft of the wave energy converter, L is chamber length, λ is the wavelength, and d is average water level fluctuations inside the OWC for a period, and H is the wave height outside the system. Also, Eq (21) introduces the dimensionless wave frequency [26]. β represents the geometric dimensionless parameter of the opening ratio of the OWC, besides δ is the ratio of the chamber length to the wavelength. Also, μ is called the transmitted wave height [26].

4. Results

This section compares the analytical results with the experimental data, afterward by concerning the validated results, the analytical solution and the experimental experiments data have introduced.

4.1. Validation

In order to validate the analytical results, they have compared with the experimental data obtained from the surface elevation sensor. The solution results and experimental data for free surface fluctuations inside the OWC and wave-tank have compared, and the analysis carried out for three draft depth which is 5, 15, and 25 cm. The comparison is shown in Figure 6 to Figure 11, as it is noticeable the solution has a good agreement with experimental data.

On the other hand, the rate of error for each draft depth is also shown in

Table 3; as can be seen from the table, the highest average error rate is only 5.55%, which indicates a good agreement with the experimental values. The cause of these errors can be found in the problem assumptions; since in solution, the fluid assumed to be incompressible, non-viscous, and non-rotational, and this is different from the actual physical condition of the problem.

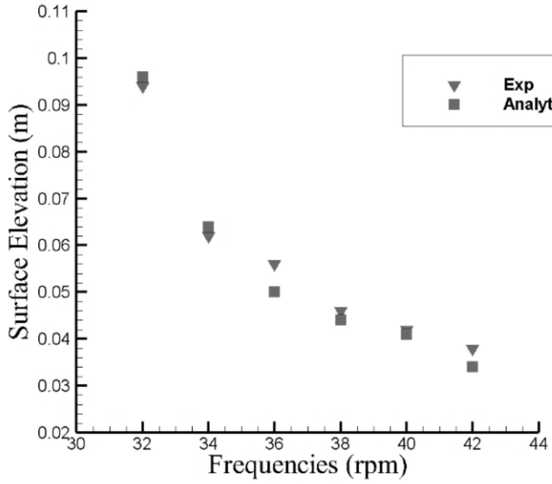


Figure 6- Validating the wave height inside the OWC for the draft depth of 5 cm

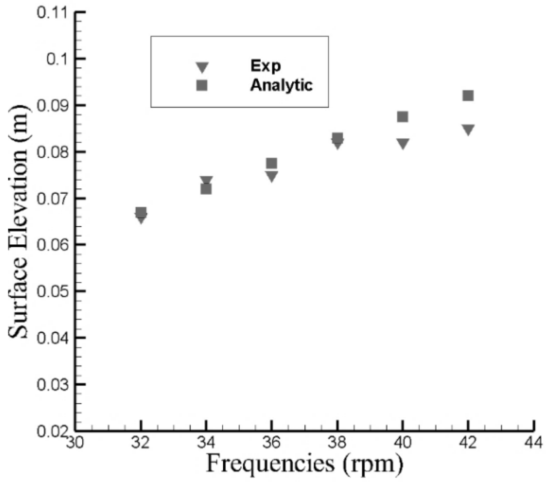


Figure 7 - Validating the wave height outside the OWC for the draft depth of 5 cm

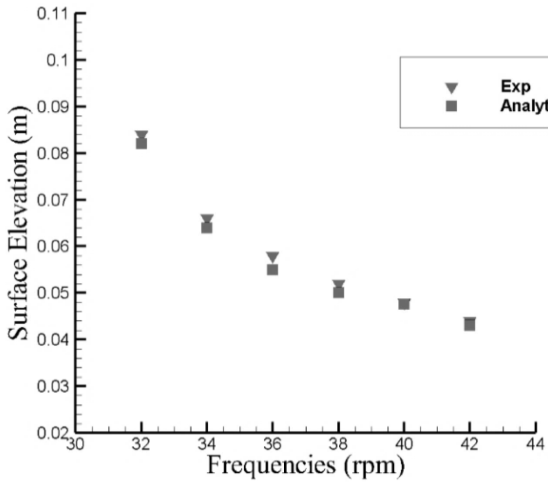


Figure 8 - Validating the wave height inside the OWC for the draft depth of 15 cm

