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Performance and Theoretical Cycle of a Oscilating Water Column Converter With Differential Pressure Storage Tanks

R. Borrás-Formoso[1,2,*], R. Ferreiro-García[1,3] and F. Miguélez-Pose[1,4]

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ABSTRACT

The aim of this article is to describe a wave energy converter, of the oscillating water column type, with a novel alternative design to the conventional ones attempting to attain enhanced conversion efficiency. The encountered drawbacks with regard to the conventional wave energy based power plants are described as well as a discussion concerning the advantages and disadvantages that supposes the alternative proposed design.

To estimate theoretically the power obtainable, we use a performance simulation under ideal conditions, considering: regular waves, evolution of air as an ideal gas, adiabatic compression and expansion and pressure losses in valves negligible...

The results show that by means of the suitably adjusting of the turbine differential pressure, the obtainable power can be maximized. In this way it is concluded that the proposed innovations points in the direction of achieving a maturing technology applicable to this type of converters.

1. Introduction

The need for the gradual replacement of energy sources from fossil fuels, by reason of the progressive depletion and environmental deterioration, imposes to continue and deepen the way of energy transition. The target 20-20-20 of the European Union Parliament, embodied in the directive 28 of 2009, marks this future line with the triple objective of 20% by 2020:

- A 20% reduction of emissions of GHG, with respect to the year 1990.
- That 20% of the final energy consumed comes from renewable energy sources
- An improvement of 20% efficiency

Where it seems more difficult to proceed the change of fossil-fuels is in the automotive industry since the technical limitations of alternative designs are remarkable. It is therefore in the generation of electricity from renewable sources where the R+D may lead to practical results in the short term. Within the renewable sources, some can generate CO^2 and others, such as the one from the oceans, are also free of emissions.

Marine renewable energies constitute huge potential energy sources but they are very little developed. In the current state of the technic multiple devices are designed to take advantage of marine energy also known as power from the seas or oceans. Some take advantage of the power of the tides (tidal), other energy from ocean thermal gradients (OTEC), other osmotic energy (from salinity gradients), other offshore wind (produced by marine winds), other energy of sea currents (inertial) and finally, as the one described in the article, the energy which harnesses the wave energy, also known as olamotriz or wave energy.

Regarding the location of the converters on the coast, i) ones are built on deep water (50 m), away from the coast (offshore), submerged or afloat, anchored both; ((ii) others in shallow water (10-40 m), either near the shore (nearshore), anchored float-

[1]Universidad de La Coruña. Spain
[2]Departamento de Ingeniería Industrial. E-mail address: ramongborras@gmail.com
[3]E-mail address: ferreiro@udc.es
[4]Departamento de Física. E-mail address; fermigue@udc.es.
[*]Corresponding Author. E-mail address: ramongborras@gmail.com.

ing or with structure supported at the bottom and iii) others are built on the rocks on the coast (onshore).

The energy associated with the waves varies from some areas to others. It is higher between the 30° and 60° Parallels in both hemispheres. In the Galician and Cantabrian coast, average value exceeds the 40 kW per m of wave front.

A simplified formula that is commonly used to estimate the energy of the waves, power per wave front lineal metre in the case of deep water, is given by: [Perera J., 2010]

$$P_m = \frac{1}{32\pi}\rho g^2 T H^2 \approx T H^2\ (kw/m)$$

However, the total average wave energy per unit surface area, specific energy or energy density, sum of the potential and kinetic energy, also for deep water, can be estimated by:

$$E_s = \frac{\rho g H^2}{8} \approx 1,25 H^2\ \ (kJ/m^2)$$

Thus, dividing the energy density by the wave period we get the wave power density in watts per square meter:

$$P_s \approx 1,25\frac{H^2}{T}\ \ (kW/m^2)$$

The first patents for the wave energy exploitation date back to the year 1799 in France (Girard and son), and Great Britain in 1833. Today they exceed the thousand [Vicinanza, D., 2012]. All converters of power from waves (Wave Energy Converters, WEC) of water column rocking (within Wave Column, OWC) are functioning as well as which are under construction, both off-shore and on-shore, have a provision which can be schematically represented as shown in Figure 1 for a converter installed on the coast. The turbine shaft can be arranged vertically, as in the headquarters installed in Mutriku (Guipúzcoa, Spain), either horizontally, as in the case of Pico stations (in the Azores) or that on the island of Islay (Scotland).

The way of working of a conventional converter OWC, explained in a simplified way from Figure 1, is as follows: when the wave reaches the converter, the water level inside the chamber, inside, is lower than that outdoors. It will start to ascend the water level in the chamber, in the inside, by compressing the air during the travel upward in the water column, and this compressed air operated an air turbine that drives an electrical generator. This process will continue until the water column reaches its top level. When the wave, on the outside, withdraws it will begin the downward travel of the water column, the increased volume of air inside the chamber will result in a decrease in pressure, below the atmospheric, and this pressure drop will result in a flow of air, contrary to the previous, driving back to the turbine. It is customary to employ self-rectifying turbines, for example the Wells, Dennis-Auld, McCormick or the reaction-self-rectifying ones that keep the rotation direction regardless of the direction of air flow. The use of self-rectifying turbines, solving a problem in a satisfactory manner, has the advantage of leverage both routes of the column of water for energy conversion. It's already very experienced air turbines and with a mature technology.

