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Installation Depth and Incident Wave Height Effect on Hydrodynamic Performance of a Flap Type Wave Energy Converter: Experimental Analysis

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ABSTRACT

The effect of installation depth and height of the incident wave on the hydrodynamic and economic performance of an oscillating wave surge converter (OWSC) wave energy converter is crucial. In this study, an OWSC by considering 1:8 scale has been studied under Caspian Sea wave conditions for 8 water depths from the semi-submerged to fully submerged. The study has been conducted to achieve the best draft ratio and evaluate the systems performance imposed to Caspian waves condition by experimantal method.The results are presented in three parts. The first part studied the converter's flow, power, and sensitivity to the installation depth on a laboratory scale. In the second part, the system results were converted to the main scale 1:8 by using Froude scaling method, and finally, the performance from an economic view evaluated. Results showed that the draft depth has a non-linear effect on the power. System's power in the dimensionless draft depth of 0.59 is better, and can produce 61 kW. Also, it can pump up to 50 l/s of water. Likewise, suppose the system is used for electricity generation, In that case, it sells $22500 of electricity to the grid annually, and if it is used as a pump, it can supply water to 4710 households on average.

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1. INTRODUCTION

Today, fossil fuel resources have increased due to the high rate of population growth and industry development. Fossil fuels can cause many problems like rising atmospheric carbon dioxide, global warming, and climate change [1]. Therefore, the development of technologies that can produce economical and clean energy from renewable energy sources has become one of the main goals of modern industrial societies. Renewable energy sources include wave energy, solar energy, wind energy, and geothermal energy. Ocean wave energy has a higher energy density than other energy sources. Global wave energy sources are estimated to be more than 1 TW [2].

Wave energy converters come in various designs and sizes that use a wide range of energy conversion techniques. Oscillating Wave Surge Converters (OWSC) is a type of wave energy converters with a higher theoretical efficiency due to oscillations in surge direction [2]. OWSC is designed for areas near the coast, with water depths between 10 and 20 meters [3]. The energy conversion chain in these converters has three stages; In the first stage, the flap is affected by the force of the wave, due to the oscillating motion of the flap, the wave energy is converted into mechanical energy; In the second stage, mechanical energy is converted to potential energy stored in the fluid by the power transmission system, and in the third stage, to convert the energy of the waves into electrical energy, the high-pressure fluid causes the turbine or hydraulic motor to move [3]. However, these converters are used only to pump seawater in some applications.

Folley et al. [4] experimentally investigated the effect of water depth on the performance of a 1:40 model of an OWSC. Henry [2] experimentally studied the performance of a 1:40 model of an OWSC based on

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different incident wave characteristics; The results showed that the maximum power occurs in a period of 10s. Gomes et al. [5] investigated an OWSC's hydrodynamics. Their parametric analysis for several configurations showed that the submerged flaps have a smaller excitation torque amplitude than the semi-submerged flaps. Xu et al. [6] conducted an experimental study on OWSC and the effect of wave conditions and water depth in both submerged and semi-submerged flap modes has been studied. Ning et al. [7] experimentally investigated the performance of a 1: 5 model of OWSC. The results showed that the efficiency of the converter is affected by the incident wave amplitude and increasing the amplitude reduces the converter performance. Chow et al. [8] showed that the use of fast cameras can be a good tool for measuring the hydrodynamic responses of a screen converter in experimental studies. Brito et al. [9] experimentally investigated the performance and hydrodynamic response of a 1:10 model of a regular-wave OWSC. Their results showed that the power transmission system, frequency and height of the incident wave have an important effect on the performance and hydrodynamic response of the OWSC.

A review of studies performed on OWSC showed that the studies done on the OWSCs have been based on the conditions of waves in the high seas, and this type of converter has not been studied for supplying water to households from an economic point of view; Therefore In this regard, in this paper, the performance of the converter under the effect of the world's largest lake (Caspian sea) with special and unique wave conditions (high frequency and low wave length) have been studied with two perspectives of electricity production and household water supply. On the other hand, considering the effect of installation depth (water draft depth) on the hydrodynamic performance of the converter, one of the important results presented in the literature is the importance of wave height in determining the appropriate installation depth. Therefore, in this paper, an OWSC wave energy converter with a scale of 1:8 under the effect of wave conditions of the Caspian Sea (with a shorter period and wavelength than the high seas) in the wave flume was experimentally investigated. In order to achieve the appropriate installation depth, the effect of water draft depth on the converter performance for all sea wave conditions was investigated. For better evaluation, water draft depth and wave frequency in each test were considered constant, and the effect of different wave heights (4 dominant heights of the Caspian Sea) on system performance was evaluated. The tests were repeated for 8 draft depths. Finally, to achieve a realistic assessment, the power and flow of the converter on a laboratory scale were converted to the main scale using Froud scaling method and the performance of the OWSC has been studied for two applications first annual energy production has been calculated and secound the system was considered as water supply pump and the household supply was determined.