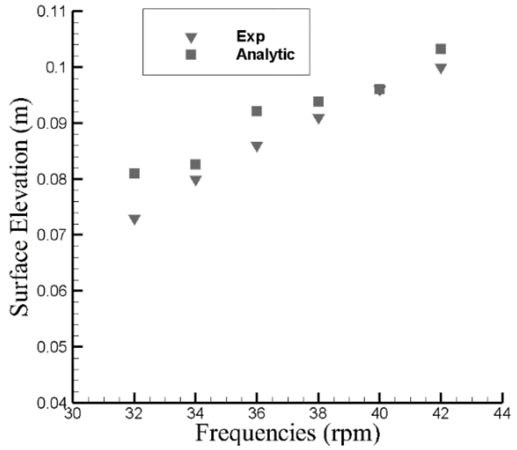


Figure 9 - Validating the wave height outside the OWC for the draft depth of 15 cm

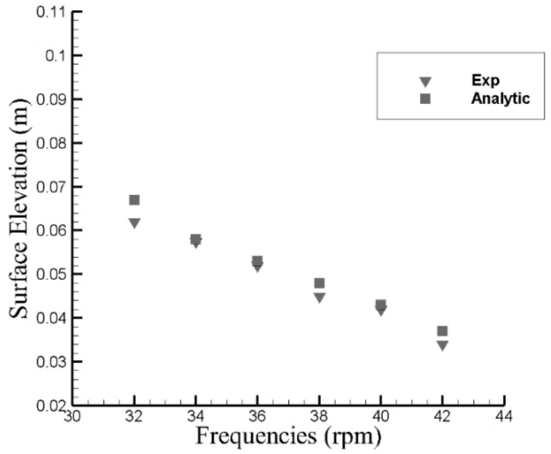


Figure 10 - Validating the wave height inside the OWC for the draft depth of 25 cm

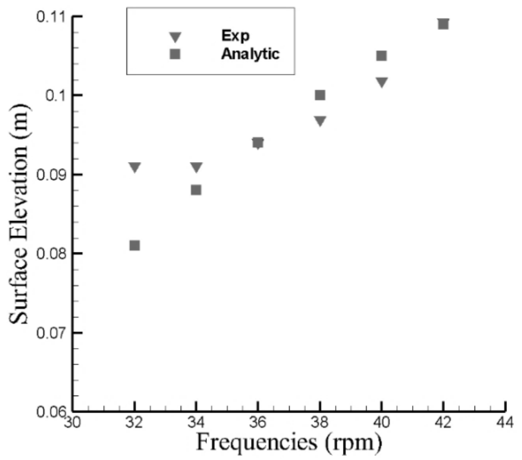


Figure 11 - Validating the wave height outside the OWC for the draft depth of 25 cm

4.2. Results of the Analytical Solutions of OWC in Lab-Scale

Figure 12 to Figure 14 illustrates the effect of different frequencies (32 to 42 rpm) on free surface fluctuations in OWC and wave-tank; These results were obtained for drafts of 5, 15, and 25 cm, respectively. As has been illustrated, the increase in frequency leads to a

Table 3. Average error rate

Parameter	Error
Error at the draft depth of 5cm inside the OWC	5.55
Error at the draft depth of 5cm inside the wave-tank	3.95
Error at the draft depth of 15cm inside the OWC	2.92
Error at the draft depth of 15cm inside the wave-tank	4.27
Error at the draft depth of 25cm inside the OWC	4.79
Error at the draft depth of 25cm inside the wave-tank	3.71

.

Slightly rise in the amplitude of the wave in the wave tank, and the cause of growth can be investigated in the dispersion relation, given this relationship, the increase in frequency has increased the wavenumber and finally it can lead to a rise in wave height. However, when the frequency increases, the period will decrease, and the free surface tends to move to trough before reach to the crest. In Figure 15, the changes in the velocity of the free surface by time in m/s and second has shown, the diagram illustrates the velocity and time for three different drafts. It is noticeable that the increase in frequency and draft lead to a slight fall in the period. Therefore, the velocity will decrease gradually. Considering the analytical solution, whereas the velocity reduced at the free surface, the flow rate in orifice declines because of the continuity equation; therefore, the power will drop dramatically.

