JOURNAL OF MARITIME RESEARCH

Vol XIII. No. III (2016) pp 3–8

ISSN: 1697-4040, www.jmr.unican.es

Mass Flow in the Wave Energy Converters with Differential Pressure Storage Tanks

R. Borrás [1,2,*], R. Ferreiro[1,2], F. Antelo[1,3]

ARTICLE INFO

Article history:
Received 14 April 2016;
in revised form 20 April 2016;
accepted 1 October 2016.

Keywords:
Ocean Energy, Renewable energy, Wave energy converter (WEC), Oscillating water column (OWC), Wave Energy Converter with Differential Pressure Storage Tanks (OWC- DPST).

ABSTRACT

Among the devices for sea energy use in order to obtain power to be poured to the net, the present article discusses the performing of the oscillating water column wave energy converters (OWC) of the type of differential pressure storage tanks with (DPST) to be mounted on the coast (shoreline) or offshore (nearshore), as an alternative of improvement over conventional designs. In the operation of these kinds of converters, it is required the constancy of the mass flow rate of internal circulation as average value over a reduced interval (dependent on the size of the tanks), therefore it is studied the conversion performance dependence for each of the tanks according to the pressure in each of them, concluding that it is possible to work in a wide range of performance while maintaining the performance transformation close to maximum.

Nomenclature

g : Acceleration of gravity $[9.81 m/s^2]$
H_i : Initial upstroke $[m]$
H_o : Minimum height of the air $[m]$
H_S : Initial downstroke $[m]$
H_w : Wave height $[m]$
P : Power $[W]$
P_{atm} : Atmospheric Pressure $[Pa]$
P_{Ch} : Pressure in chamber $[Pa]$
P^*_{Ch} : Relative pressure in chamber $[Pa]$
P_H : Pressure in High Pressure Tank $[Pa]$
P^*_H : Relative pressure in High Pressure Tank $[Pa]$
P_L : Pressure in Low Pressure Tank $[Pa]$
$P{*}_L$: Relative pressure in Low Pressure Tank $[Pa]$
T : Period of wave $[s]$
U : Internal energy $[J]$
W : Energy $[J]$
W_D : Energy in the upstroke $[J]$

Greek Letters:
η_i water level inside $[m]$
η_o water level outside $[m]$
ρ Seawater density $[1025 kg/m^3]$
γ Specific heat ratio
Δ Level difference in the upstroke $[m]$
Γ Level difference in the downstroke $[m]$

[1]Universidad de La Coruña. Escuela Técnica Superior de Náutica y Máquinas .Spain
[2]Departamento de Ingeniería Industrial. Email: ferreiro@udc.es
[3]Departamento de Energía y Propulsión Email: felipe.antelo@udc.es
[*]Corresponding author: R. Borrás. E-mail: ramon.borras@udc.es.

1. Introduction

It can be read in a recent report: ”The global technical potential of wave energy is estimated at 11.400 TWh per year.” ”Its sustainable generating potential of 1.700 TWh per year equates to about 10 per cent of global energy needs”; and also ”22 is the number of wave energy devices in 2010 and 22.000 the predicted number of wave energy devices in 2030” but says ”The data presented here for the purpose of scenario constructions are based on simplistic projection and should be used with caution” (Global Marine Trends 2030, 2013)

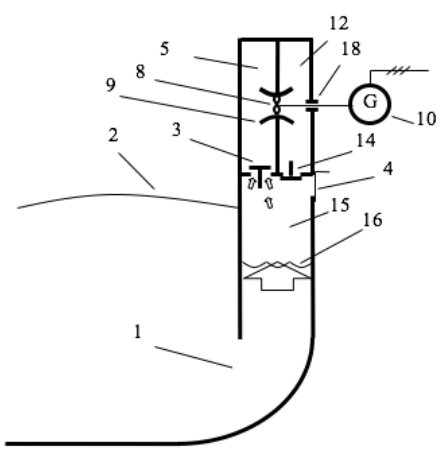
In another report: ’Europe has a large amount of natural resource across the three offshore renewable energy sectors.’ Technically offshore wind, wave and tidal together could supply 100% of Europe’s future electricity demand. ”These resources present significant opportunities with respect to increased energy security, emissions reductions, and economic benefits including job creation" (Jeffrey and Sedwick, 2011)

To allow the necessary takeoff of the massive use of wave converters it is required an evolution of current designs, a maturation of the applicable technology.