2. System Description

This study evaluates an OWSC with rectangular cross section and hinges from below. The scale of the model is 1:8 and has been designed and built by the Sea-Based Energy Research Group at Babol Noshirvani University of Technology in Babol. This model includes a floating flap in the form of a rectangular cube with dimensions of 1.1 m in length, 1.2 m in width, and 0.25 m in thickness. The OWSC was placed on the centerline of the wave flume, 13 m from the wave-maker. To measure the wave height, level gauge sensors were installed at 1.2 m and 2.4 m from the converter (Figures 1 and 2). Experimental tests were performed for depths from 0.8 to 1.5 m, wave frequency is 0.4, and wave heights vary from 0.04 to 0.1 m. The OWSC was placed by two bearings on a holder base in the flume bed, and two beams were used as a support to prevent the base from separating from the flume bed. The power transmission system from a hydraulic circuit includes a hydraulic jack, check valves, plastic hoses and a water tank with a diameter of 0.16 m and a height of 0.25 m. The water tank is installed at a vertical distance of 5.5 meters from the pool bed. In order to observe and study the water level inside the water tank, a water index has been installed in the vicinity of the tank (Figure 3). The movement of the flap is converted to hydraulic energy by a pressurized fluid using a hydraulic jack, which pumps water into the tank and stores water in the tank.

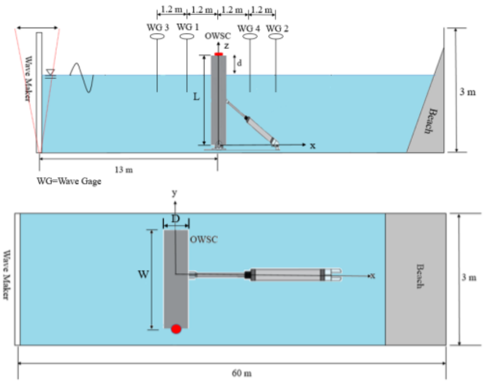
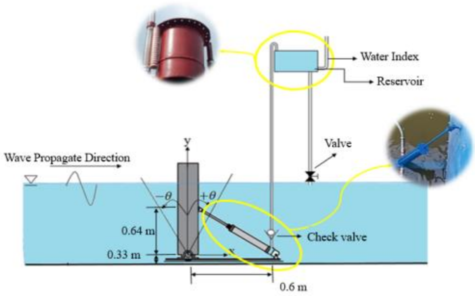


Figure 1. Schematic of a OWSC in a wave pool, Side view and Top view

Figure 2. Views of a 1: 8 scale OWSC wave energy converter made in a laboratory

(a)



(b)

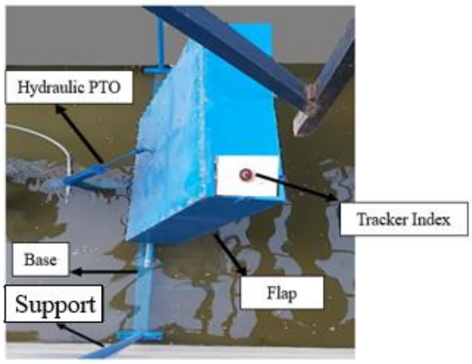


Figure 3. a) Schematic of power transmission system b) View of laboratory model including power transmission system

3. Experimental Modeling

The equation for wave maker is in Equation 1 was used to calculate the power of the page converter [10-13].

$$P_{OWSC} = \frac{1}{T}\int_{t}^{t+T} (P.Q)dt \qquad (1)$$

Q is the flow rate in the hydraulic circuit, and P is the pressure in the cylinder chamber. Equations 2 and 3 were used to calculate the flow in the hydraulic circuit.

$$\dot{L} = \frac{L}{\Delta t} \qquad (2)$$

$$Q = \dot{L} \times (A_1 + A_2) \qquad (3)$$

L is the variation in height of the water level inside the tank and $\boldsymbol{\Delta t}$ is time for a variation. The variation in height can be measured using a water index installed next to the tank. $\boldsymbol{A_1}$ is the cross section of the tank and $\boldsymbol{A_2}$ water index area.