On the other hand, the rise in water draft and frequency leads to compression in line graphs, which is noticeable in Figure 15. In Figure 16 the graph shows changes in power by time in kilowatt and seconds respectively, the main facts that stand out are that in low frequencies rise in frequencies causes a significant increase in power, however, in high frequency, the changes are not noticeable. It is important to note that when both parameters (frequency and draft) rise, the power decreases slightly.

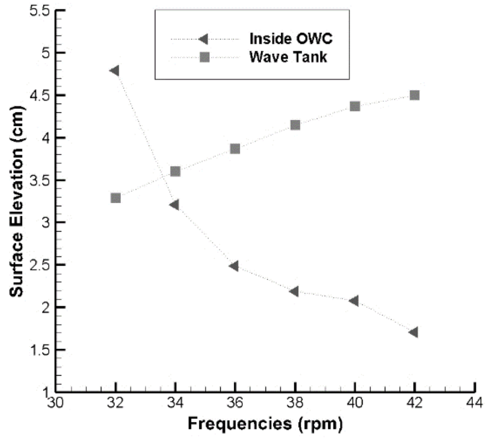


Figure 12 – Wave height inside the OWC and wave-tank with the draft depth of 5 cm

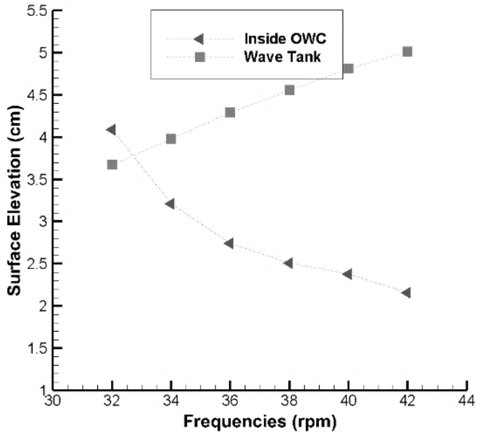


Figure 13 - Wave height inside the OWC and wave-tank with the draft depth of 15 cm

