Resonating wave energy converter for delivery of water for desalination and energy generation

Davide Magagna[1]; Dimitris Stagonas[1]; David Warbrick[1]; Gerald Muller[1]

[1] Sustainable Energy Research Group, School of Civil Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, United Kingdom

Abstract

The supply of clean drinking water is of great concern in many remote coastal areas. One method of providing this clean water is the process of desalination of seawater. This process generally requires either high temperatures (evaporation processes) or very high pressures (6MPa for reverse osmosis processes).

Current research at the University of Southampton focuses on the development of a wave powered stand-alone system for desalination and/or electricity production. A high pressure pump has been developed for pressurization of seawater for direct use in a reverse osmosis desalination process. The high pressure pump is driven by a supply of water, of 2 meter head, delivered by a simple wave energy converter. The proposed system has the benefit of simple technology and possesses significant potential for use in developing countries. This paper focuses on the device which will deliver water to the high pressure pump. The delivery device constitutes a wave energy converter and uses the principles common to most Oscillating Water Column (OWC) systems to pump water.

Keywords: OWC, desalination, energy conversion

Nomenclature

α	=	output duct angle
$\xi_{I,E}$	=	friction losses coefficient at entry
ξ_{Ex}	=	friction losses for outflow of water from OWCP
$\xi_{I,E}$	=	friction losses for inflow of water into OWCP
ξ_R	=	radiation damping
ω_p	=	natural frequency of oscillation pump
A	=	cross sectional area of the pipe
d	=	water depth at rest
D	=	damping coefficient
g	=	gravitational constant
H	=	incoming wave height
H_p	=	pumping height
l_1	=	length of input duct
l_2	=	length of output duct
l	=	total length of pipe representing mass of water at rest
l_a	=	added length of water in the pipe following a wave surge
L_F	=	length of fluid existing the output duct
MWL	=	Mean Water Level
OWC	=	Oscillating Water Column
OWCP	=	Oscillating Water Column Pump
RO	=	Reverse Osmosis
T	=	Wave Period experimental setup
T_{max}	=	Maximum T_w to give significant amplification
T_{min}	=	Minimum T_w to give significant amplification
T_n	=	Natural period of oscillation pump
T_{peak}	=	T_w at which amplification was maximum
T_w	=	incoming wave period
V_p	=	pumped volume
x	=	vertical displacement
xH	=	Amplification factor of H

1 Introduction

Most existing desalination systems present limitations, such as high costs and energy requirements, which have prompted researchers to explore alternative energy sources to power desalination plants. Solar, wind, biomass, wave, and hybrid systems have all been implemented worldwide.

Whereas solar and biomass technology have been widely employed, wave energy driven systems have only seen significant development over the last 20 years and have still to find wider applications [1] .

The development of wave energy driven desalination has been inhibited by the difficulties of harnessing wave energy in an efficient way. Solving the issue related to wave energy will aid the development of wave driven desalination.

The practical application of most of the existing renewable energy driven desalination systems is limited by the high level of technical knowledge required by the operators and the complexity of the systems. This has inhibited the installation of desalination technologies for supplying clean water in poor and undeveloped areas; areas where this technology could be of greatest benefit [2] .

In these rural areas a different approach to the design of desalination technologies is needed to reduce the total costs of installation and operation and hence enable the wider use of this technology [3].

It is therefore important to define the main features that need to be taken into account in the

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implementation of a renewable energy driven system for supplying fresh water in rural areas. In particular the following two points must be satisfied for successful implementation:

- ease of use; in order to reduce the technical knowledge needed for operational management
- low cost technology; robust and simple to build and maintain .

A wave energy driven desalination system has been developed and it is characterized by being designed as a stand alone system – not requiring connection to an electricity grid - and not requiring electricity or supervision during normal operation. The system comprises of two main units: the WaveCatcher, a pressure intensifier, and a delivery pump, OWCP; which effectively uses the momentum contained in the incoming waves together with resonance principles to lift water to the WaveCatcher. (Figure 1)

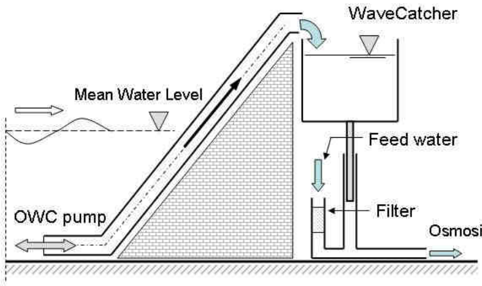

Figure 1: Proposed installation of the OWC wave Pump with WaveCatcher.