The conventional wave energy oscillating water column converter designs, WEC-OWC, show several problems. Among others: very low yield of the transformation of energy, electric power provided by the generator attached to the turbine makes it for a small fraction of the work cycle and in addition with a highly variable value. The alternative design presented in this paper, tries to solve the mentioned problems, analyzing the operation with the help of the working cycle.

2. OWC-DPST Converter

Figure 1: OWC-DPST converter principle diagram



The water level inside the Chamber, as in all converters OWC, tries to follow the outside water level with a certain delay.

Figure 1 represents in a simplified way, the OWC-DPST converter. The number 5 represents the high pressure storage tank, HPT, which introduces, through the remote operated valve 3, HPV, the compressed air from the chamber during the upward travel of the oscillating water column. The 5, tank pressure is a gauge pressure, relative pressure, positive. The LPT low pressure storage tank is represented with the number 12. This tank is extracted from air by suction, through a remote operated valve 14, LPV, during the downwards route of the water column. In this tank the gauge pressure, relative pressure, is negative.

Venting valve, VV, marked with the number 4, allows you to make more efficient the process of filling and emptying of storage tanks. It's a remote operated valve which opens before the water column reaches its upper level, once the loading period has ended, and allows you to evacuate to the atmosphere the over- pressure air that is still in the chamber, facilitating water levels continue to rise. It must also open after the period of LPT tank air suction ends, so air retracts into the chamber until reaching the pressure outside, the atmospheric pressure.

Between one storage tank and the other, there will be a drop in pressure, differential pressure, which, if the volume is sufficient, allows a nearly constant and continuous airflow over the conventional high performance turbine, which turbine drives the electric generator, for example a 3-phase alternator, which may be coupled directly to the mains. Another possibility would be to use a doubly-fed induction generator (DFIG) as it can work as synchronous machine, by turning at the most suitable speed, which are commonly used also with wind turbines (Giménez and Gómez, 2001)

The volumes of accumulator tanks have to be far greater than the volume of the chamber so that the pressure, for a period, hardly suffers variation. In Figure 1 the accumulator tanks are not represented to scale. The tank volume is equivalent to the capacity of the filter condenser in an electrical equipment power supply. Pressure, continuing with the same analogy, would be equivalent to the electric potential and the mass flow rate to the current.

3. Working Cycle

To simplify the explanation, let us consider a regular swell, with a series of wave fronts at the same time approaching the converter, with a constant amplitude, and constant period. The converter will work then repetitively.

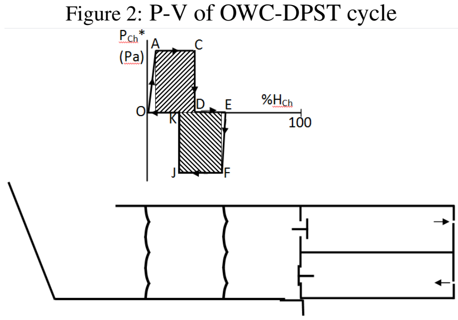
It will be explained how to work through the theoretical cycle p-v (Borrás-Formoso, 2014b), shown in Figure 2, with ideal conditions enabling to represent the sections operating. Concerning the behavior of the sea water within the chamber, it is supposed that if the chamber was connected permanently with atmosphere, vertical oscillation would be equal to the height of the wave (Bakar, 2011), consistent assumption with application to our case of the Bernoulli theorem, expressed in Equation 1 appropriate for use in numerical simulation with CFD (Computational Fluid Dynamics) (Setürk and Özdamar, 2011), and that one also used by Hiramoto (Hiramoto, 1978). Or, better, given a wave that causes a swing that let HW, we assume an Airy wave on the outside with a height of wave HW and behavior such as described in the previous section in a chamber open to the atmosphere. Resonance effects are not considered.

