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Research Article

STUDY OF THE OSCILLATING WATER COLOUMN (OWC) WHICH IS ONE OF THE MOST USED SYSTEMS IN CONVERTING WAVE ENERGY INTO ELECTRICAL ENERGY

Abdi Kükner *[1]

[1] Istanbul Technical University, Faculty of Naval Architecture and Ocean Engineering, İstanbul, Turkey
ORCID ID 0000-0002-3746-4445
kukner@itu.edu.tr

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* Corresponding Author
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ABSTRACT

The Oscillating Water Column (OWC) system converting wave energy to electrical power have been investigated. The theoretical analysis of the power generated by the wave energy system is presented. The system is considered as two-dimensional, linear boundary value problem. The system is simulated for the Marmara Sea where the significant wave height is 3.3 meters and the significant wave period is 7 seconds. Results of the theoretical analysis of the wave energy conversion system for Marmara Sea is presented.

Keywords: *Oscillating Water Column, Wave Energy, Wave Energy Conversion, Water Wave Generator, Marmara Sea, Wave Period*

1. INTRODUCTION

Nowadays electrical energy is one of the most required and not dispensed with a basic energy which is necessary to do routine works in our life. Unfortunately, during the conversion of most energies into the electrical power poisoned gases have been produced and other ecological damages have been occurred. These problems have been waiting for the scientists to be solved. Therefore, it is important to think about clean and economical conversation systems which do not damage the nature. Outgoing from this point, we are able to say that wave energy is one of the cleanest, renewable and unbounded energy source to convert into the electrical power. Hence it must be thought about wave energy as one of the alternative energy for the future.

Given the massive energy resources carried in the waves of Oceans, breakthroughs in marine energy technology are expected to enable this energy source to become a major renewable energy supply in the long term. With many contending marine energy devices under development in many countries, the race to prove the fundamental technology type is on. Meanwhile, assessment and mapping of wave energy resources is also underway in many countries to identify sites for deployment of the successful products.

There are a variety of different concepts for wave energy conversion. The devices are generally categorized by the method used to capture the energy of the waves, but can also be categorized by location and by the power take-off system. Method types are point absorber or buoy, surfacing following or attenuator oriented parallel to the direction of wave propagation, oscillating water column, oscillating wave surge converter, terminator (or possibly the new unestablished term quasi point absorber) oriented perpendicular to the direction of wave propagation, overtopping, submerged pressure differential.

Oscillating water column (OWC) systems are one of the most popular technologies for wave energy conversion (Şentürk and Özdamar, 2012; Zhang *et al.*, 2012; Heath, 2012). OWC generates energy from the rise and fall of water caused by waves in the ocean. This system uses a large volume of moving water as a piston in a cylinder. Air is forced out of the column as a wave rises and fresh air is drawn in as the wave falls. This movement of air forcing the air upwards through the air turbine. This pressure forces the turbine to spin, which is how the energy is harnessed by the waves. As the waves retreat, air enters back into the air chamber from the other side of the turbine. Several prototype scale OWCs have been constructed and operated with varying degrees of success over the last two decades. There are examples of shoreline, near-shore and breakwater devices in a number of countries.

Converting the energy from ocean waves into useable energy forms is not a new concept as the first related patent was filed in 1799 by Girard and Son and the first operating system, an oscillating water column (OWC), supplied a house with 1 kW in 1910 (Clement *et al.*, 2002; Morris-Thomas, 2007). However, the first serious studies into wave energy took place after the oil crisis in the 1970s and early1980s, where it started being considered as a possible source of power supply (Salter, 1974). Since then, the development of wave energy has gone through a cyclic process of phases of enthusiasm, disappointment and reconsideration. Although budgets have been cut and increased at various occasions, the research and development has persisted, resulting in a constant gain in experience and improved performance, which has brought commercial exploitation of wave energy closer than ever before (Clement *et al.*, 2002). Early theories for wave-energy devices related to the rigid-body models had been investigated by Evans (1976), Mei (1976), Newman (1976) and Budal and Falnes (1977). They provided useful and interesting theoretical results for such problems, both in two and three dimensions. An application of the rigid-body theory to a simple OWC model was provided by Evans (1978) and McCormick (1974) Despite the great variety of wave energy converters proposed since the pioneering works of Masuda, McCormick, Budal and Falnes and others, only very few devices have been deployed in real seas.