The WaveCatcher, a high pressure pump, was developed in order to pressurize seawater, which is then fed directly into a RO membrane for desalination. It comprises a large container, into which the wave pump empties the water, a small diameter high pressure piston onto which the full weight of the container acts thus generating a very high pressure, and an RO membrane, Figure 1. The design characteristics of the WaveCatcher allow for generation of at least 6 MPa of pressure (RO requirements) from low head pressure differences [4].

Whilst the high pressure pump can operate continuously to generate and maintain the required osmotic pressure, it is necessary to maintain a continuous supply of water, of 1-2 m head, from wave action. The delivery of water to the High pressure pump is achieved by an Oscillating Water Colum wave Pump (OWCP).

The OWCP consists of a pipe with a horizontal underwater section and an inclined pumping section, which extends above MWL (Figure 2). As waves pass, the pipe acts as a resonator with a natural period of oscillation, T_N. To maximize water delivery, the pump must be tuned to the incident wave period.

This paper discusses the use of the OWCP as an active wave energy converter for the delivery of water at 1 – 2 m head and presents recent developments in this field. It has to be noted that although the water for the high pressure pump is lifted above the structure, the OWCP does not constitute a classical overtopping device, such as the Tapchan or the WaveDragon. It is a resonator which shows a dynamic response to the incoming wave and uses this effect to transport water above crest height of the incoming waves.

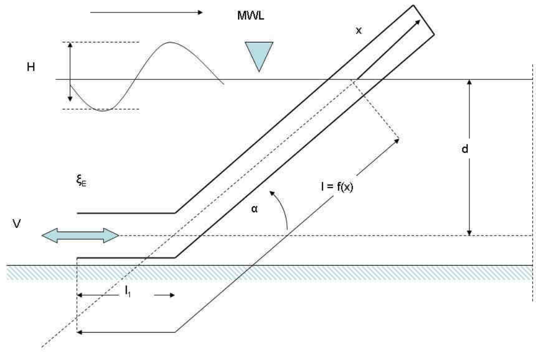

Figure 2: OWC Wave Pump - Theoretical variables l_1 the length of the input duct, d the water depth, H the incident wave height, l the total length of the column of water contained in the pipe and α the angle of inclination of the output duct.

2 Resonating wave energy converter

The OWCP proposed here is based on a principle first presented by Evans [5] and a somewhat similar but significantly more complex device previously developed by Czitrom et al., [6, 7]. The new OWC pump system is composed of a two part resonant duct connected with a flexible joint, allowing resonance control by varying the angle of the output duct (Figure 2). The OWC pump works effectively as an energy converter, changing the kinetic energy of the incoming wave into potential energy to lift the water inside the tubes. The difference to Czitrom's SIBEO device is the way in which resonance control is achieved, describing the pump as a damped oscillator.

In the original design [6] resonant conditions were maintained through control of the air compression chamber; adjustment of the volume of air contained in the chamber to modify the stiffness of the air spring [8]. In order to modify the air spring and the volume of air contained within the chamber, the SIBEO was equipped with a microchip that sampled the wave conditions and varied the volume of air in the chamber accordingly [9]. The system proposed by the authors for maintaining resonant conditions, by varying the angle of the output duct, is a simplification of the OWC pump aimed at reducing costs and increasing ease of use; both of which have been identified as essential for the application of this technology in rural areas and developing nations.