To check the sensitivity of the system to the incident wave, the difference between the maximum power and flow should be calculated. For this purpose, the following equation is used.

$$\Delta P_{max} = P_{max} - P_{min} \qquad (4)$$

$$\Delta Q_{max} = Q_{max} - Q_{min} \qquad (5)$$

In equations 4 and 5, P_{max} and P_{min} is maximum power and minimum power in each draft ratio, and Q_{max} and Q_{min} is maximum flow and minimum flow in each draft ratio. In order to study the system's performance in a year, annual energy production in each draft ratio has been calculated as followings:

$$draft\ ratio = \frac{d}{h} \qquad (6)$$

$$AEP = \sum_{i=1}^{j}\sum_{i=1}^{j} Pa_{ij} \qquad (7)$$

In equation 6, d is draft and h is the water depth. AEP is annual energy production in MWh and a_{ij} is the wave scatter diagram hours and P is the Power.

The variables used in the equations are shown in Figure 4.

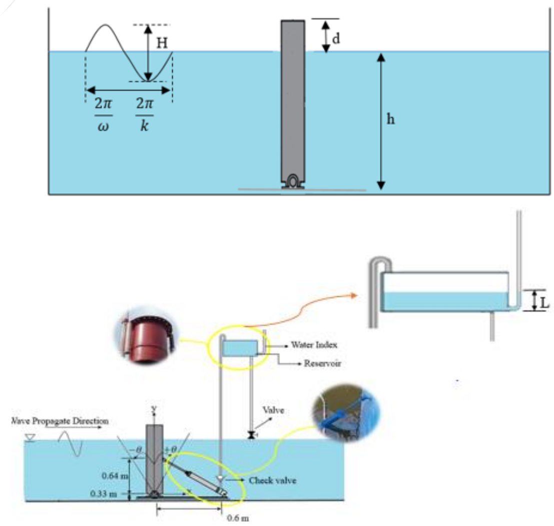


Figure 4. Schematic of the variables used in the equations

4. Laboratory Equipment and Data Collection

The wave flume of the Sea-Based Energy Research Group at Babol Noshirvani University of Technology in Babol was used for experimental tests (Figure 5). This flume's length, width, and height are 33 meters, 3 meters, and 3 meters. This pool can generate regular waves in a wide range of height and wave period characteristics. The US-100 ultrasonic sensor was used to measure wave heights (the uncertainty analysis of the system discussed in literature [10-14]) and the Arduino board was used to process it. Also, a webcam was used to measure the height of water in the water tank in order to calculate the water flow rate in the hydraulic circuit (Figure 6 and Table 1).

Figure 5. Wave, wave flume and damper pool view in the Marine Energy Research Group

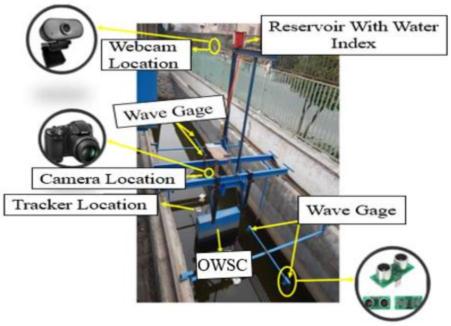


Figure 6. Location of measuring equipment

TABLE 1. Measuring devices information

Equipping measurement	Accuracy	picture
US-100 sensor	Detection range: 2 to 450 cm Measurement error: 1 mm	
Webcam ROTEL-RW120	Video recording speed: 30 frames per second	

5. RESULTS AND DISCUSSIONS

The results of the experimental study in this paper are presented in three parts. In the first part, the experimental results of the incident wave conditions and water draf depth on flow, pressure, and power were presented. In the second part, all the results in the prototype scale were given, and the effect of the incident wave conditions on the performance of the OWSC in the main scale was also shown. Finally, in the last part, the annual energy production of the converter on the prototype scale and water pumping system was studied.