Figure 1: Conventional OWC converter

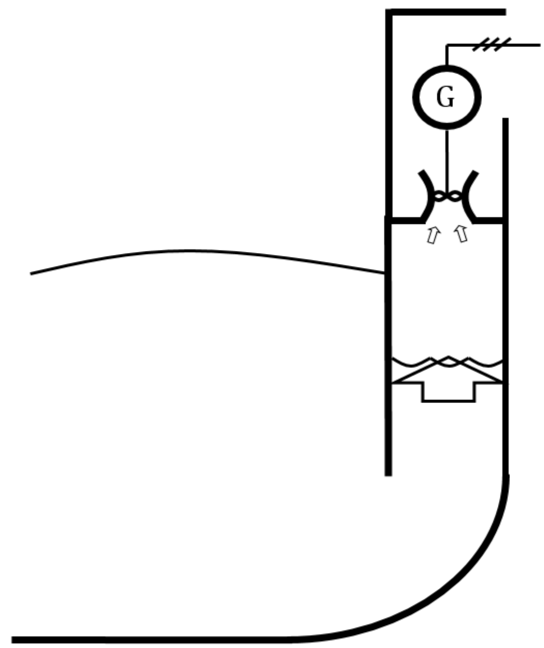

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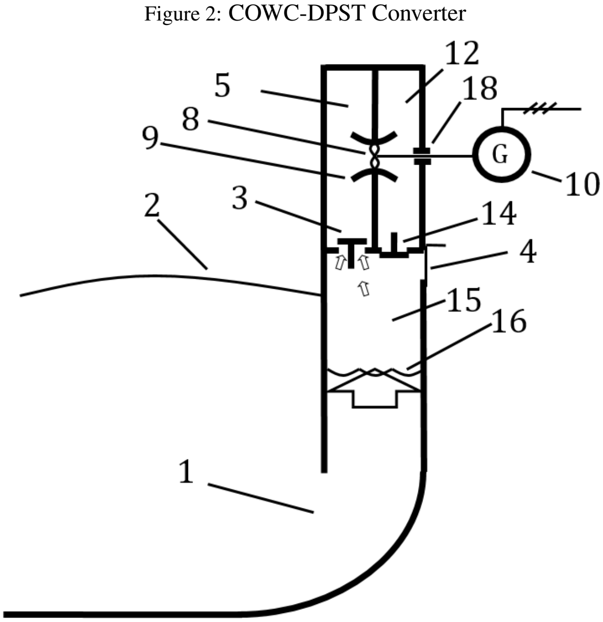
Figure 2: COWC-DPST Converter



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However, by the way these converters work presented several weaknesses arising from the fact that the working, air, fluid flows are [Borrás-Formoso, R. et al. 2014]:

a) variable in amplitude

b) variable in direction

c) intermittent

d) non-controllable.

Let's look briefly at the implications of each of these features. a) both the process of compression during the travel upward in the water column, and the suction during the descending route, are not constant pressure. This gives rise to very variable amplitude air flows because the pressure in the chamber is very variable. The effect is that the torque provided by the turbine will also be variable and zero in much of the cycle. Furthermore, in addition to other problems, it will lead to sub-optimal operating conditions (maximum performance condition) and therefore a low performance of the conversion will be obtained. The operating range is very narrow for good performance [Setoguchi, T. et al. 2001]. The sudden lifting of the pressure in the chamber can cause failure to the blades [Brito-Melo, A. et al. 2002]. The phenomenon of "stalling" makes fall performance from certain flows [Alberdi, M. et al. 2011]

On the other hand, for the sizing of turbine and electrical generator will have to consider the maximum values of power and torque, well above the average values.

(b) That the air flow is variable in its sense implies that: 1st: or well next is the grinding of the airflow if using a turbine conventional type, i.e. for one direction of flow, and therefore with greater performance, but that requires the use of various valves and elbows in the ducts in the changes of direction with the consequent effect of pressure drops and losses in the conversion.

2nd: or well used an self-rectifying turbine, leading to a significantly lower level of efficiency [Maeda, H. 1999].

(c) That there is a change in the direction of the flow of air in the turbine vent already implies, mathematically, that the flow should undergo zero twice per cycle, i.e., two moments in which no energy being transferred to the turbine. But in addition, when the level of the water column reaches its lower level and from the air in the chamber pressure equal to atmospheric pressure, it will take a while until it begins its upward motion and one while longer until you get to compress the air in the chamber at a pressure sufficient to produce an air flow rate through the turbine to transmit torque. Up to that moment no energy is transferred to the turbine. Something similar happens when the water column is at its top level. By this, it is clear that, during much of the cycle, energy is not being transferred to the turbine. The converted energy is therefore intermittent [Muthukumar, S. et al. 2005].