Mechanical similitude of the OWC wave pump

Research into the performance of OWC devices has been conducted since the 1970s [5], followed by a detailed mathematical description of the forces acting on such systems [10, 11]. More details can be found in

Chung's review of the oscillatory motion of water in an open pipe [12]. In the literature, the OWC wave pump was characterized as a damped oscillator. The OWC effectively acts as a resonator, described by its natural frequency of oscillation ω_s determined as shown in equation (1)

$$\omega_s = \sqrt{\frac{g}{l}} \tag{1}$$

Where *l* represents the total mass of water contained in the pipe and depends on the angle of inclination *α* as described by equation (2)

$$l = l_1 + \frac{d}{\sin \alpha} \tag{2}$$

Alternatively the OWCP is described by it natural period of oscillation. Whilst T_N can generally be expressed as $T_N = 2\pi / \omega_s$ it is important to include the effect of damping (*D*) on the natural period of oscillation as shown in equation (3)

$$T_N = \frac{2\pi}{\sqrt{(g/l)(1-D^2)}} \tag{3}$$

To reach resonance, it is necessary that the pump is tuned with the wave climate, hence that $T_N = T_w$. When, resonance conditions are reached, lift heights considerably exceeding the wave height can be achieved. Damping effects are due to friction inside the pipe and turbulence at the entry ($\xi_{I,E}$) and to radiation of waves outside the OWCP (ξ_R). The overall effect D is given by

$$D = \xi_{I,E} + \xi_R \tag{4}$$

It can now be observed that the angle *α* effectively acts as a resonance control; when the angle of inclination is changed the natural frequency of oscillation ω_s varies accordingly as shown in Figure **3**, widening the ranges of frequencies that amplify the lift height achievable to a maximum.

Previous work showed that alterations of a single parameter of the system can cause changes in the resonance control of the OWC pump [13].

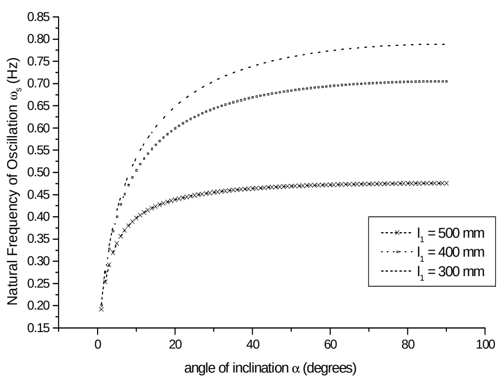

Figure 3: Frequency vs. angle, for different input pipe length

The theory behind the OWC pump has so far proven that a device like the one presented here can act as a wave energy convertor (WEC) for delivery of water and can easily be tuned to different wave conditions. Physical testing is, however, required to determine the capability of the OWCP to deliver water to a fixed position.

Consequently, laboratory studies were conducted along with theoretical analysis with the aim of facilitating the implementation of the OWCP at full scale.

3 Methodology

The performance characteristics of the OWCP will be determined using a combination of physical model tests and theoretical modelling. A 1:40 model of the OWCP was built and tested in a wave flume at the University of Southampton, UK, in order to determine the performance under varying incident wave conditions and to evaluate the maximum lift heights achievable. For simplicity, a range of different configurations of the OWCP were used - rather than the proposed flexible joint - for analysis of the resonance control. Implementation and testing of the flexible joint will be carried out at later stage.

The physical model testing allowed for the determination of the relationship between the wave regime (wave height and period) and the lift height achievable.

Different configurations of the OWC pumps and wave flume conditions were taken into account in order to produce the highest possible number of scenarios. The main parameters varied during the experimental procedure are given in Table 1.

Different pump diameters were used to reduce the effect of friction losses (larger diameters yields a smaller friction effect) and to identify damping and scale effects due to the testing conditions.

Parameters	Range of values	Increase Step
Angle of inclination	15 º -30 º	5 º
Internal diameter	15-25 mm	10 mm
Water Depth inside tank	80-105 mm	5 mm
Angle of incoming wave	0 º-15 º	5 º(*)
Type of Slope	1:20 – 1:8	
Location of OWC Pump	Bottom/ half d	

Table 1: Parameters varied during the physical model testing of the OWC PUMP. For each run a parameter was changed, generating 768 possible testing configurations. (*) A programme of testing in a 5m by 2m wave basin is planned to assess 3D effects.