5.1. Lab Scale Results

The Figure 7 shows the effect of water draft depth on the flow rate of the converter for all wave heights. As shown in the figure, increasing the wave height increase the output flow of the PTO, and increasing the draft depth from the lowest draft depth to the fully submerged state can cause a nonlinear (parabolic) behavior in the converter. Increasing the draft depth to a certain value can increase the output flow of the system. However, the system will decrease the flow rate after passing the dimensionless draft depth value of 0.59 .

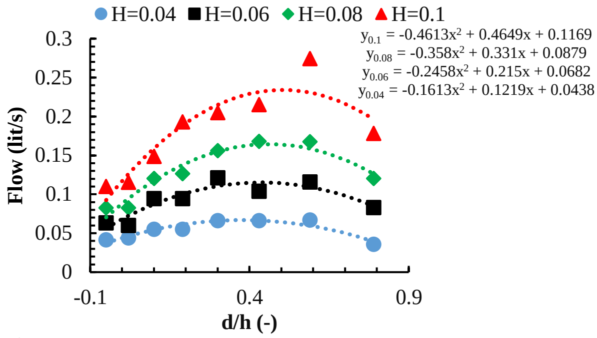


Figure 7. Depth ratio effect on the flow rate

Figure 8 shows the effect of water draft depth on the output power of the converter for all wave heights. As observed in the figure, increasing the draft depth increases the output power of the converter first and then decreases it, so the draft depth has a nonlinear effect on the output power of the converter. The converter has the maximum power at dimensionless water draft depth of 0.59, as the water draft depth decreases, the power of the converter decreases due to the decrease in the acceleration of the converter due to the increase in the added mass; Also, with an increase in the water draft depth, the power of the converter decreases due to the decrease in the torque of the wave. Also, the power results showed that increasing the wave height increases the output power of the converter. In fact, when the wave collides with the converter at a higher altitude, the wave is more energetic and causes more power output. Another point that should be considered in the tests is the effect of incident wave conditions on the sensitivity of the OWSC performance for different draft depths.

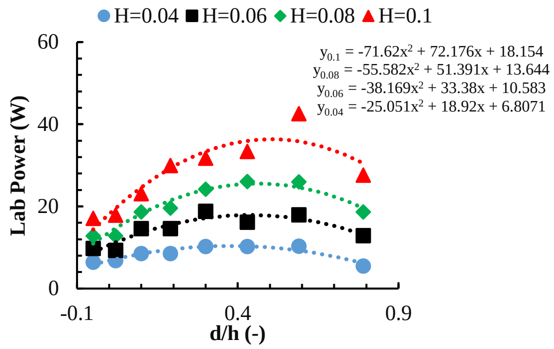


Figure 8. Depth ratio effect on power

To show the sensitivity of converter to incident wave conditions, the ΔP_{max} and ΔQ_{max} have been calculated and showed in Figure 9. As it is clear from this diagram, the system is less sensitive to the incident wave at low dimensionless water draft depth. With an increase in dimensionless water draft depth, the system becomes more sensitive to the incident wave, and by reaching the dimensionless water draft depth of 0.59, and after passing this value, the system's sensitivity to the incident wave decreases. In fact, in this diagram, we can see the importance of choosing the right dimensionless water draft depth on the hydrodynamic performance of the OWSC. Adjust the right draft depth in all wave conditions can increase the power and flow.