Also, in the present analysis, for modelling waves and wave-structure interaction, linear potential flow theory was used. It relies on assumptions of inviscid fluid, irrotational flow and small wave amplitudes relative to the wavelength.(Babarit, 2012)

$$\eta_0 + \frac{p_{atm}}{g \cdot \rho} = \eta_i + \frac{p_{Ch}}{g \cdot \rho} \tag{1}$$

For the air, as working at low pressures, it can be assumed that it behaves as perfect gas diatomic with a value of 1.39 γ (ratio of specific heats). It is assumed that compressions and expansions of the air in the chamber, as being in a short time interval, they are adiabatic (Babarit, 2012). Pressure drops in HPV and LPV valves are neglected because they are remote operated and the order of closing occurs when the pressure in the tank and the chamber are equal.

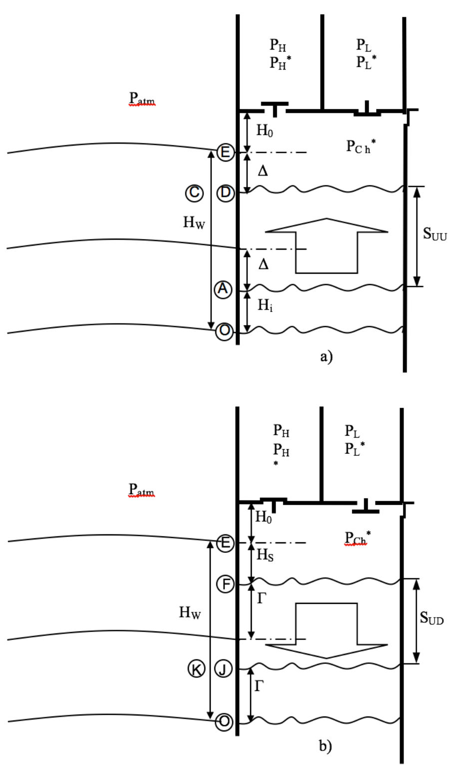
Figure 2: P-V of OWC-DPST cycle



It is assumed that the horizontal dimension of the chamber is small with respect to the length of the wave.

According to the nomenclature of Figure 3, the cycle starts at the point O corresponding to the water level, both outside and inside the chamber, at its lowest level (low dead center in an alternative machine analogy). All the valves are closed and the chamber pressure is equal to atmospheric pressure. Water level in the outside of the converter rises and, therefore, it will also rise, with a certain delay, inside the chamber, acting the water surface as a rigid piston (Evans, 1982) following the trapped air in the chamber an adiabatic compression process. When the level has gone up the distance H_i, pressure will have reached the high pressure tank. Point A of the cycle.

Figure 3: Chamber in a OWC-DPST converter during the stroke a) upwards b) downwards.



From the point A the opening order is given to the remote operated HPV valve. The water level continues to increase during the movement, that will be called SUU, useful upstroke, by entering air the high pressure tank. During the movement of water level from $'A'$ to $'C'$, the pressure (and temperature) will remain substantially constant and the air mass between these two levels is that one introduced in the high pressure tank. The pressure in the tank will hardly suffer no variation due to its high volume (in figures 1 and 7 storage tanks are not shown to scale). After the useful upstroke, point $'C'$, the closing order is sent to HPV valve and then the opening order to the vent valve communicating the chamber with atmospheric pressure, evacuating air to the outside until the pressure in the chamber is the same as the atmospheric one, point $'D'$. The water level will continue to rise easily, as there is no backpressure, until it is similar to the outside level, point $'E'$. Arrived at this point the upstroke is completed, the valve of venting is closed (all valves are closed) and when the water level on the outside of the chamber starts to lower, the downstroke on the inside of the chamber starts. The drop in level, being the vent valve closed, will be accompanied by a decrease in the chamber pressure, following an adiabatic evolution, section from $'E'$ to $'F'$. Arrived at this point the valve LPV is opened, and during the "downstroke useful", SUD, the pressure remains significantly constant, section $'F'$ to $'J'$. At the $'J'$ point, the order of closing the LPV valve and the opening order VV valve are given, passing the chamber pressure to the atmospheric pressure, section $'J-K'$. With the chamber opened to the atmosphere, the water level continues to fall until it reaches the minimum level in the outside of the chamber, section $'K-O'$, completing the cycle.