(d) The three above points suggest that air through the turbine flows are highly variable, which means that it is not used as machine driven by the turbine to a three-phase alternator directly connected to the network. A doubly-fed induction generator can be used. Another option is to resort to double conversion rectification-inversion with static elements.

It can be used a turbine controller system acting on a variable blade distributor, to partly mitigate the effects of flows highly variable. In any case, this type of converter control poses major theoretical and practical problems.

It should be added to the above that, inevitably, there will be salt water particles crawls which will impact on the blades of the turbines with the undesirable effects of erosion and fouling. Another problem, from the environmental point of view, is the high noise coming from the turbine air outlet in the peaks of greater speed, which prevents these converters from being located in the vicinity of inhabited areas.

The proposed, WEC-OWC, with differential pressure storage tanks (DPST) is designed to avoid many of the disadvantages of conventional OWC converters. Another aspect that is necessary to innovate in this kind of devices, and that is not addressed in this article, is about the design allow withstand heavy sea storms [López, A., 2011]

2. Description of the Proposed Converter

Figure 1 shows a simplified diagram of a conventional OWC converter. The extraordinary simplicity of its principle of operation can be seen. The level of water inside the chamber tries to follow, with a certain delay, the level of the water from the outside.

Figure 2 shows, also in a simplified manner, the OWC-DPST converter. The number 5 represents the storage tank of high pressure, 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. Tank 5 pressure is a pressure gauge, relative, positive pressure. The low pressure storage tank, LPT, is represented with the number 12. From this tank air is extracted by suction, through a remote operated valve 14 (LPV) during the downstroke of the water column. In this tank the gauge, relative pressure is negative.

The vent valve (VV) marked with the number 4, allows more efficiently the process of filling and emptying of storage tanks. It is a remote operated valve which opens before the water column reaches its upper level, once the charging period is completed, allowing the pressurized air which is still in the chamber to be evacuated into the atmosphere, thus permitting the water levels to continue to rise. This valve should open at the end the period of air suction from the LPT tank, allowing air to enter the chamber until the pressure is equal to the outside atmospheric pressure.

Between one storage tank and the other there will be a leap in pressure, differential pressure, which, if they have sufficient volume, allows a nearly continuous and constant air flow over the conventional high performance turbine, which will drag the electric generator, for example a three-phase alternator, which can be attached directly to the mains. Another possibility is to use as a generator the doubly-fed induction generator (DFIG) as it can work as a synchronous machine, rotating at a more suitable speed, such as it is done with the wind turbines [Gimenez, J. 2011]. The volumes of storage tanks have to be much greater than the volume of the chamber.

2.1. Operating Principle

Like the existing OWC, it is a converter, either offshore or onshore, that harnesses the energy of the sea waves and converts it into electricity. Let's assume that it is a converter located on the coast. Built structure, partially submerged, closed on the top and open side towards the sea located partly under the water level, in the presence of waves the water within the structure level will continue - by the principle of communicating vessels - variations in the level of the waves. During the upward movement of the waves, the air that is trapped within the structure, camera, will suffer a decrease of volume and consequently an increase in pressure, to act as a "rigid piston" [Evans, DV.1982] water column. When this pressure slightly exceeds the existing pressure inside the accumulator tank of high pressure air, the air will flow naturally through an open valve, HPV (preferably, but not necessarily, a remote operated valve) which communicates the chamber with the high pressure accumulator tank.

Similarly, when it begins the downward movement of the wave, the water level inside the chamber will fall, there will be a progressive increase of the volume in the chamber and thus a decrease in pressure. When the pressure in the chamber is slightly bellow that within the low pressure accumulator tank, the air will flow naturally from low pressure tank, through another open remotely operated valve, LPV, towards the camera, then slightly decreasing pressure in the low pressure accumulator tank. As just seen, there will be two tanks available, one with air at high pressure, positive relative pressure, and another with a negative relative pressure. Between these two tanks there is a differential pressure and therefore a duct or conduit can be used to connect the two tanks. Within this duct a turbine is placed driving an electric generator.

In conventional OWCs, during the upstroke turbine works between the compression chamber pressure and atmospheric pressure whereas during the downward stroke it works between atmospheric pressure and the suction pressure. The same is however not true for the proposed OWC-DPST. The gauge pressure in the accumulator tank of high pressure could be for example 10kPa positive, i.e. 10 kPa gauge. The gauge pressure in the accumulator tank of low pressure may be, for example, 10 kPa negative, i.e., -10 kPa gauge. With these data, the pressure drop in the turbine of the OWC-DPST converter would be 20 kPa, providing a constant supply air flow to the turbine.