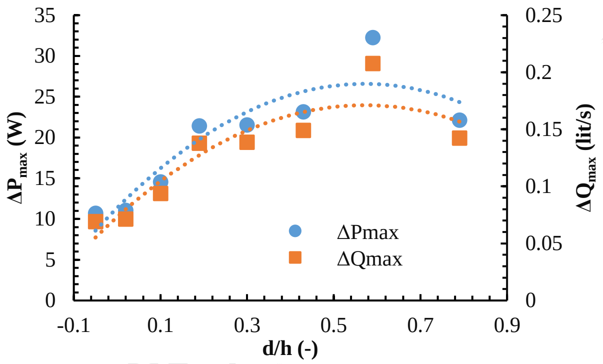


Figure 9. Depth ratio effect on ΔP_{max} and ΔQ_{max}

5.2. Full Scale Results

By Froud scaling method, the power of the laboratory scale OWSC can convert to the power of the prototype scale; Given that the model scale is 1:8, Figure 10 shows the effect of water draft depth on power for all wave heights, as shown in the figure below, the system in optimized draft ratio produces 61.7 kW, and if it is in a fully submerged state, the power drops to 24.8 kW, and if it is in the lowest submerged state, the power decreases to 40.1 kW. In fact, it can be said that if the system is located at a better water draft depth, its performance will increase significantly. Also, the behavior of the diagram shows that with increasing the height of the incident wave, the power will increase so that the OWSC power at the best water draft depth for the maximum wave height is 4.11 times more than the lowest wave height (considering the amplitude of wave height in Caspian Sea). Also, the converter's performance is not affected much at low wave height from the draft depth, but with an increase in wave height, the converter performance is greatly affected by the draft depth.

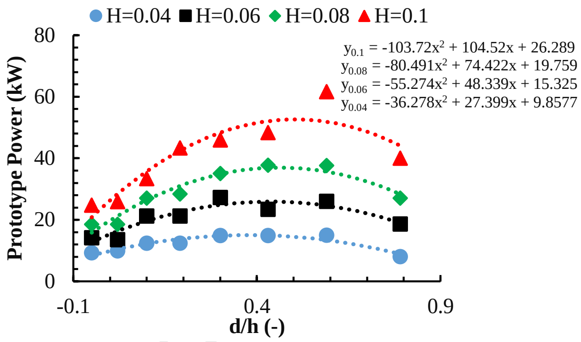


Figure 10. Depth ratio effect on prototype power

To investigate the effect of water draft depth on the OWSC behaviour, numerical derivation was performed for OWSC power in each water draft depth at any given wave height; The results can be seen in Figure 11, as shown in the figure below. In 0.59 draft ratio the derivative is zero, which indicates that the converter is at its extreme point. For all wave heights, the power derivative at dimensionless water draft depth reaches 0.59 to zero and tests is in best performance at this point. The second point to be considered in this diagram is that when the system is in a fully submerged state, its performance is very low. Immediately after passing the fully submerged state, it experiences a sudden increase in power; therefore, the power derivative is very high in that water draft depth.

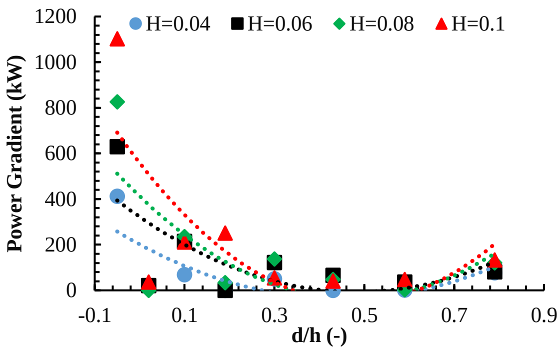


Figure 11. Power gradient with depth ratio in each wave height

5.3. Economic Results

Due to the fact that the conditions of the sea waves change during the day and night, the annual energy production of wave energy converter should be considered; The annual energy production in terms of MWh for all depths of the draft ratio is shown in Figure 12. The state of optimal draft ratio system can produce

878 MWh of power per year. If system is fully submerged, it produces only 406 MWh of power. Considering that the purchase price of electricity in Iran is $0.026 per kWh, the optimal system can sell $22500 of electricity per year. In other words, system optimization can sell $12095 more electricity per year compared to the maximum performance before optimization.

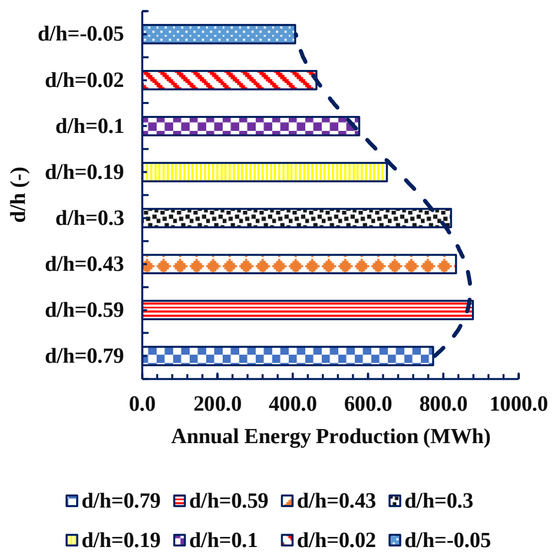


Figure 12. Annual energy production with draft ratio

The electricity sell to the grid for each draft ratio is shown in Figure 13.