On the y axis the value of relative, positive pressure in HPT tank, and negative in the LPT tank pressure are represented. On the $'X'$ axis it is shown the volume of the chamber expressed in % of the value corresponding to the volume when the water level is at its minimum. Therefore, for a given converter, each % represents a particular value.

Since a part of the fluid involved in a cycle acts again in the following cycle, we can talk about a semi-closed cycle.

To represent the cycle in the $'P-V'$ plane, the enclosed area represents a job, exploited converted energy.

In Figure 7 a diagram representation of a modified OWC-DPST converter (down 90 degrees) is accompanied with the $'P-V'$.

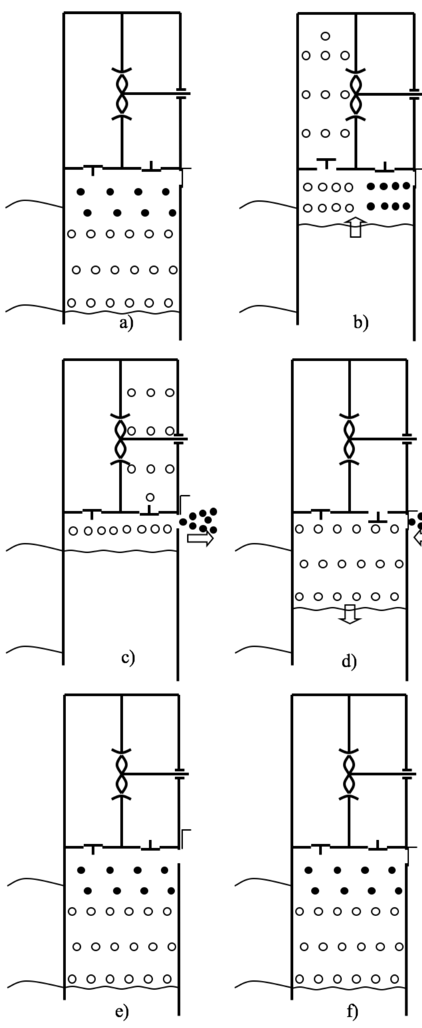
4. Constancy of the Mass Flow

It is important to note that while some air flows are produced from the camera to the outside, and conversely, when VV valve is open, the average value of the mass flow over the cycle (kg/s) is constant inside the converter. That is, over a cycle the mass of air in circulation from the chamber to the high tank, from the high tank through the turbine to low tank and from the low tank towards the chamber, should be equal.

An approximation to the movements of the mass of air over the cycle is represented in Figure 4. The hollow circumferences represent the air molecules that constantly remains within the converter border. Some of them are those that participate in the workflow. The black circles, filled, represent the air molecules that are exchanged between chamber and atmosphere. These molecules of air are not turbined. The rest of air molecules, which occupy the rest of the tanks, are not represented.

By opening the valve of the high tank, a part of the air will be transferred to high tank. It is what represents the graphic b) in Figure 4. The work of compression of the entire mass of air that remains within the chamber, is lost. There would be the possibility to take advantage of it, for example using a small turbine working among the chamber pressure and the atmosphere. In the case of the represented $'P-V'$ cycle is not considered. The amount of air that leaves the camera into the atmosphere is necessary to recover atmospheric pressure, that is, gauge pressure in the chamber equal to zero. It is the situation represented in graphic c) in Figure 4

Figure 4: Displacement of the working fluid



After the end of the useful downstroke, the venting valve opens and the same amount of air that had left the Chamber reenters. It is the amount of air required to recover atmospheric pressure with water at its lowest level. This is what the graphics d) and e) in Figure 4 show.