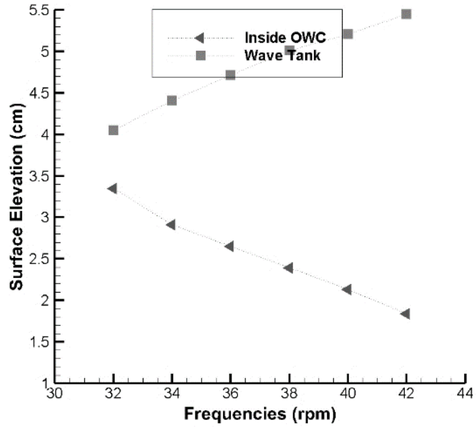


Figure 14 - Wave height inside the OWC and wave-tank with the draft depth of 25

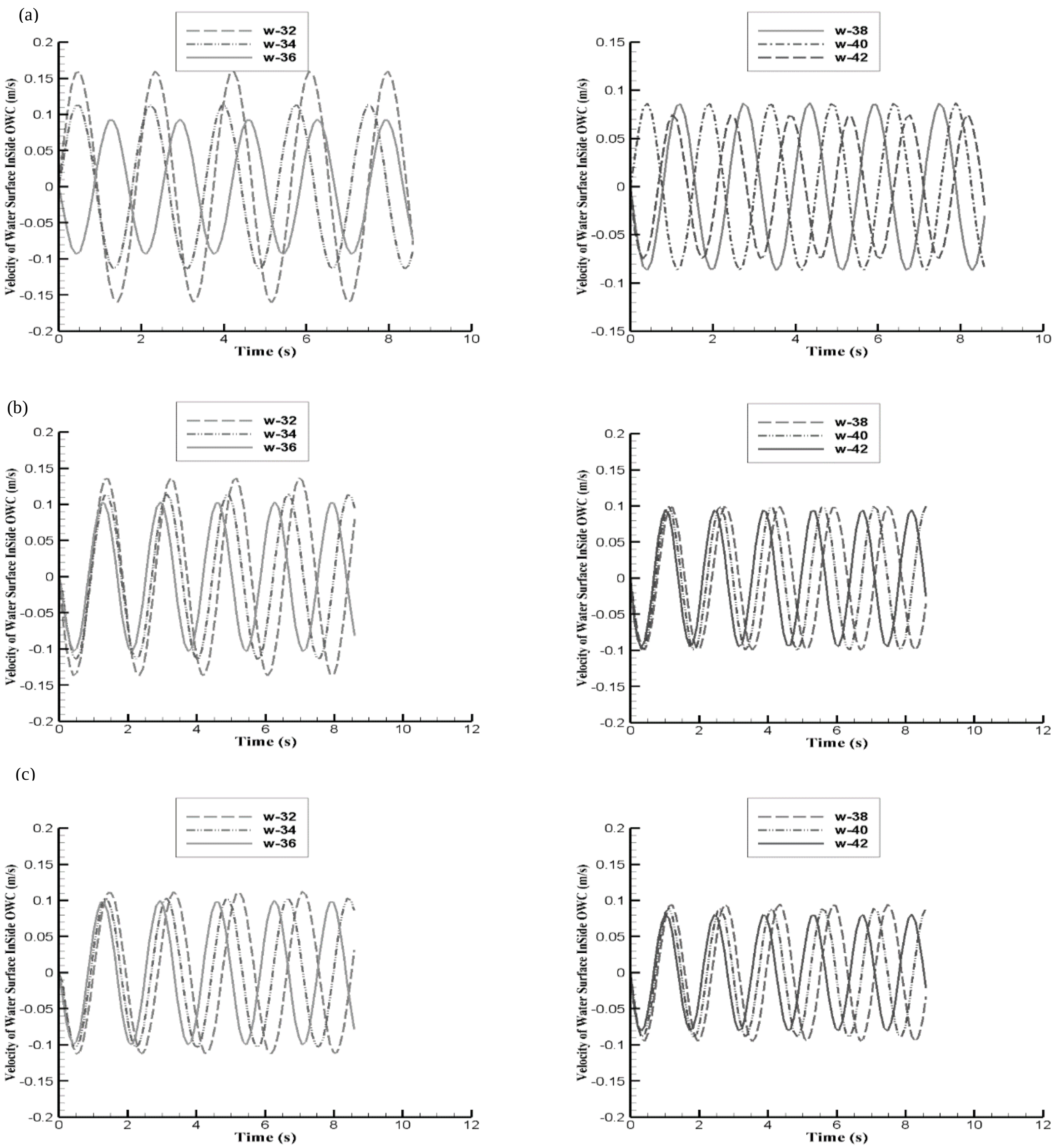
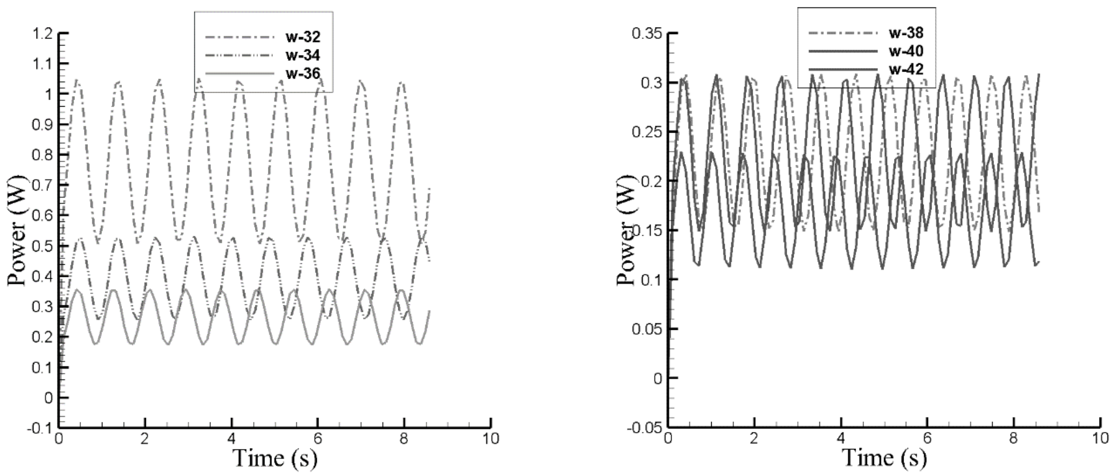
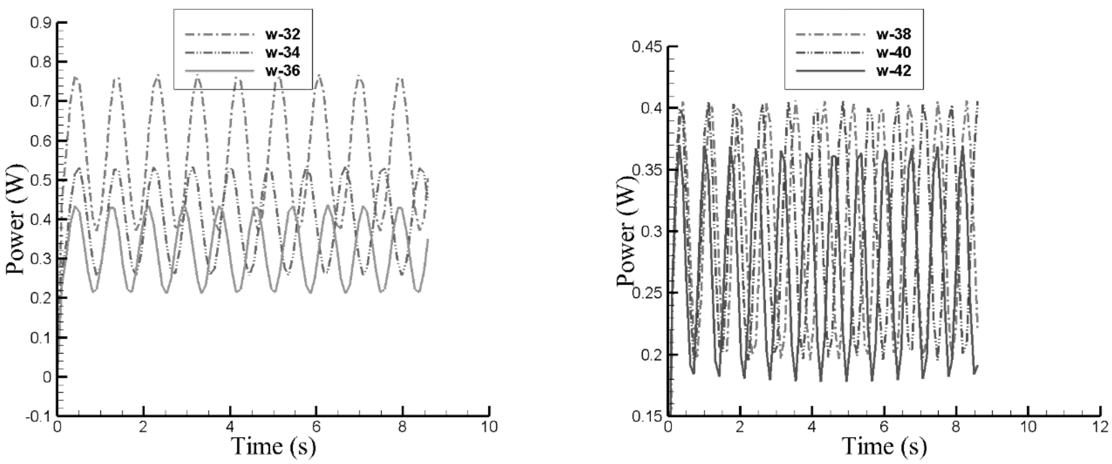