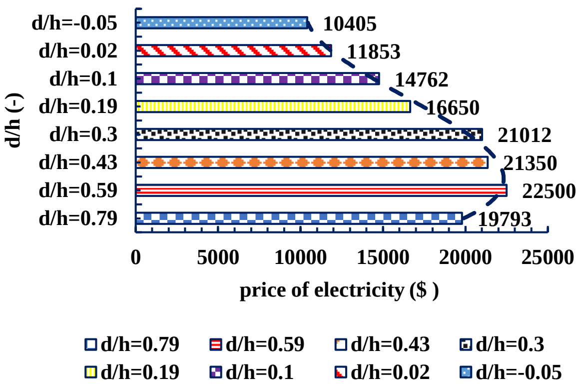


Figure 13. Electricity sell to the grid for each draft ratio

Another application that can be considered for the OWSC converter is water pumping to water supply systems, so in the following figure, with the help of Froude scaling, it was converted to prototype-scale flow; As can be seen from the figure below (Figure 14), if the system is installed at an optimal water draft depth, it can provide a maximum water flow rate of 50 liters per second and a minimum water flow rate of 12 liters per second. Also, if the performance of the system in the fully submerged state is compared with the optimal semi-submerged state, it can be concluded that the system in the semi-submerged state pumps 158% more flow.

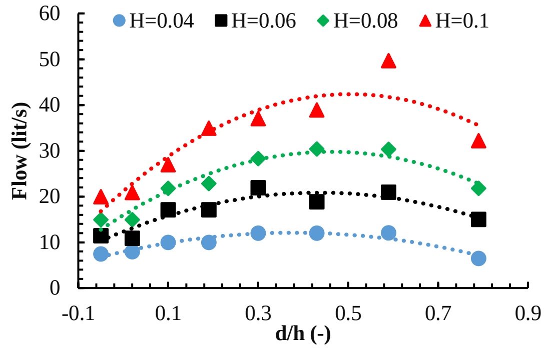


Figure 14. Depth ratio effect on prototype flow

In designing water supply systems for each household of 3 people, 0.6 liters per second of water can be considered. Therefore, Figure 15 shows the performance of the system to meet the water demand of households. As can be seen from the figure below, if the system is installed at an optimal water draft depth, 8,279 households are supplied for the maximum wave height, also, if the system is installed at an optimal water depth, 1078 households will be supplied at the lowest wave height.

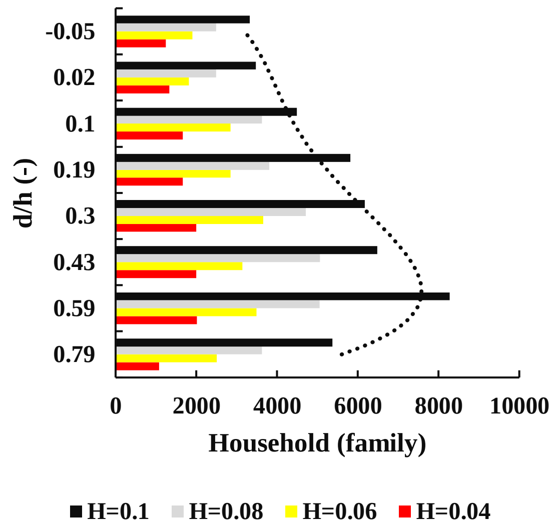


Figure 15. Depth ratio effect on water supply household

Due to the fact that the height of the waves changes during the day and night and is not constant, the water consumption for the household at each water draft depth was averaged from wave height of 0.4 m to 1 m and the effect of the system at each water draft depth to supply water consumption of household on average is shown in Figure 16, as can be seen from the diagram below, system in best draft ratio can supply water 210% more than fully-submerge state.