When the inlet of air is complete, the venting valve is closed and we are again in the situation shown in the graphic f) in Figure 4.

If the condition of constancy of flow mass was not fulfilled, pressure tanks not would remain stable. As an example, suppose that the system is working under stable regime conditions, if the power demanded to the turbine-alternator group increases, the flow rate will increase through the turbine becoming greater than the mass flow from the chamber to the high-pressure tank. This will lead to the fact that the mass of air, and the number of moles, within the tank will decrease. The immediate effect, by application of the gases state equation, is that the pressure in the high tank will decrease gradually. On a complementary basis, in the low pressure tank the mass flow of suction from the chamber will be lower than the mass flow through the turbine and as a result in low tank the pressure will rise (it will lose vacuum). The result will be that pressure in the accumulator tanks trend to equalize losing ”differential pressure” condition.

5. Pressure inside the tanks

The pressure chosen for accumulator tanks will impact directly on the transformation performance. So, if we refer for example to the usable work during the upward stroke of the column for a given wave height, if the high tank pressure is highrise, as the valve HPV (3) will not open until the pressure in the chamber equals the pressure of the accumulator tank, HPT, useful movement on the upstroke, SUU, will be very short. If a too high pressure is chosen, the valve HPV will not open and therefore the energy used during the upward stroke will be zero. Similarly, if the HPT pressure is too low, say as extreme case equal to the atmospheric pressure, the compression work will also be zero. Between these two values with zero, zero transformation performance use, any other value will result in an increase in internal energy, ΔUH, in the accumulator tank of high pressure which can be expressed as (Borrás-Formoso, 2014b)

$$\Delta U_H = (P_H - P_{atm}) \cdot H_W - \frac{(P_H - P_{atm})^2}{\rho \cdot g} - (P_H - P_{atm})(H_0 + H_W)\left[1 - \left(\frac{P_{atm}}{P_H}\right)^{\frac{1}{\gamma}}\right] \quad (2)$$

From the previous expression, we can obtain the value of pressure within the high tank PH, which maximizes the use of energy on the upstroke, and for a given wave condition, therefore a maximum power available. We deduce the mass of air that enters the tank in each ”upstroke”, for an arbitrary pressure between the limits referred to above, if it is taken advantage of the maximum useful stroke, SUU.

From Figure 4 observation of the value of the useful upstroke is deducted:

$$S_{UU} = H_W - H_i - \Delta \quad (3)$$

The initial upward stroke, H_i, will be worth:

$$H_i = (H_0 + H_W)\left[1 - \left(\frac{P_{atm}}{P_H}\right)^{\frac{1}{\gamma}}\right] \quad (4)$$

And the gap between outside and inside level, Δ, will be given by:

$$\Delta = \frac{P_{Ch} - P_{atm}}{\rho \cdot g} \tag{5}$$

Substituting the expressions 4 and 5 in 3, it is obtained that, 6

$$S_{UU} = H_W - (H_0 + H_W)\left[1 - \left(\frac{P_{atm}}{P_H}\right)^{\frac{1}{\gamma}}\right] - \frac{P_H - Patm}{\rho \cdot g} \tag{6}$$

The air temperature after compression, TH, by an adiabatic process will be:

$$T_H = T_{amb} \cdot \left(\frac{P_{atm}}{P_H}\right)^{\frac{1-\gamma}{\gamma}} \tag{7}$$