Figure 15 – Water free-surface velocity inside the OWC at the draft depth of a) 5cm b) 15cm c) 25cm for various frequencies by time

(a)



(b)



(c)

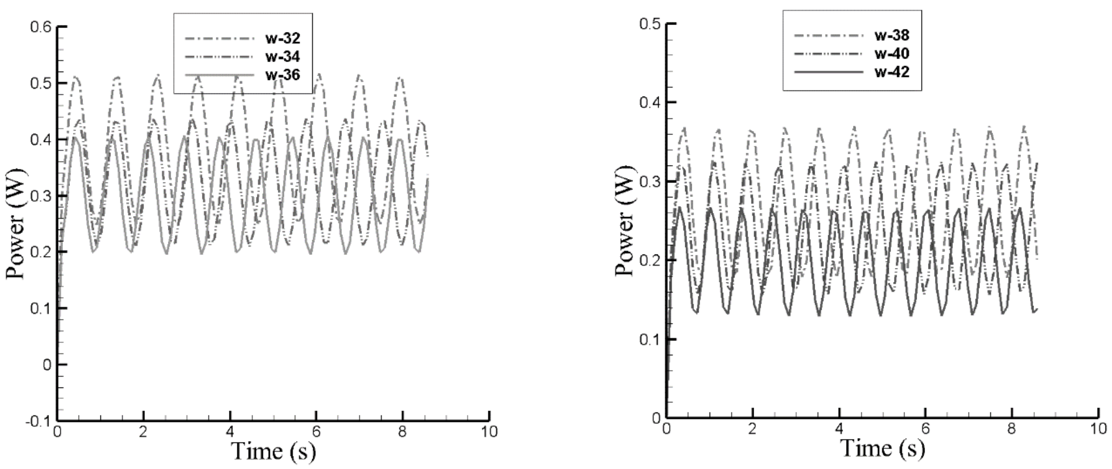


Figure 16 – Output power of the OWC at the draft depth of a)5cm b)15cm c)25cm for various frequencies by time

4.3. Characteristics of the prototype model of the OWC

In this section, the results of the prototype model obtained by applying the Froude scaling method. The mentioned method would implement in problems that the viscous effects are negligible, especially for wave energy converters. Therefore, according to the validation performed, it was found that considering the fluid as an ideal flow or, in other words ignoring the viscosity, the error rate has an acceptable value. As a result, Froude scaling method can also be a fair scheme to obtain energy conversion in the prototype. Table 4 demonstrates the crucial data of the 1:10 scale OWC in the prototype size; as it has calculated, the prototype would generate 2.45-kilowatt electricity on average at 50cm draft. In Figure 17, the changes in the power of the OWC by β and frequency illustrated, as it is noticeable, β increase leads to a gradual decrease in power. Figure 18 demonstrates the changes in the transmitted wave height of the OWC by dimensionless frequency since the frequency rise causes a reduction in the free surface fluctuation of the OWC then it can drop the transmitted wave height. In Figure 19, the variation of the captured wavelength ratio by transmitted wave height showed, growth in capture wavelength ratio would increase the transmitted wave height of the OWC because the energy of the wave is dependent on wavelength and rise in wavelength tend to increase in wave amplitude in the OWC.