2.1.1. Detailed Operating Description

Last paragraph gave one sufficient explanation to understand the operation. A full description of the way of operation will be posted in this section. This converter is controlled by a processor which receives the signal from the pressure transducers of the high pressure storage tank, the low pressure accumulator tank and the pressure from the chamber as well as water level sensors of the inside and the outside of the chamber. From the processor the command order is given to HPV, LPV and VV valves and turbine power is controlled by adjusting the flow rate, for example by opening or closing the passage of air to a greater or lesser number of pallets, as it is done in the steam turbines.

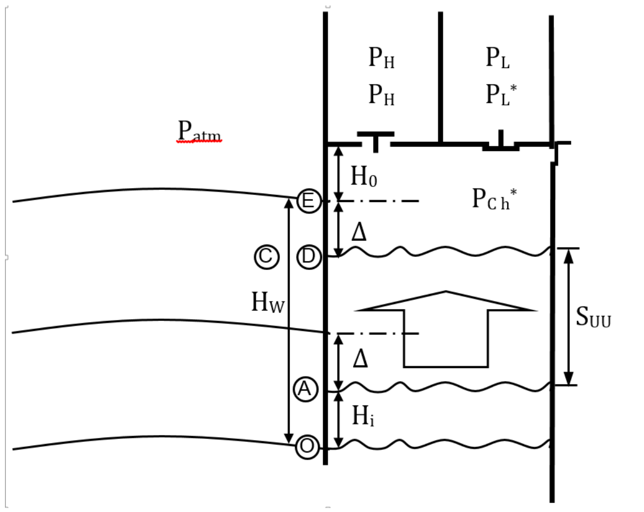
Following in Figure 2, when the water level in the oscillating column chamber is at its lowest, the air pressure in the chamber (15) is equal to atmospheric pressure (relative pressure gauge, zero) to open the venting valve. HPV valve that connects the oscillating water column chamber with HPT high-pressure accumulator air tank, as well as the valve LPV (14) that communicates the camera from the oscillating water column with LPT low-pressure accumulator tank (12), are closed. Then, the venting valve is closed. When the upward movement of the water column starts, the air in the chamber pressure increases slightly, but all air remains confined within the camera. The water level will keep rising and the air pressure will continue to increase until the moment in which the air in the chamber pressure exceeds pressure inside the high-pressure accumulator tank, HPT. From that moment it will be given the order of opening valve HPV and air will flow naturally through the valve HPV open, slightly rising pressure in the high-pressure accumulator tank.

When completed the introduction of air into the high pressure accumulator tank, the HPV closes and opens the venting valve VV to release air in oder to reach the atmospheric pressure in the chamber. The water level in the chamber will match the level of water in the outside. Once the water in the chamber reaches its highest level, the venting valve VV is closed and as the water level lowers, the pressure in the chamber will lower as well. As soon as the pressure in the oscillating water column chamber drops below the existing in the low pressure accumulator tank LPT, the valve LPV will opened and air will flow naturally from the inside of the low pressure accumulator tank LPT to the chamber. When the passage of air from the LPT towards the chamber stops, it will close the LPV valve, and then it will open the venting valve VV, giving air to reach the atmospheric pressure in the chamber. The water level of the oscillating column will drop until reaching the lower level. From here the cycle is repeated.

When the HPT and LPT accumulator tanks reach the desired pressures, the turbine can be fed by air flowing from the HPT to LPT, remaining pressures from both accumulator tanks significantly constant, if they have a high enough volume. In order it can work in a stable, continuous way, the air consumption of the turbine (mass flow) in a cycle will have to be equal to the amount of air that enters a cycle in the HPT and also to the amount of air extracted from the LPT throughout a cycle.

If you want the turbine to power an electric generator (threephase alternator) which will be attached to the network, it is imposed that the rotational speed is fixed. To provide a certain power, the volumetric flow rate shall be function of the pressure in the tanks. If we want the usage to be maximum, we must ensure that the turbine works in the condition of maximum performance or at least in the environment of that maximum and that implies that the pressure in the tanks have to remain substantially constant and this means that the higher the volume of accumulator tanks is, the lower the pressure fluctuation will be. So the convenience of operation of the turbine between air defined pressure tanks is justified.

Figure 3: OWC-DPST converter chamber. Upstroke movement.