The number of moles of the introduced air during the upstroke, nH, per square meter of the chamber, can be obtained from the equation of state of gases:

$$n_H = \frac{P_H \cdot S_{UU}}{R \cdot T_H} \tag{8}$$

And by replacing expressions 6, 7 in 8: Equation 9

$$n_H = \frac{P_H \left\{H_W - (H_0 + H_W)\left[1 - \left(\frac{P_{atm}}{P_H}\right)^{\frac{1}{\gamma}}\right] - \frac{P_H - P_{atm}}{\rho \cdot g}\right\}}{R \cdot T_{amb}\left(\frac{P_{atm}}{P_H}\right)^{\frac{1-\gamma}{\gamma}}} \tag{9}$$

Similarly, the increase in internal energy in the tank low pressure during the downstroke is given by [BorrÃ¡s-Formoso, 2014]

$$\Delta U_L = (P_L - P_{atm})\left[H_W - H_0\left(\frac{P_{atm}}{P_H}\right)^{\frac{1}{\gamma}} + H_0 - \frac{1}{\rho \cdot g}(P_{atm} - P_L)\right] \tag{10}$$

It can calculated the number of moles of extracted air from low pressure tank during the downstroke, n_L, proceeding in a similar way as it was done for the upstroke, obtaining:

$$n_L = \frac{P_L \left\{H_W - H_0\left[\left(\frac{P_{atm}}{P_L}\right)^{\frac{1}{\gamma}} - 1\right] - \frac{P_{atm} - P_L}{\rho \cdot g}\right\}}{R \cdot T_{amb}\left(\frac{P_{atm}}{P_L}\right)^{\frac{1-\gamma}{\gamma}}} \tag{11}$$

And, as mentioned above, the condition of continuity of the mass flow will be fulfilled when the average n_H value is equal to n_L.

6. A case study and result

In order to make a numerical quantification of the variation of the internal energy depending on the chosen pressure, visualizing the result, we will study a specific case: a value of height in wave, $HW = 2m$ with a height of vacuum column, $HO = 1m$.

Figure 5: Performance according to the storage tank pressure.

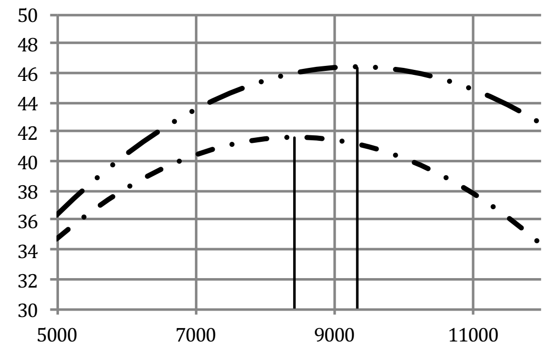
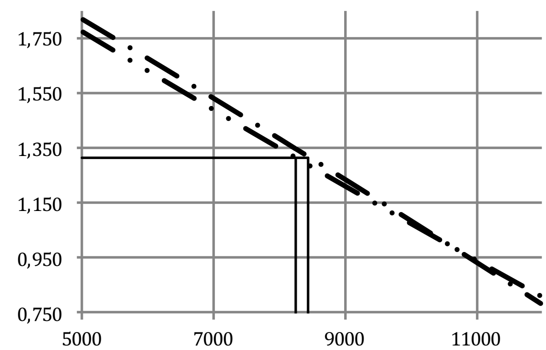


Figure 6: Mass flow rate, per stroke and m2, depending on the storage tank pressure.



In Figure 5, the scale is lineal, but to better appreciate the variation, shafts do not start from zero. The horizontal axis represents the value chosen for pressure in the accumulator tank (pressure gauge, relative). For low pressure tank, the value is presented with the sign changed. Ordinate shows the transformation performance expressed in %. The curve below (point and stroke) is the result for the upward stroke. Maximum upstroke use, with a yield of 41.7%, indicated on the graphic with a vertical line, corresponds to a high, PTH, 8440 *Pa* tank pressure. It is interesting to indicate that quite different pressure performance is only slightly lower. Thus, to 7000 Pa would be 40.5%, and 10,000 *Pa* of 40.3%. For the downstroke of the water column, the graphics are stroke and colon; the pressure is also relative, but shifted sign pressure.