Wave flume test setup

Wave flume tests were conducted in a 6 m long, 0.2 m wide and 0.2 m deep, clear acrylic sided, table top wave flume. A piston type wave paddle was used to generate small, monochromatic waves with heights ranging between 1 to 5 cm. Wave periods also ranged between 0.5 - 1 s within the flume, corresponding to prototype scale waves of approximately 4.9 to 9.9 seconds wave period using Froude's scaling. Three resistance type wave gauges were used to monitor the wave conditions. In this first testing phase only monochromatic waves have been used.

A Styrofoam ball was placed in the centre of each pump, on a specially designed rail to follow the movement of the water surface. The ball displacement was recorded by a digital camera (60fps) and subsequent image analysis revealed the lift heights achieved (Figure 4).

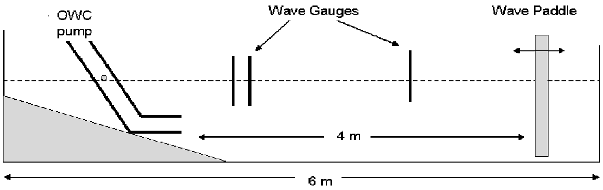

Figure 4 Setup for wave tank physical experiment.

Field tests

In order to verify the response of the OWC pump to real seas and random waves and to test the survivability of the pump under adverse weather conditions, sea testing was started.

A first phase of sea testing started in February 2009 at Milford on Sea (50.71227 N, -1.61415 E) on the South Coast of England.

The location was chosen due the availability of accurate sea state data allowing the rapid mobilization of the equipment in response to favorable conditions.

Wave data, including dominant and peak, deep water wave height, wave period and direction were provided by wave rider buoy located in the English Channel in close proximity to the testing site. The wave data was provided by the Channel Coastal Observatory, UK (CCO).

The wave data was supplemented with local shallow water measurement of incident wave conditions made from the shore during testing of the OWCP. Nearshore measurements consisted of shallow water wave height, wave period and direction, and the vertical lift height achieved by the OWC.

For the sea tests, a pipe with 110 mm diameter was used. The length of the input duct (l_1) was of 1m, while the length of the exit duct was of 5m (l_2). The pipe was positioned at a water depth of 0.9 m, and was attached to a groyne for stability.

For the preliminary testing, an opaque pipe was used; hence, it was necessary to devise a method of extracting the water level within the pipe. To do this, holes of 5mm diameter were drilled at a spacing of every 100mm along the exit duct. The lift height was estimated with the use of a videocamera; using the highest hole where water was seen to escape as a guide to the water level within the duct. The dimension of the holes was such to have negligible effect on the water level achieved within the OWCP, however the spacing of the holes is considered likely to result in a slight underestimation of the lift height achieved, of the order of 100mm. A second phase of testing is underway at the time of writing. This phase of testing has been broadened in order to measure the volume of water delivered to a fixed height for each incoming wave using an array of pipes each tuned to a particular wave frequency. This is because, as seen in the laboratory results and in the literature[7], each configuration of the OWC pipe responds monochromatically to a polychromatic input. Full results of real sea testing of the OWC pump are expected by June-August 2009.

Mathematical Model for the OWCP

A simple linear mathematical model was initially developed. Comparison with experimental results however indicated that a linear model was not suitable. The model was therefore expanded to include two non-linear terms:

1. The mass contained in the tube; $m = \rho\ (l + l_a + x / \sin \alpha)$ whereby x is the vertical displacement

2. The damping: turbulent damping at the entry/exit is considered to be dominating; this is however a function of $(dx/dt)^2$ with different loss factors for inflow ($\xi_I = 1.0$) and exit ($\xi_E = 0.5$).

The model is needed to validate the data obtained from physical testing and better evaluate parameters such as friction and damping. The model, once validated will be used to forecast real sea applications.