Source: Authors

2.1.2. Pressure Inside the Tank

This section will now analyze the process of energy storage in tanks starting with the upward movement, with the help of Figure 3, an expansion of the area of the camera. The relative pressure is indicated with (*) as superscript. Without superscript indicates the absolute pressure. First let's look at the upstroke in the water column. The work converted, transformed into pressurized air, is given by:

$$W = \int_{H1}^{H2} P.A.ds \qquad (1)$$

In this converter, for a given height of wave and tide, we can choose the value of P and the integration limits, for each of the upward and downward movements, to operate within the range of defined values such that maximize the value of the function (1)

When the water level reaches its lowest position (the wave is in its Valley position), "O" level, the vent valve is closed, the relative air pressure chamber is zero, and the HPV and LPV valves are closed. The approaching wave introduces an amount of water into the chamber without difficulty rising up the level. Because all valves in the chamber are closed, the air pressure will rise. The absolute air pressure in the chamber depending on the water gap between the inner and the outer chamber levels, Δh, is given by:

$$P_{ch} = P_{atm} + \rho.g.\Delta h \qquad (2)$$

If the gauge pressure in the high pressure accumulator tank, HPT, is PH * (PH, absolute pressure,), let us determine how much the water level inside the chamber had to raise, so that the air pressure reaches this value.

Assuming an adiabatic compression, and according to the nomenclature indicated in Figure 3:

Wg Gravity acelleration [9,81m/s^2]
P Power [W]
P_{atm} Aatmospheric Pressure [Pa]
PCh Chamber pressure [Pa]
P^*_{Ch} Chamber relative pressure [Pa]
P_H High pressure tank pressure [Pa]
P^*_H Relative high pressure tank pressure [Pa]
P_L Low pressure tank pressure [Pa]
P^*_L Relative low pressure tank pressure [Pa]
H_i Initial upstroke movement [m]
H_s Initial downstroke movement [m]
H_o Lowest air column height [m]
H_w Wave height, valley peak [m]
T Wave movement period [s]
U Inner Energy [J]
W Energy [J]
ρ Sea water density [1.025kg/m^3]
γ Specific heat relationship.
Δ Upstroke movement level gap [m]
Γ Downstroke movement level gap [m]

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

yieling Hi as

$$H_i = (H_0 + Hw)\left[1 - \left(\frac{P_{atm}}{P_H}\right)^{\frac{1}{\gamma}}\right] \qquad (3)$$

The gap between the inside and outside of the camera to keep pressure $P_{Ch} = P_H$ in the chamber, Δ, shall be in accordance with the Eq (2):

$$\Delta = \frac{P_{ch} - P_{atm}}{\rho.g} = \frac{P^*_{Ch}}{\rho.g} \qquad (4)$$

Once reached the high pressure PH within the chamber, the valve HPV opens, and as it continues to rise the water column, air is entering the accumulator tank HPT. The upward movement from the water column, during which air is introduced, is called "upward stroke", SUU, and is defined as:

$$S_{UU} = H_w - H_i - \Delta \qquad (5)$$

The amount of storage energy in the accumulator tank HPT during this column movement, per m^2 of horizontal surface into the chamber, will be:

$$\Delta U_H = P^*_H.S_U = P^*_H.(H_w - Hi - \Delta) \;\; J/m^2 \qquad (6)$$

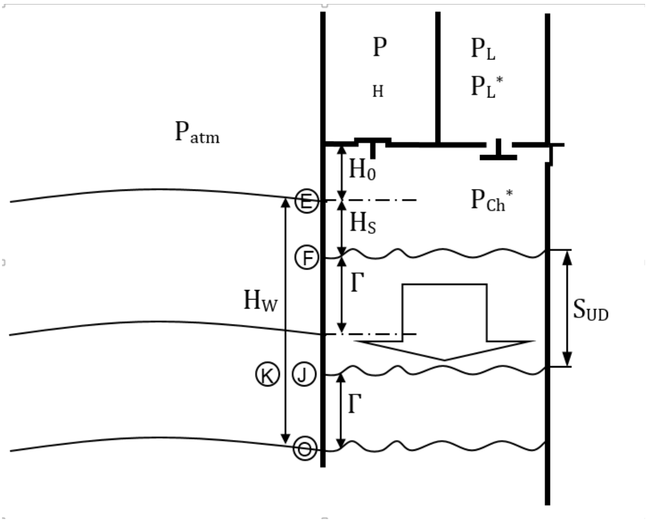
Replacing the Eqs. (4) and (3) in Eq. (6), this yields:

$$\Delta U_H = P^*_H.(H_w - Hi - \Delta) \qquad (7)$$

which expressed in absolute pressure yields:

$$\Delta U_H = (P_H - P_{atm}).H_w - \frac{(P_H - P_{atm})^2}{\rho.g} - \qquad (8)$$
$$-(P_H - P_{atm})(H_0 + H_w)\left[1 - \left(\frac{P_{atm}}{P_H}\right)^{\frac{1}{\gamma}}\right]$$

Figure 4: Converter chamber OWC-DPST. Downstroke movement



Source: Authors

Once the water column rise ends, the HPV valve closes and then the VV valve opens and the compressed air in the chamber is evacuated restoring the atmospheric pressure Patm, and the water column rises, already without back up pressure, up to the level of the outside. Arriving at this point, the valve VV is closed. Now with all valves in the chamber closed, the downstroke will begin, following the descent of the water from the outside of the chamber, with some steps similar to those described above, but with negative pressures.