It is worth noting that, in most of the studies carried out so far, OWC converter can be considered into two parts. These are namely as the air turbine and the column that are investigated separately. In spite of the fact that the coupling between both plays a fundamental role in the performance of the system (Curran *et al.*, 1997). In effect, the turbine should ideally provide the pneumatic damping (pressure drop through the turbine) for the chamber to work at, or near, resonant conditions, and the chamber, in turn, should provide the amount of pneumatic power that maximizes the turbine output.

2. ANALYSIS OF THE SYSTEM

It is well known that the wave energy for a unit wide is given by:

$$E = \frac{1}{2}\rho g \zeta_a \lambda$$

where g is gravitational acceleration (m/sec^2), ρ is the density of water (kg/m^3), ζ_a is the half of the wave height (m) and λ is the wave length in meter.

In this study, our aim is to convert this wave energy as much as possible into the electrical energy. Naturally, there will be some energy lost during conversion because of the transportation, storing and friction. In order to keep this lost as low as possible, different kind of devices and theories related with these systems have been developed. One of these is the oscillating water column (OWC) system which is shown in Fig. 1. Theoretical analysis of the system has been studied by many scientists and researchers such as McCormick (1974). It is possible to determine this system by the linear theory, which is solutions are nearly to the nature.

The following given theoretical analysis for the wave energy conversion buoy consists of a circular floatation body which contains a vertical center column that has free communication with the sea. Hence, the water surface in the center of the column rises and falls with the same period as that of the external wave.

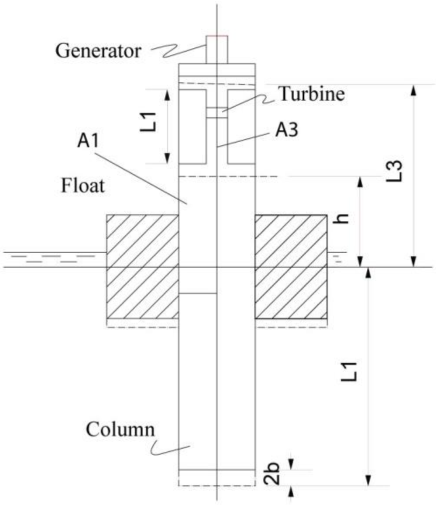

Fig. 1. Oscillating Water Column (OWC)

As is shown in Fig. 1., there is a circular ring around the column which keeps the system on the free surface. When the system moves up and down the air inside the column is compressed or decompressed by the motion of the wave. During the compression or decompression of the air it rotates the turbine propellers which are located on the top of the vertical column. Rotating direction of the propellers will be the same in either compression or decompression case. The air turbine, in turn, drives an electrical generator that produces an energy to be used directly or storage in collecting systems.

In this study, the linear theory presented by Mc Cormick (1974) was used to design a water wave generator for the Marmara Sea. Simulating wave energy for the Marmara Sea, the specific data is needed. It gives us the certain limits and the energy in Joule which was obtained from the paper given by Atkins (1996). By applying the unsteady energy equation between the internal free surface and the exhaust one obtains:

$$\frac{P_1}{\gamma_a}+\frac{\bar{V}_1^2}{2g}=\frac{\bar{V}_3^2}{2g}+\sum h_i+\frac{1}{g}\int_{\xi_1}^{\xi_3}\frac{\partial\bar{V}}{\partial t}\delta\xi+\frac{dW}{dw_a} \quad (1)$$

In this equation, the subscripts 1 and 3 show positions. Position 1 is the internal part of the column right over the water. Position 3 stands for the exhaust on the top of the column. Where P is pressure (kg/m^2), V is velocity (m/s), h is height (m), γ_a is specific weight of air (kg/m^3), t is time given in seconds, ξ is curvilinear coordinate system, W is energy (Joule), w_a is weight of air (kg).