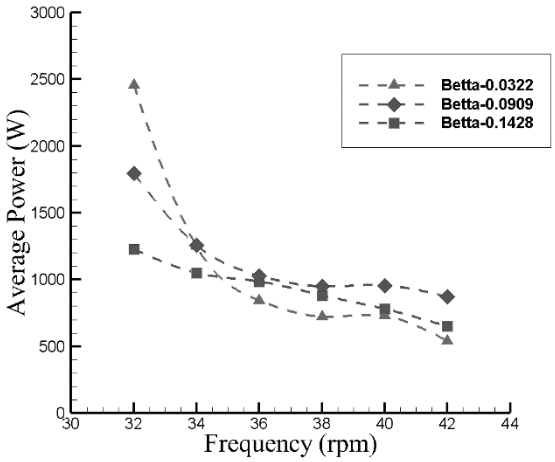


Figure 17 – Prototype average power change by frequency

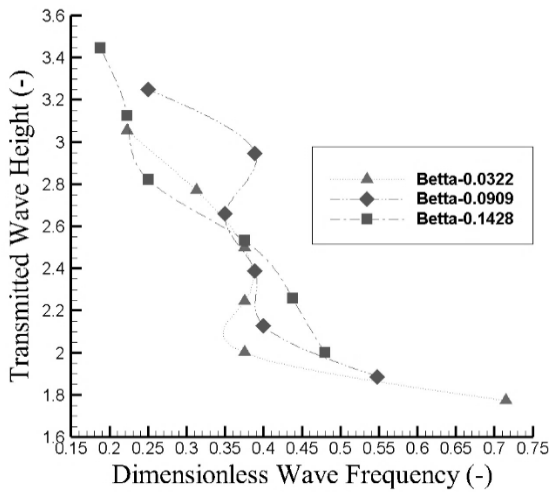


Figure 18 – Prototype transmitted wave height variation by dimensionless frequency

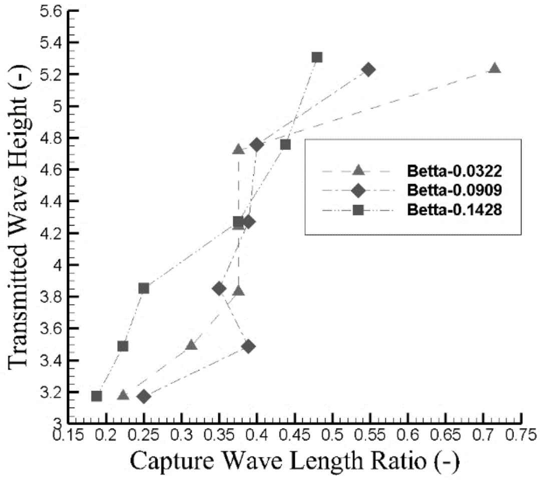


Figure 19 - Change of transmitted wave height with capture wavelength ratio

Table 4. Comparing the model with the prototype

Parameter	model	prototype
Orifice maximum velocity at the draft depth of 5cm [m/s]	2.14	6.8
Orifice maximum velocity at draft depth of 15cm [m/s]	1.83	5.8
Orifice maximum velocity at draft depth of 25cm [m/s]	1.5	4.74
Wave height inside the OWC at the draft depth of 5cm [cm]	4.8	48
Wave height inside the OWC at the draft depth of 15cm [cm]	4.09	40.9
Wave height inside the OWC at the draft depth of 25cm [cm]	3.35	33.5
Mean power at the draft depth of 5cm [W]	0.78	2466.6
Mean power at the draft depth of 15cm [W]	0.57	1802.5
Mean power at the draft depth of 25cm [W]	0.39	1233.3

5. Conclusion

In this paper, a 1:10 scale oscillating water column is experimentally and analytically investigated according to the conditions of the Caspian Sea wave characteristics. The analytical solution of the OWC was carried out by implementing the potential function and measuring the velocity at the orifice of the oscillating water column experimentally in the wave-tank of the Sea-Based Energy Research Group of the Babol Noshirvani University of Technology. By driving the potential solution, the free surface fluctuations were calculated, and the results were compared with the experimental data, and the results showed good agreement with experimental data.