The maximum energy that can be accumulated by each upstroke from the column is obtained by taking the partial derivative of the previous expression (8) with respect to high pressure and equating to zero. This is expressed as,

$$\begin{aligned}\frac{\partial U_H}{\partial P_H} &= H_w - \frac{2}{\rho.g}(P_H - P_{atm}) - \\ &-(H_0 + H_w)\left[1 - P_{atm}^{\frac{1}{\gamma}}.P_H^{\frac{1}{\gamma}}\right] - \\ -(P_H - P_{atm})(H_0 + H_w)&\left(P_{atm}^{\frac{1}{\gamma}}.\frac{1}{\gamma}P_H^{\frac{1+\gamma}{\gamma}}\right) = 0\end{aligned} \tag{9}$$

Since γ and g, P_{atm}, ρ, because of their low variation, can be taken as constant, a PH function for each wave height, H_W, and the minimum height, H0, such that maximizes the accumulated energy per cycle can be achieved. For a constant wave height, the value of H_0 will vary continuously according to the height of the tide.

The chosen pressure for the high pressure tank, P_H, will have a direct effect upon the useful energy.

Look at now, with the help of Figure 4, the downstroke of the oscillating water column. From the level "E", water level in the maximum, minimum value of height of vacuum gauge H_0, with all valves closed and chamber pressure equal to atmospheric pressure. As the water level outside the chamber decreases, the water level within the chamber will also decrease causing the air volume to increase and the pressure to drop until the pressure in the chamber equals the pressure in the low pressure accumulator tank, P_L when it comes to the "F" level. The order of opening the LPV is now given. Assuming an adiabatic expansion, it follows that:

$$\frac{P_L}{P_{atm}} = \left(\frac{H_0}{H_0 + H_S}\right)^{\gamma}$$

and solving for H_s yields:

$$H_s = H_0\left[\left(\frac{P_{atm}}{P_L}\right)^{\frac{1}{\gamma}} - 1\right] \tag{10}$$

At that time there will be a gap between the outside water and the water level within the chamber, Γ, given as

$$P_L = P_{atm} - \Gamma.\rho.g$$

where Γ is given by:

$$\Gamma = \frac{P_{atm} - P_L}{\rho.g} \tag{11}$$

As shown in Figure 4, the working stroke during the downstroke, SUD, will be:

$$S_{UD} = H_W - H_S - \Gamma \tag{12}$$

The converted energy from the LPT,$WL = \Delta UL$, during the useful part of the "downstroke", from the "F" level to "J" will be:

$$\Delta U_L = P_L^*(H_W - H_S - \Gamma) \tag{13}$$

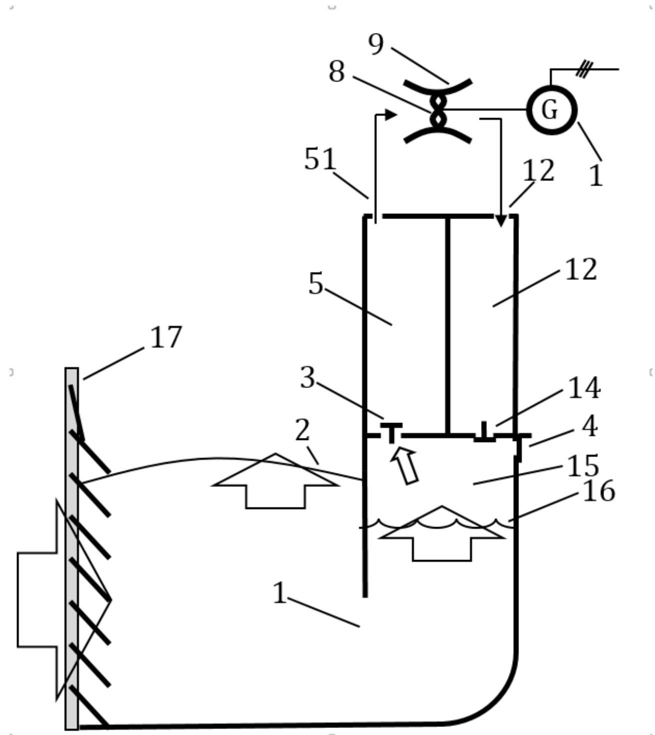
After the useful stroke, with the chamber water level at "J", the LPV valve is ordered to close, and an opening command is given to the VV valve, until the level becomes "O", that is, when the water column decreases to match with the minimum level on the chamber outside, valley of the wave. Thus, substituting equations (10) and (11) to (13) we can obtained the specific energy (energy per m^2) on the downstroke, of horizontal section of the chamber, J/m^2:

$$\begin{aligned}\Delta U_L = (P_L - Patm).\\ .\left[H_W - H_0\left(\frac{P_{atm}}{P_L}\right)^{\frac{1}{\gamma}} + H_0 - \frac{1}{\rho.g}(P_{atm} - P_L)\right]\end{aligned} \tag{14}$$