After making some assumptions, details are shown in references (McCormick, 1974) and Bak (1999), one obtains the chamber pressureP_1 in the following form:

$$P_1=-\rho_w(L_1+\zeta)\frac{d^2\zeta}{dt^2} \quad (2)$$

where L_1 stands for the part of the column inside the water (m). ζ means the height of the water from its equilibrium position (m) and ρ_w mass density of the water (kg/m^3). Because of the specific geometry of the system, the added mass excited by the heaving circular floatation body can be written as

$$m_w=C\rho_w\pi(R-r_1)^3 \quad (3)$$

In which C stands for the added mass coefficient. R is the radius of the floatation and r_1 is the radius of the column. The natural circular frequency of the system is obtained by the following equation

$$w_N=\sqrt{\frac{c}{m+m_w-\rho_w\pi r_1^2 L_1}} \quad (4)$$

where c represents the hydrostatic restoring force (kg/s^2), which is given by

$$c=\rho_w g\pi(R^2-r_1^2) \quad (5)$$

Finally using this equation in order to get energy expression and take its derivative by time, the unit power for a second (known as Watt) is obtained. Thus, the final equation is found as

$$\frac{dW}{dt}=\rho_a\zeta\pi r_1^2 g\frac{dW}{dw_a}$$

$$=\rho_a\zeta\pi r_1^2 g\left\{\frac{P_1}{\gamma_a}-\left(\frac{1}{2g}\right)\left[\left(\frac{A_1}{A_3}\right)^2-1\right]\zeta^2-\right.$$
$$\left.\sum_i\delta_i\frac{d\zeta}{dt}\left|\frac{d\zeta}{dt}\right|\left[-\frac{1}{g}\right]\left[h+L_t\frac{A_1}{A_3}-\zeta\right]\frac{d^2\zeta}{dt^2}\right\} \quad (6)$$

where, A means the area (m^2), δ_i is the damping coefficient (s^2/kg), ρ_a is mass density of air (kg/m^3), L_t and h are lengths (m) as shown in Fig.1.

3. APPLICATION OF THE OSCILLATING WATER COLUMN SYSTEM TO THE MARMARA SEA

For the Marmara Sea, the significant wave height ($H_{1/3}$) can be taken as 3.3 meters and the significant wave period (Ts) as 7.0 seconds (Atkins, 1996). The following results are obtained by using these values and the water mass density of 1025 kg/m^3 for a system having the mass m=1200 kg and the added mass m_w=975 kg (taken from experimental result of buoy used by Masuda (1971). It should be noted that the added mass and the mass of a system depend on the size and the materials used on a system. The power variation as a function of wave period for a wave height at H=3.3 m is shown in Fig. 2.

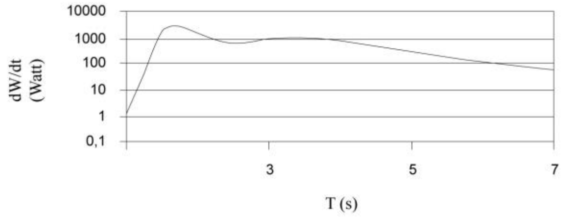

Fig. 2. Power variation as function of the wave period at a wave height H=3.3 m

As can be seen from Fig. 2, the maximum power appears at the wave period T=1.7 seconds. The most effective length of the underwater column is obtained by using this wave period. The result is shown in Fig. 3.

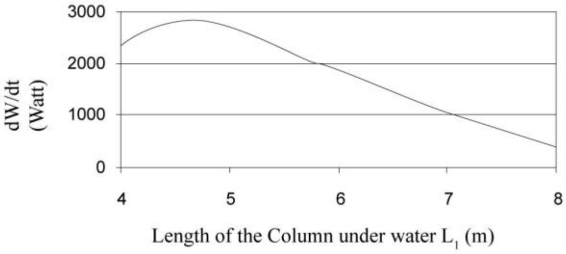

Fig. 3. Power variation of the underwater column-length at a wave period T=1.7 second

This graph can be put into a normalized peak average power variation curve by dividing power with the maximum value of the power variation for the underwater column-length at wave period T=1.7 seconds. The normalized power variation is shown inFig.4.

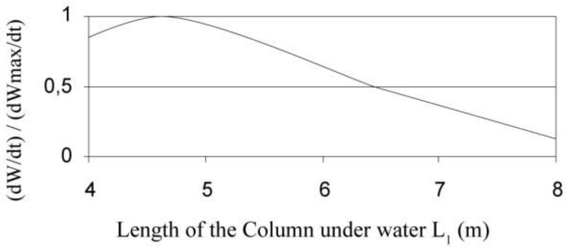

Fig. 4. Normalized average power variation underwater column length

The ideal under water column-length, L_1, can be found from Fig. 3 and Fig. 4 as 4.572 meters. The values of chamber Pressure (P), power (dW/dT), and amplitude at a wave period T=7.0 seconds are obtained by using L_1=4.572 m for the Marmara Sea. The results are presented in Fig.5.