Maximum achievement for the downstroke, with a yield of 46.4%, indicated also with another vertical line, corresponds to a pressure tank of high, LPT, - 9319 *Pa*. Also for quite different pressures performance is only slightly lower. Thus, for - 8000 *Pa* would be 45.5%, and - 11.000 *Pa* of 44.9%.

Figure 6 drew is taking for each tank pressure of high, the mass of air that enters the tank, per square meter of horizontal surface camera during the upstroke useful. The line that corresponds to this tank is also to point and stroke. The result for downward stroke is to stroke and colon. Equally, when it comes from a negative gauge pressure, to represent it on the same axis, change the sign. Taking into account the evidence of the mass flow, if taken for example to HPT the value indicated above, *Pa* 8440, tracing a horizontal line, the value that corresponds to LPT must be *Pa* - 8243. Taking into account the energy transferred in each of the races, the total performance for the cycle will be of 87.4%. Note that the same as the values are not symmetrical to the pressures of maximum performance; yields are not equal in every stroke, nor the working stroke.

7. Conclusions

The oscillating water column with storage tanks under differential pressure, OWC-DPST, arises in order to increase the efficiency and performance with respect to the OWC conventional converters. It has some advantages over these. Able to work the air turbine with a constant, stable pressure drop, the turbine can be flow one way, working in continuous regime and resulting in higher performance. It allows, therefore, to avoid working to impulses and therefore you can send to the net constant value over time of electric power.

Due to its way of working, the OWC-DPST converters require that the mass flow rates on the inside of the converter are identical. Given that the flows between chamber and tanks depends on chosen pressures and transformation performance is depending on the chosen pressures, in general it will happen that the pressures of tanks that give maximum transformation yields will not give the same mass flow rates, so it will not be compatible. Therefore, they must be chosen within the pressures which give the same mass flow rates, those values give, for each of the strokes, next to the maximum performance. Fortunately, as it could be seen in the case study, the performance curve as a function of the pressure presents near the maximum a slight variation.

References

Babarit, A., 2012. Numerical benchmarking study of a selection of wave energy converters. Renewable Energy Vol 41, pp 44–63.

Bakar, B., 2011. Mathematical model of sea wave energy in electricity generation. International Power Engineering and Optimization Conference (PEOCO2011), Malaysia.

Borrás-Formoso, R., 2014a. Making use of coastal wave energy: A proposal to imporve oscillating water column converts. Dyna-Colombia Vol 81 (No. 185), pp 211–218.

Borrás-Formoso, R., 2014b. Performance and theorical cycle of a wave oscillating water column coverter with differential pressure storage tanks. Journal of Maritime Research Vol XI (No. III), pp 97–105.

Evans, D., 1982. Wave-power absorption by systems of oscillating surface presure distributions. Journal of Fluids Mechanics Vol 114, pp 481–499.

Gervelas, R., 2011. A. time-domine simulator for an oscillating water column in irregular waves at model scale. Ocean Engeineering Vol 38, pp 1007–1013.

Giménez, J., Gómez, J., 2001. Wind generation using different generators considering their impact on power sistem. Dyna-Colombia Vol 169, pp 95–104.

Global Marine Trends 2030, 2013. Lloyd's register, qinetiq. University of Strathclyde.

Hiramoto, A., 1978. The theorical analysis of an air turbine generation system. International Symposium on Wave and Tidal Energy, pp 73–84.

Jeffrey, H., Sedwick, J., 2011. Orecca european offshore renewable energy roadmap. University of Edinburgh.

Josset, C., Clément, A., 2007. A time-domain numerical simulator od oscillating water column wave power plants. Renewable Energy 32, pp 1379 – 1402.

Setürk, U., Özdamar, A., 2011. Modelling the interaction between water waves and the oscillating water column wave energy device. Mathematical and Computational Applucations Vol 16 (No. 3), pp 630–640.