Just as we did for the upstroke, the pressure in the low pressure tank, PL, which maximizes the power accumulated power for the portion of the cycle corresponding to the negative pressures, can be achieved by taking the partial derivative of the function (14) with regard to PL and equating to zero, which corresponds to the equation:

$$\begin{aligned}\frac{\partial \Delta U_L}{\partial P_L} =\\ = \left[H_w - H_0\left(\frac{P_{atm}}{P_L}\right)\frac{1}{\gamma} + H_0 - \frac{1}{\rho.g}(P_{atm} - P_L)\right] +\\ +(P_L - P_{atm})\left[H_0 P_{atm}^{\frac{1}{\gamma}}.\frac{1}{\gamma}P_L^{\frac{1-\gamma}{\gamma}} + \frac{1}{\rho.g}\right]\end{aligned} \tag{15}$$

Figure 5: Alternative design for a OWC-DPST converter



Source: Authors

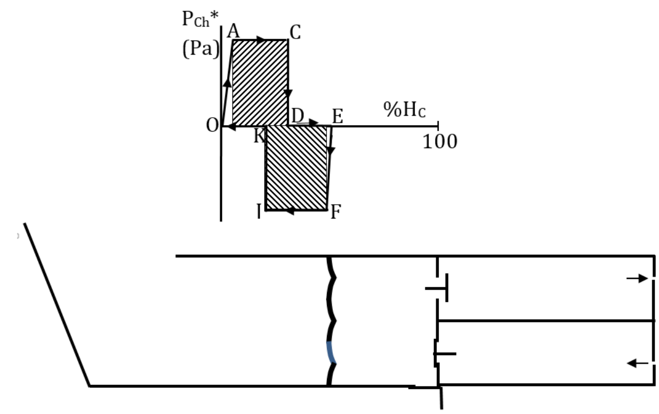
2.1.3. Alternative Designs

Figure 2 shows the basic idea of the OWC converter with differential pressure accumulator tanks. Other designs, with the same operating principles, can be made but that enhance certain practical aspects. Such is the case in Figure 5, where the turbine is located on the outside of the tanks, preventing the shaft way through one of the walls of the tank, eliminating the consequent problem of water tightness. The possibility of incorporating a previous grinding barrier, marked with 17, which allows the passage of water into the converter, but that makes it difficult for the passage in the opposite direction, holding water near its maximum level for a while could be. In this case, the actual behavior would be closer to the theoretical exposed behaviour

2.2. Theorical Cycle

To explain how to work through the theoretical cycle p-v, we will consider the ideal conditions enabling to represent the stages of operation. First the following assumptions are considered: regular waves, with a series of wave fronts at the same time approaching the converter, with a constant amplitude, and periodicity, which is the theoretical case. In terms of the behaviour of the sea water within the chamber, it is assumed that if the chamber were permanently connected with the atmosphere, the vertical oscillation amplitude would be equal to the height of the wave [Bakar, B.A. et al. 2011] as shown in Figure 6. Or, better, given a wave that causes a chamber connected with atmospheric pressure in a swing that let HW, we assume a height of wave H_W abroad and a behavior such as described in paragraph 2.1.1. Clearly, the design of Figure 5 presents this behavior. Resonance effects are not considered.

Figure 7: P-V cycle fot the OWC-DPST converter



Source: Authors

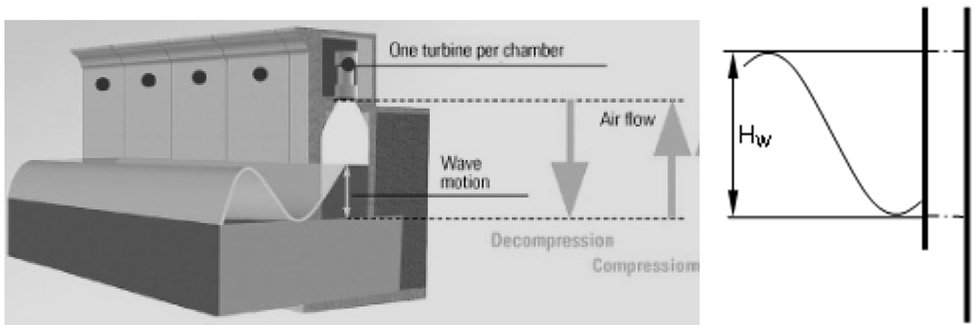
For the air, working at low pressures, it can be assumed to have a behaviour of perfect gas diatomic with a value of 1.39 γ (ratio of specific heats). It is assumed that the phases of compression and expansion of the air in the chamber, in a short time interval, are adiabatic [Gervelas, R. 2011]. In HPV and LPV valves pressure drops are neglected because they are remotely controlled and they will be closed when the pressure in the tank and the chamber are equal.

