Desalination and Water Treatment
www.deswater.com
7 (2009) 47–52

A wave energy driven RO stand-alone desalination system: initial design and testing

Davide Magagna*, Gerald Muller

Sustainable Energy Research Group, School of Civil Engineering and the Environment, University of Southampton, Highfield, SO17 1BJ, UK
Tel. +44 2380 594656; Fax +44 2380 677519; email: dm7@soton.ac.uk

Received 30 September 2008; Accepted 28 May 2009

ABSTRACT

Traditional desalination systems have high energy requirements which can be considered as the limiting factor for their application. Using renewable energy sources for desalination of seawater and brackish water can help to alleviate water scarcity in those areas with no electricity grid connection or supply shortages. This paper describes the development of a stand-alone, off-grid desalination system powered by wave energy. The device is designed to drive a reverse osmosis (RO) membrane. No electricity is required. The system consists of two main parts; a high pressure pump (WaveCatcher) that allows generation of a high pressure head from low head differences, and a wave driven pump to supply the necessary head to the WaveCatcher. The high pressure pump is designed to produce 6 MPa of pressure which is necessary to drive a RO membrane for desalination of water. A 1:6 scale physical model was built and tested; pressures of 42 m were achieved from an initial pressure head of 0.2 m. Delivery of water to the WaveCatcher is to be achieved through the use of an oscillating water column (OWC) pump. The pump consists of a two-part resonant duct, which allows resonance control by varying the angle of the output duct. Maximum lift heights of five times the wave height were reached. The initial experiments showed that the WaveCatcher can generate the necessary pressure to run the RO membrane for the production of drinking water without the use of electricity.

Keywords: Reverse osmosis; Wave energy conversion; Sustainable development

1. Introduction

The limitations of traditional desalination systems have prompted researchers to focus on alternative energy sources to power desalination plants. Solar, wind, biomass, wave, and hybrid systems have all been implemented and installed worldwide.

While solar and biomass technology have been widely employed , wave energy driven systems were developed mostly in the last 20 years and still have 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.

Furthermore, for all renewable energy driven desalination systems, the technical knowledge and complexity of the system always lead to restrictions in the use of clean desalination technologies for supplying water in poor or

---

*Corresponding author.

Presented at EuroMed 2008, Desalination for Clean Water and Energy Cooperation among Mediterranean Countries of Europe and the MENA Region, 9–13 November 2008, King Hussein Bin Talal Convention Center, Dead Sea, Jordan.

undeveloped areas [2]. In order to provide clean water for rural areas, a different approach for desalination technologies is needed, aiming at reducing the cost of the technology, hence making desalination widespread [3].

Two main features of the system can be defined:

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

Although efficiency in traditional desalination systems is fundamental for reducing running costs of the system, it cannot be used as a limiting factor when the production of clean water is aimed at satisfying primary needs.

This paper describes the development of a simple off-grid wave energy driven desalination system. The system presented here was designed to drive a reverse osmosis (RO) membrane by using wave energy, thus requiring no electricity. The main requirements for the system is the conversion of wave energy into a pressure head, and the provision of the very high pressure needed for the RO cell of 6 MPa or 600 m water column (w.c.) from the low head difference generated by wave action. The system consists of two main parts: (1) a high pressure pump (WaveCatcher) for the generation of a high pressure head from low head differences, and (2) a wave driven pump to supply the necessary amount of water to run the WaveCatcher.

2. The WaveCatcher system

The WaveCatcher system has been designed in order to drive a RO desalination membrane without the generation of electricity. The energy needed to pressurize the feed water will is generated from the high pressure pump, trough conversion of the energy content of the incoming waves.

The key points upon which the design of the WaveCatcher was based were:

- installation in rural areas, requiring ease of use of the system, and therefore minimum maintenance
- installation of the device nearby the sea or ocean in order to exploit energy from wave action [4]
- structure of the WaveCatcher capable of resisting harsh environmental conditions such as wave impact and corrosion.