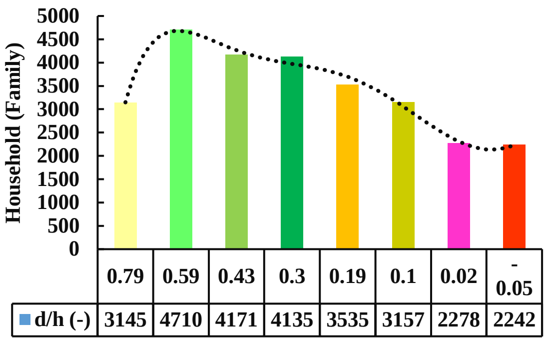


Figure 16. Depth ratio effect on average water supply household

6. CONCLUSIONS

In this paper, the effect of incident wave conditions and installation depth on the power and flow of the OWSC was investigated experimentally. For this purpose, an OWSC converter was constructed and tested in the Sea-Based Energy Research Group of Babol Noshirvani University of Technology in Babol. The installation depth is presented as the dimensionless draft ratio for experimental modeling and determining the optimal depth. The converter operated at a constant frequency of 0.4 Hz for 8 water intakes and 4 wave heights. The results of the experimental study in this paper are presented in three parts. The first part presents the experimental results of the incident wave conditions and water draf depth on flow, pressure, and power. In the second part, all the results in the prototype scale were given, and the effect of the incident wave conditions on the performance of the OWSC in the main scale was also shown. Finally, in the last part, the annual energy production of the converter on the prototype scale and water pumping system was studied, the results obtained show:

- Increasing the height of the incident wave leads to an increase in power and flow of the PTO and also the effect of installation depth on the performance of the converter is non-linear so that at low draft depth converter performs weak and at high draft depth (fully-submerged) converter performance is also inappropriate
- The results showed that the sensitivity of the system to impact wave conditions is low in two modes and those two modes are low installation depth and high installation depth (submerged). If the installation depth is low or high, the system is less sensitive to the impact wave height, but when the system is at a water intake depth of 0.59, it is more sensitive to the wave height and produces more power by receiving a higher wave.
- The system at a depth of 0.59 can generate 878 MW of power annually, which according to the price of electricity in Iran, with this amount of power, the system sells 607228000 Rials of electricity to the grid annually.
- Suppose the system is also used as a pump for water supply. In that case, it can supply water for 3492 households of 3 people in the main scale for wave height of 0.4 (worst case) and for wave height of 1 meter (best case) for 8279 A three-person household will supply water, since the wave height varies around the clock, so on average the system can respond to 4710 households.
- The maximum values of the performance parameters of the converter are given in Table 2.

TABLE 2. The maximum values of the performance parameters of the converter

	Lab Scale	Full Scale
Power	42.6 W	61.7 kW
Water flow rate	0.3 lit/s	50 lit/s

7. List of symptoms

Symbols	
d	Draft (meters)
H	Incident wave height (meters)
h	Water depth (meters)
P	Power (W)
Q	Flow (cubic meters per second)
AEP	Annual Energy Production (MWh)

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تأثیر عمق نصب و ارتفاع موج فرودی بر عملکرد هیدرودینامیکی و اقتصادی مبدل انرژی موج مبدل موج نوسانی (OWSC)بسیار مهم است. در این مطالعه، یک OWSC با در نظر گرفتن مقیاس 1:8 در شرایط موج دریای خزر برای 8 عمق آب از نیمه غوطه‌ور تا کاملاً غوطه‌ور بررسی شده است. این مطالعه به منظور دستیابی به بهترین نسبت پیش نویس و ارزیابی عملکرد سیستم های تحمیل شده به شرایط امواج خزر به روش تجربی انجام شده است. نتایج در سه بخش ارائه شده است. بخش اول جریان، توان و حساسیت مبدل به عمق نصب را در مقیاس آزمایشگاهی مورد مطالعه قرار داد. در بخش دوم، نتایج سیستم با استفاده از روش مقیاس بندی فرود به مقیاس اصلی 1:8 تبدیل شد و در نهایت عملکرد از منظر اقتصادی مورد ارزیابی قرار گرفت. نتایج نشان داد که عمق پیشروی اثر غیرخطی بر توان دارد. قدرت سیستم در عمق کشش بدون بعد 0.59 بهتر است و می تواند 61 کیلو وات تولید کند. همچنین می تواند تا 50 لیتر در ثانیه آب پمپاژ کند. به همین ترتیب، فرض کنید این سیستم برای تولید برق استفاده می شود، در این صورت سالانه 22500 دلار برق به شبکه می فروشد و اگر به عنوان پمپ از آن استفاده شود می تواند به طور متوسط 4710 خانوار را آبرسانی کند.