Each test was performed five times due to achieving reliable results and by applying uncertainty analysis. In these experiments, the free surface fluctuations of the water inside the OWC and Wave-tank and the velocity of the orifice outflow were measured experimentally. A total of 270 data were collected and categorized to evaluate the most reliable results. According to the studies carried out, the following main results were obtained:

- In this study, it was found that increasing the draft depth of the OWC leads to a slight decrease in OWC power generation. Although the frequency of the wave increases as the wave height outside the oscillating column increases, it reduces the oscillation of the wave inside the oscillating water column and decreases the output power.
- The system was also investigated by Froude scaling method, which showed that at low frequencies for different β¬s the average power was measured at 2453 watts, 1794 watts and 1230 watts respectively, and increasing draft depth cause reduction in power generation.
- Due to the size of the oscillating water column, the best operation condition has found in 5 cm draft depth and 32 rpm.

In the future, geometrical parameters for improving the performance of the system can also be investigated, and the system can be modeled by CFD packages to determine the accuracy of the CFD results by comparing with the experimental data; also the best turbine damping coefficient and orifice diameter can be an important subject to investigate.

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7. References

1- LÓPEZ, I., ANDREU, J., CEBALLOS, S., DE ALEGRÍA, I. M. and KORTABARRIA, I.,(2013), *Review of wave energy technologies and the necessary power-equipment*, Renewable and sustainable energy reviews, 27, p. 413-434.

2- AMIRI, H. A., SHAFAGHAT, R., ALAMIAN, R., TAHERI, S. M. and SHADLOO, M. S.,(2019), *Study of horizontal axis tidal turbine performance and investigation on the optimum fixed pitch angle using CFD,* International Journal of Numerical Methods for Heat & Fluid Flow.

3- FALCÃO, A. F., HENRIQUES, J. C., GATO, L. M. and GOMES, R. P.,(2014), *Air turbine choice and optimization for floating oscillating-water-column wave energy converter,* Ocean Engineering, 75, p. 148-156.

4- ANTONIO, F. D. O.,(2010), *Wave energy utilization: A review of the technologies,* Renewable and sustainable energy reviews, 14(3), p. 899-918.

5- HEATH, T.,(2012), *A review of oscillating water columns*, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 370(1959), p. 235-245.

6- GROVE-PALMER, C.,(1982), in *Proceedings of the 2nd International Symposium on Wave Energy Utilization*. p. 22-24.

7- FALCÃO, A. F. and HENRIQUES, J. C.,(2016), *Oscillating-water-column wave energy converters and air turbines: A review,* Renewable Energy, 85, p. 1391-1424.

8- WHITTAKER, T., MCILWAINE, S. and RAGHUNATHAN, S.,(1993), in *Proceedings of First European Wave Energy Symposium*. National Engineering Laboratory East Kilbride, p. 283-286.

9- SUZUKI, M., ARAKAWA, C. and TAKAHASHI, S.,(2004), in *The Fourteenth International Offshore and Polar Engineering Conference*. International Society of Offshore and Polar Engineers.

10- SHENG, W., ALCORN, R. and LEWIS, A.,(2013), *On thermodynamics in the primary power conversion of oscillating water column wave energy converters,* Journal of Renewable and Sustainable Energy, 5(2), p. 023105.

11- EVANS, D.,(1982), *Wave-power absorption by systems of oscillating surface pressure distributions,* Journal of Fluid Mechanics, 114, p. 481-499.

12- WEHAUSEN, J. V. and LAITONE, E. V.,(1960), *Encyclopedia of Physics, Vol. IX,* Fluid Dynamics III, Springer-Verlag, Berlin.

13- SARMENTO, A. J. and FALCÃO, A. D. O.,(1985), *Wave generation by an oscillating surface-pressure and its application in wave-energy extraction,* Journal of Fluid Mechanics, 150, p. 467-485.