On this basis a design of the system was developed: initially the WaveCatcher was designed to achieve at full capacity the generation of high pressure head (6 MPa or 600 w.c.) from a low head difference (0.02–0.03 MPa) corresponding to a mean wave height ranging between 2–3 m.

The working principle of the WaveCatcher is based upon the accumulation of water from wave action to cyclically drive a piston: water is collected in a tank; the weight of the water then activates a piston system which generates high pressures.

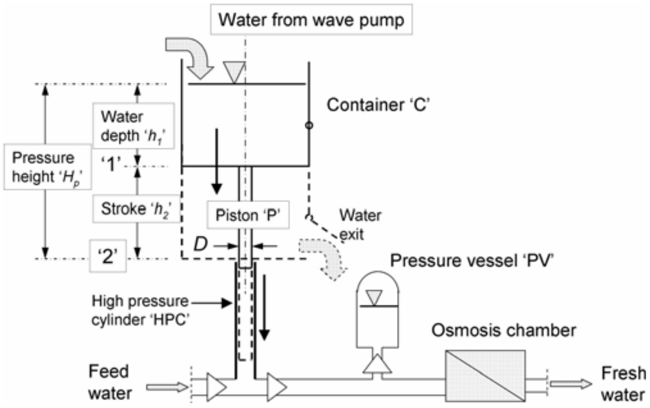

Fig. 1. Scheme of the working principle of the WaveCatcher. The water collected in container C of depth h_1 and area A, drives the piston P of stroke h_2 and diameter D. The feed water is pressurized and sent to the RO chamber. The pressure vessel (PV) is used to avoid pressure surges on the membrane. The system works if the weight of the water in the container generates a pressure of more than 60 MPa (600 m w.c.).

In Fig. 1 a sketch of the installation of the WaveCatcher describing the main components of the system is presented. A series of pressure vessels, valves and a storage tank are installed at the output of the WaveCatcher pump. This allows for the pressurized water to be stored without pressure losses. The use of the storage tank is necessary in order for the WaveCatcher to maintain the required pressure on the RO membrane [5].

$$\frac{\rho g A h_1}{(D^2/4)\pi} \geq 6\,\mathrm{MPa} \tag{1}$$

An initial analysis was conducted to determine the efficiency of the system with regards to the location of the installation, considering the WaveCatcher as a simple potential machine. The overall efficiency of the system depends on two main design parameters: the depth of the collection tank h_1 and the length of the piston stroke h_2 as reported in Fig. 1. Two types of installations were analyzed theoretically with the piston stroke starting at the mean water level (m.w.l.) and with the stroke starting above m.w.l. (Fig. 2). From testing it has been determined that in order to operate at higher efficiency it is necessary to install the WaveCatcher above the main sea level and to be designed to work at high h_2/h_1 ratios. Fig. 3 illustrates how efficiency is maximized by high h_2/h_1 values, suggesting models with wide collecting area and shallow depth, with the piston above m.w.l.

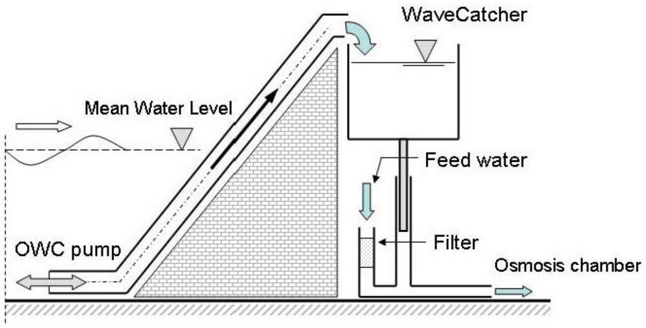

Fig. 2. Proposed installation of the Wavecatcher with OWC pump on an existing breakwater.