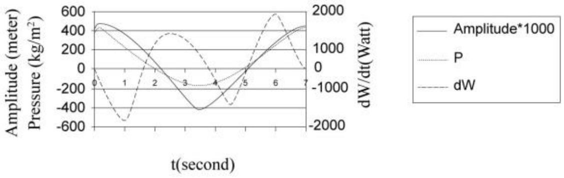

Fig. 5. Power, Pressure and Amplitude variations at a wave period of T=7.0 seconds for a system with water column-length of L_1=4.572 m

The radius of the float, which keeps the system above the water surface, is not necessarily needed for the computations. Therefore, it could be kept as it is. On the other hand, the variation of the radius of the column will change the volume of the internal water and will affect the results. In order to see the result of this, one can assume the radius of the float as R=1 m and change the radius of the column as r=0.1 m, r=0.2 m and r=0.3 m respectively (if r is assumed to be as $r \geq 0.3$, then some of our assumptions cause a non-imaginary result. This makes some troubles for the explanation of the results). When this operation is performed, the following results is obtained.

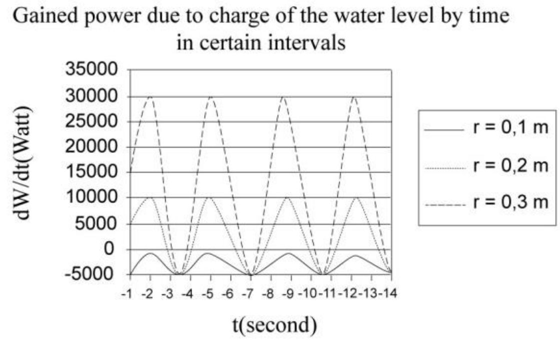

Fig. 6. Power change due to change of the radius of the column

As mentioned before, the wave period for the Marmara Sea is 7 seconds. In Fig. 6, the time interval is taken as 14 seconds in order to cover two wave periods and show that the power changes are periodic. This figure shows that the maximum value of power is produced when the wave is at the top and the lower position of the inside column. In case of the equilibrium wave condition, the system does produce any power. Another important point is that the value of the power increases at the highest value of column radius. This means, the volume of the internal column is directly proportional to the radius of the column. If this approach is correct, the length of the column must also directly proportional to the radius of the column and to the volume of the water inside the column since a longer system would cause a greater amount of water to keep in. In order to see this difference, it has to be used a certain time, in which one gets the maximum power, for example t=5 seconds, that is shown in Fig. 7.

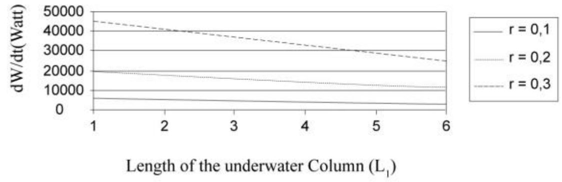

Fig. 7. Power variation at different column radii with changing the underwater column length L_1

As can be seen in Fig. 7, the power decreases with increasing the underwater column length (L_1). There is only one explanation for this result that is: in a deep water, the velocity of the water particles is assumed to be zero at the depth of the half water length and are maximum on the water surface. This means the length of the column under water (L_1) is of second order, this would be contrary to our work, since we work with the linearized equations. This occurs when the underwater column length is very short. Unfortunately, this length cannot be made zero, because of the stabilization of our system.

Keeping the underwater column-length (L_1) very short, could cause the system to flip over. At the same time makes the systems-life very short since the turbine contacts to the salty water during oscillating of the column. The most advantage of our system is that keeps the turbine and the generator out of the salty water which is highly corrosive for every kind of metal. On the other hand, if we talk about a systems-life, we can also talk about different building materials, which would mean the change of mass and the added mass of our system. The power variation according to changing in underwater column length for the radius of r=0.3 m, having different mass and added mass, is given in Fig. 7. It would be sufficiently enough, if the proportion of the original system between the mass and the added mass is kept constant.

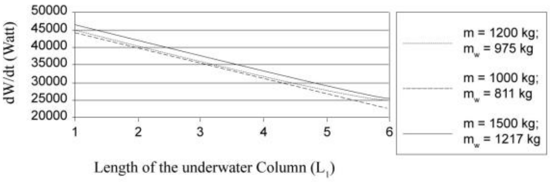

Fig. 8. Power variation by changing the underwater column length (L_1) for the radius r=0.3 m with different mass and added mass system.