14- JEFFERYS, R. and WHITTAKER, T., (1986), in *Hydrodynamics of Ocean Wave-Energy Utilization,* Ed^Eds, Springer, p. 281-291.

15- WEBER, J. and THOMAS, G.,(2001), in *The Eleventh International Offshore and Polar Engineering Conference*. International Society of Offshore and Polar Engineers.

16- WANG, D., KATORY, M. and LI, Y.,(2002), *Analytical and experimental investigation on the hydrodynamic performance of onshore wave-power devices,* Ocean Engineering, 29(8), p. 871-885.

17- HONG, D., HONG, S. and HONG, S.,(2004), *Numerical study on the reverse drift force of floating BBDB wave energy absorbers,* Ocean Engineering, 31(10), p. 1257-1294.

18- SUROSO, A.,(2005), *Hydraulic model test of wave energy conversion,* Jurnal Mekanikal, (19), p. 84-94.

19- NAGATA, S., *et al.*,(2011), in *Proceedings of the 9th European Wave and Tidal Energy Conference*. p. 5-9.

20- ŞENTÜRK, U. and ÖZDAMAR, A.,(2012), *Wave energy extraction by an oscillating water column with a gap on the fully submerged front wall,* Applied Ocean Research, 37, p. 174-182.

21- MALARA, G. and ARENA, F.,(2013), *Analytical modelling of an U-Oscillating Water Column and performance in random waves,* Renewable Energy, 60, p. 116-126.

22- CASHMAN, D. P., O'SULLIVAN, D. L., EGAN, M. G. and HAYES, J. G.,(2009), in *Proceedings of 8th European Wave and Tidal Energy Conference*. p. 924-933.

23- KAMATH, A., BIHS, H. and ARNTSEN, Ø. A.,(2015), *Numerical modeling of power take-off damping in an oscillating water column device,* International Journal of Marine Energy, 10, p. 1-16.

24- NING, D.-Z., WANG, R.-Q., ZOU, Q.-P. and TENG, B.,(2016), *An experimental investigation of hydrodynamics of a fixed OWC Wave Energy Converter,* Applied energy, 168, p. 636-648.

25- CHANG, C.-Y., CHOU, F. N.-F., CHEN, Y.-Y., HSIEH, Y.-C. and CHANG, C.-T.,(2016), *Analytical and experimental investigation of hydrodynamic performance and chamber optimization of oscillating water column system,* Energy, 113, p. 597-614.

26- ÇELIK, A. and ALTUNKAYNAK, A.,(2018), *Experimental and analytical investigation on chamber water surface fluctuations and motion behaviours of water column type wave energy converter,* Ocean Engineering, 150, p. 209-220.

27- ALAMIAN, R., SHAFAGHAT, R., HOSSEINI, S. S. and ZAINALI, A.,(2017), *Wave energy potential along the southern coast of the Caspian Sea,* International Journal of Marine Energy, 19, p. 221-234.

28- ALAMIAN, R., SHAFAGHAT, R. and SAFAEI, M. R.,(2019), *Multi-objective optimization of a pitch point absorber wave energy converter,* Water, 11(5), p. 969.

29- ALAMIAN, R., SHAFAGHAT, R., MIRI, S. J., YAZDANSHENAS, N. and SHAKERI, M.,(2014), *Evaluation of technologies for harvesting wave energy in Caspian Sea,* Renewable and sustainable energy reviews, 32, p. 468-476.

30- DEAN, R. G. and DALRYMPLE, R. A.,(1991), *Water wave mechanics for engineers and scientists*, World Scientific Publishing Company, vol. 2.

31- SHALBY, M., WALKER, P. and DORRELL, D. G.,(2016), in *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*. IEEE, p. 183-188.

32- SHALBY, M., WALKER, P. and DORRELL, D. G.,(2017), *Modelling of the multi-chamber oscillating water column in regular waves at model scale,* Energy Procedia, 136, p. 316-322.

33- EBRAHIMPOUR, M., SHAFAGHAT, R., ALAMIAN, R. and SAFDARI SHADLOO, M.,(2019), *Numerical investigation of the savonius vertical axis wind turbine and evaluation of the effect of the overlap parameter in both horizontal and vertical directions on its performance,* Symmetry, 11(6), p. 821.