The numerical scheme used takes into consideration the wave conditions generated in the physical modeling and computes the movement of the mass of water inside the OWCP at the passing of each wave. Each incoming wave exerts a force $F(t)$ acting on the input pipe of the OWC pump and at any time can be expressed by equation (5)

$$\rho\left(l + l_a + \frac{x}{\sin\alpha}\right)\frac{d^2x}{dt^2} + \rho g x \sin\alpha + \operatorname{sgn}\left(\frac{dx}{dt}\right)(\xi_{I,E} + \xi_R)\frac{\rho}{2}\left(\frac{dx}{dt}\right)^2 = F(t) \qquad (5)$$

The first part of equation (5) includes terms for the mass acceleration inside the pump; the losses due to friction and the action of the restoring gravitational force. In the numerical solution, the $(dx/dt)^2$ damping term is multiplied with sgn(dx/dt) in order to maintain energy extraction from the system. The mathematical model has also been implemented for the determination of the volume of water that can be pumped for a given pump height H_P. The pumped volume V_P is given by equation (6)

$$Vp = (x - H_p) \times A \qquad (6)$$

The pumped volume corresponds to the amount of water that can be delivered to the High Pressure desalination pump and the influence of the cycle time of the WaveCatcher. The pumping action was implemented into the numerical model, and the pumped volume per wave can then be expressed as the length of fluid L_F which exits the pump at the prescribed pumping height H_P. Both values are non-dimensionalised by dividing them by the wave height H. **Figure 5** shows the normalized pumping volume L_F /H as a function of the ratio of wave period and natural period of the pump for relative pump heights H_P /H ranging from 2 to 4.

The removal of mass and energy from the system increases the system bandwidth as expected; the more energy that is extracted, the wider the response curve becomes.

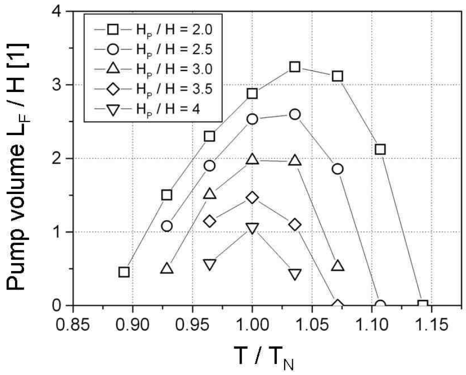

Figure 5: Pumping volume as function of pump height, wave height and period

4 Results and discussions

Video analysis was used to determine the lift height achieved at various stages of the process, for both resonant and non resonant conditions. From image analysis it was possible to determine the wave height of the incoming wave, the maximum height of wave on the column and the maximum lift height inside the pump.

Analysis of the data obtained from physical testing of the OWCP have shown that the maximum lift height for a 30º angle pump with 95 mm water depth was 45 mm (taken at the level of Styrofoam) for 20 mm incident deepwater wave height, giving an amplification factor of 2.25*H*. The maximum lift height achieved for the same test, taken as the maximum height a particle of water can achieve is of 60 mm, 3 times *H*.

and Figure 7 present frameshots highlighting the effect of the incoming wave period on the maximum lift height that is achievable for two different wave conditions for the same pipe configuration (30º angle at 95 mm water depth).

For each of the OWCP model presented in Table 1, the natural period of oscillation was determined along with the range of periods that produced remarkable amplification of the incoming wave height. These are reported in Table 2 along with the average amplification factor determined for the case study presented.

Angle	T_{min}	T_{max}	T_{Peak}	*xH*
15 º	1.12	1.53	1.25	1.9
20 º	1.11	1.42	1.17	2.0
25 º	0.83	1.05	1.00	2.2
30 º	0.76	0.95	0.85	2.25

Table 2 Natural Period of oscillation for specified configuration of the OWC tested with 95 mm water depth

Damping, friction and scale effects

Strong damping effects were observed in all the physical model tests.

For the 30º angle at 95 mm water depth a theoretical value of the natural period of oscillation was determined as 0.98 s; damping and friction effects shifted the observed value to 1.41 s. The fact that damping increases the natural period of the system means that it can be employed to tune the pump to the prevailing wave period.

Furthermore the use of dye allowed the observation of the friction and reflection effects that occurred at the mouth of the input duct of the pipe as well as the visualization of the behaviour of the mass of water contained in the OWCP. (Figure 8): dye was inserted when maximum amplification was achieved within the pipe. The use of dye was considered suitable since the interest focused on the visualization of the mass of water and its dispersion while exiting the mouth of the input duct.

Figure 6 Frameshots of incoming wave exerting force on the pump at non resonant conditions. (a) Incoming Wave and measurement of wave height on the slope; (b) maximum wave height achieved and (c) maximum lift height.