As shown in Fig. 8, the power varies with the systems mass and added mass. This means, we have to use high density column materials and should be cheaper. The concrete will be a suitable material for selection.

Until now, we only have looked at the variation of the underwater column-length. But what is going to happen if we change the duct-length or the column-length over water?

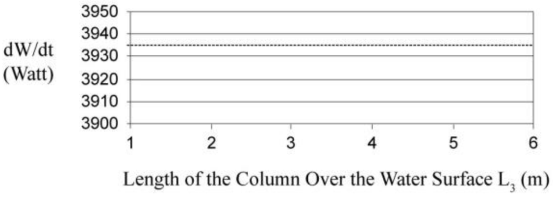

Fig. 9. Power variation while changing the column length over water

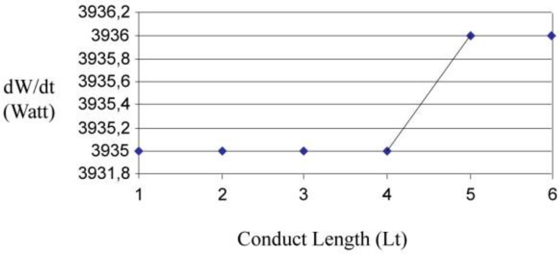

Fig. 10. Power variation while changing the conduct length

From Fig. 9 and Fig. 10, it can be seen that the power will not be affected by the variation of the column-length over water and the conduct-length. Hence it can be said that this parameter will be of second order. There are many waves higher than H=7 meters in Marmara Sea since the significant wave height $H_{1/3}$ is 3.3 meter. Thus, the system must have column-length over water at least L=3-3.5 meters for the Marmara Sea. As a result, the selection of the conduct-length will depend on size of the underwater column length and higher waves, and on the type of the turbine to be used.

4. CONCLUSIONS

As a result of this study the following conclusions can be drawn.

1. The most effective area of the system is when the systems resonance period is the nearest to the wave period of the place (see eq.(4)) For the Marmara Sea this value approximately will be $\omega \cong 0.897$ rad/s for the underwater column length L_1=4.572 m.

2. The optimum oscillating water column design is when the mass of the internal water in the column is 2/3 of the sum of the mass and added mass of the system. This statement has to be considered in the assumption of the linear theory to get more optimum design.

3. The power for the Marmara Sea, produced by the system is directly proportional to the third power of the wave height and can be seen in Fig. 2, 3, 4, 5 and 6.

4. The produced energy will increase by increasing the radius of the column (in certain limits).

5. The short the column-length under water, the much power will be produced. But here, it should be noted that the column-length under water must have a certain size, in order to manage its work for the stability of the system.

6. As the power produced with this system will increase, by increasing the mass of the system, it is necessary to use cheap and high mass density materials such as concrete can be recommended.

Generally speaking, OWC devices present two main advantages over other wave energy converters. First, their simplicity; they consist exclusively of the two aforementioned elements, the chamber and the air turbine. Second, their low maintenance cost relative to other wave energy converters, which are a result of both their simplicity and the absence of mechanical elements in direct contact with seawater.

If OWCs are to have a long-term future, rate of progress must be improved. For future work well-considered proposals for reducing cost/improving performance were to be made and justified. Estimates of cost of-energy benefits. Economic models were established for shoreline and near shore devices to investigate the likely p/kWh power output cost, and to test the sensitivity of this cost to the main design elements of an OWC development. Improvements with the biggest impact on the power production cost, requiring the least effort to implement, were then identified.

Attention was then focused on the improvements of OWC system that might be made on near-shore devices by incorporating the lessons learnt from previous projects and by assessing, through analysis and related experience, the effectiveness of a range of improvements in design, fabrication and installation of OWCs. Such improvements would reap greater reward in view of the larger near-shore resource that can be realized. The key elements of improved economics are reduced structural quantities and survival loading combined with the maximum possible wave energy capture.

The basic working principle of wave energy concepts have gone in all directions with no significant convergence that has been identified yet. Many concepts have been tank tested, but only few managed to undertake sea trials. This is the result from the various types of difficulties involved in making wave energy converters cost-effective.

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