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 or corresponding to the level of water, both outside and inside the chamber, in its lower level. All the valves are closed and the chamber pressure is equal to atmospheric pressure

The water level begins to rise outside, and with some delay, also inside increasing up the level in a Hi distance and compressing the air inside the chamber, following an adiabatic evolution, until the A point in the cycle, shown in Figure 7, which is when it reaches the pressure of the high pressure accumulator tank. From the A point the opening order is given to the remotely operated valve HPV. The water level continues to rise during the way we will call SUU, useful upstroke, introducing air into the high pressure tank. This tank pressure will hardly suffer any variation due to the high volume (in figures 2, 5 and 7 storage tanks are not represented in scale). Completed the useful upstroke, point C, it is given the order of closing valve HPV and then the opening order to venting valve of communicating with atmospheric pressure chamber, point D. The water level will keep rising, with the pressure within the chamber being equal to atmospheric pressure, until it is even with the outside level, point E. At this point, the upstroke ends, the venting valve is closed (all valves are closed) and when the water level outside the chamber starts to lower, the downstroke starts. The drop in level, being the vent valve closed, it shall be accompanied by a decrease in the chamber pressure, following an adiabatic evolution, section from E to F. At this point the LPV valve is opened,

Figure 6: (a) OWC with courtesy of Voith Siemens Hydro Wavegen (b) Wave height and level oscillation in the chamber.



(a) (b)

Source: Authors

and during the "useful downstroke", SUD, the pressure remains slightly constant, from section F to J. At the J point, it is giving the order of closing the LPV valve and opening the VV valve, passing the chamber pressure at atmospheric pressure (section J-K). With the chamber open to the atmosphere, the water level continues to fall until reaching the minimum level of the chamber outside (section K-O) completing the cycle.

On the y axis the value of relative, positive pressure is represented on the HPT tank, and the negative on the LPT tank. On the x axis it is represented the chamber volume 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.

To represent the cycle in the p-v plane, the enclosed area represents a job, well-used energy. It is important to note that while some air flows are produced from the camera to the outside, and vice versa, when VV valve is open, the incoming mass flow in the tank PTH from the camera must be equal to the outgoing LPT towards the camera.

In Figure 7 a representation of the converter is accompanied with the P-V diagram (brought down 90 degrees).

Table 1 presents the numeric values for two specific conditions: i) $H_W = 2$ m; $H_0 = 2$ m and ii) $H_W = 1$ m; $H_0 = 2$m. For the purposes of calculating, the power is a period of waves, same for both cases, 10 s.

Note that for each case analysed, the particular value of H_0 and HW, the values for the pressures n the storage tanks, deduced from the equations (9) and (15), are not symmetrical

The values of Hi and Hs, are obtained from the equations (3) and (10). The "useful" stroke during the upstroke is obtained with the expression (5) and during the downstroke with the equation (12). The energy transformed into the upward stroke, WU, is obtained according to equation (6) and the downstroke, WD, according to equation (13). The sum of both, expressed in J/m^2, shown with W and P the theoretical power available.

The values for the pressure in the HPT tank correspond to maximum retrieved by solving the equation (9), however not the case for pressure LPT tank with equation (15), even if the indicated value is close to that value, since value that sets the pressure is what gives continuity in the mass flow.

The possible use of the residual energy from positive or negative pressures in the chamber and the atmospheric pressure from paragraphs C and J are not considered in this article.

3. Conclusions

In view of the above in the preceding paragraphs, with the proposed wave converter design improvements could be obtained over conventional designs, which can be highlighted in the following points:

- Energetic transformation performance comes from the accumulation pressure. The accumulator tank pressures that maximize the performance of the converter can be adjusted.

- Francis unidirectional flow turbines, with greater efficiency, can be used instead of the Wells of bidirectional flow.

- As the converter works at a steady, stable, smooth speed, dimensioned machines are not needed to work in power and torque peaks. Therefore, for a given power production, much smaller and cheaper and less powerful machines can be used.

- Synchronous generators directly connected to the grid could be used.

- A small wave height, not enough to be useful for a conventional OWC, could be capable of generating electricity in an OWC-DPST

- It could prevent erosion and deposits on blades of the turbine by impact of dragged salt water particles, requiring less maintenance cost.

- High noises coming from the output of the turbine, be avoided, which means less environmental impact

- Studying the converter performance using the cycle diagram on the P-V plane allows to understand more easily how to work.

Table 1: Quantification for two particular cases

H_W (m)	H_0 (m)	S_{UU} (m)	S_{UD} (m)	H_i (m)	H_s (m)	P^*_{HPT} (Pa)	P^*_{LPT} (Pa)	W (J/m^2)	P (W/m^2)
2	2	0,993	1,111	0,213	0,118	8000	-7768	16573	1657
1	2	0,498	0,529	0,086	0,061	4185	-4134	4272	427

Source: Authors

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