Figure 7 Frameshots of incoming wave exerting force on the pump at close to resonant conditions. (a) Incoming Wave and measurement of wave height on the slope; (b) maximum wave height achieved and (c) maximum lift height

In order to quantify the losses at lip (entrance) of the OWCP pump the us of Particle Image Velocimetry (PIV) is preferred [14].

PIV experiments for the determination of losses around the OWCP are planned at a later stage of the present research. Reduction of these losses will be beneficial to the implementation of the OWCP in future.

Figure 8 Frameshot of dispersion and losses at the mouth of the OWCP. It is possible to notice that the dye is dispersing while exiting the OWCP.

Comparison with mathematical model

The mathematical model was developed to replicate the laboratory experimental. At the present time, only a few simulations have been run to validate the numerical model against laboratory tests.

A more thorough validation of the numerical model against a broader range of laboratory tests is planned and will enable determination of the value of the ξ_E , ξ_I, ξ_R coefficients.

However, it was possible to compare the data obtained from experiments with the data obtained from the numerical model for some particular cases. Figure 9 presents the comparison of the data obtained from the simulation model and those obtained in the lab for the 30° angle, 85 mm water depth, 15 mm diameter test.

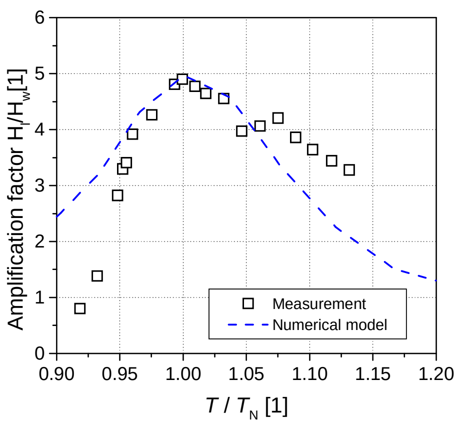

Figure 9 Comparison of the lift height amplification factor (H_l/H_w) between simulation and experiment.

The correlation obtained between simulation data and experimental data is good for values close to the natural period of oscillation; however when moving away from resonant conditions, experimental and theoretical values are found to disagree somewhat although the trends are similar (graph is skewed towards higher ration T / T_N). It is believed that pipe wall effect has a strong influence in reducing the amplification factor at low frequencies, while it amplifies the wave signal at frequencies higher than resonant. The non-linear equation does however provide a significant improvement over the hitherto employed linear models which utilized empirical 'added mass' factors to match experimental results.

5 Conclusion and further work

In this paper the use of an OWC wave pump, as an energy converter for the delivery of water to be coupled with desalination devices, was presented.

The OWC wave pump is an affordable alternative energy source that, when coupled with the WaveCatcher can be used for the supply of clean water in remote areas without the high costs of conventional desalination technology.

Experiments showed that the OWCP, fitted with resonance control is able to amplify the incoming wave signal by up to 5 times the incident wave height, with an average value of the amplification factor ranging between 2.25 and 4 time the incident deep water wave height.

With the physical model test it could be demonstrated that for each configuration the OWCP achieves it maximum delivery with waves of a period close to the natural period of the OWCP. These results show that it is possible to tune a particular type of OWC wave pump according to the dominant wave periods present in a defined area.

The research presented here provided encouraging results for the future application of the OWCP wave pump. Further work is required to more fully assess the use of the OWCP as a water delivery device. The device may also have further potential as a system for increasing water exchange between the ocean and enclosed basins for the improvement of water quality and hence amenity value.

In particular current and further work is focused on the development of a Pan-flute array of pumps each tuned to a different incident wave period; making the OWCP independent of seasonal changes of wave climate and 3D wave flume test to analyze arrays effects and determine how different angles of incoming waves affect the delivery.

The simplicity of design of the OWC pump prototype allows for efficient testing of the device at sea utilizing the availability of local wave climate data. In future work, for both sea and laboratory testing, the maximum volume of water delivered will be measured. Particle tracking software will be used to determine, with higher accuracy, the maximum achievable lift heights. Focus will also be given to analyze the changes in the resonance properties due to the removal of water from the OWCP and into the correct estimation of the values of the friction $\xi_{I,E}$, and damping ξ_R coefficients.

6 Acknowledgements

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