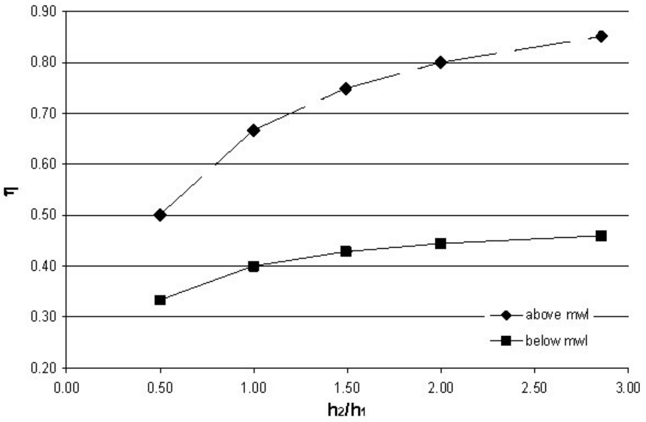

Fig. 3. Efficiency of the WaveCatcher at different configurations.

For this reason, it was determined that the ideal location for the installation of the WaveCatcher would be in the proximity of a steep shore, or on a breakwater. The delivery of water to the WaveCatcher is then of primary importance for the functioning of the system.

The WaveCatcher needs to be supplied with incoming water from wave action in order to generate the required pressure to drive a RO unit. Feed water is to be supplied to the WaveCatcher by an oscillating water column (OWC) water pump. The pump acts as an energy converter exploiting the continuity of the momentum of the incoming wave to amplify the wave height and lift the water conveyed in the ducts to a required level.

3. Methodology

The research project here presented is composed of different phases, each aimed at the development and study of every component of the system. The first phase of the project was aimed at the design, development and testing of the WaveCatcher high pressure pump: the piston pump mechanism was built in different configurations to assure a constant and automatic function of the filling/emptying mechanism of the collection tank. A 1:6 model of the WaveCatcher was built and tested under different conditions in order to determine the maximum pressure achievable. The WaveCatcher was developed to achieve full functionality with a production of 6 MPa of pressure from lift heights of about 1.2 m, i.e. initial pressures of 0.012 MPa. Experiments were conducted to determine the maximum pressure for the scale model. The design characteristics of the scale model used for investigation during the physical testing are given in Table 1. It is important to notice, that according to the required pressure to drive the RO membrane, the dimension of every component of the WaveCatcher can be changed, therefore varying the efficiency of the system and the intensity of the pressure generated

Table 1
Dimensions of the scale model and for the prototype of the WaveCatcher. h_1 and h_2 refer to Fig. 1

Dimensions	Model, mm	Prototype, m
Piston diameter (D)	13 mm	0.078 m
Piston stroke (h_2)	84 mm	0.504 m
Collection tank height (h_1)	200 mm	1.20 m
Collection tank width	200 mm	1.20 m
Collection tank breadth	200 mm	1.20 m

A second phase consisted of theoretical studies and physical testing of an efficient way to convey water to the WaveCatcher. As previously stated, in order for the WaveCatcher to generate the required pressure and achieve full functionality, it is necessary to supply the collection tank with incoming water from wave action. For this purpose two wave energy converters were initially evaluated: an overtopping ramp and an OWC pump. Both convert the kinetic energy of the incoming wave into potential energy to lift the water.

Limitations to the overtopping system were soon noticed; therefore, studies on the delivery system were mostly focused on the functioning of the OWC pump. The pump was developed on the basis of the device presented [6,7], with a different resonance control system, and it is used to convert the kinetic energy of the waves in to potential energy to drive the WaveCatcher.

The proposed OWC pump is composed of a two-part resonant duct connected by a flexible joint, allowing resonance control by varying the angle of the output duct. A sketch of the OWC pump can be seen in Fig. 4. OWC pump tests have been carried out in a 4 m long, 0.2 m wide and 0.2 m deep wave tank. The water depth during testing was of 84 mm. The internal diameter of the pump was of 15 mm, and the horizontal section had a length of l_1 = 45 mm with an inclination angle $\alpha = 30°$ for the lifting section. Tank wave periods ranged between 0.5–1 s with wavelength of testing waves ranging between 0.39 to

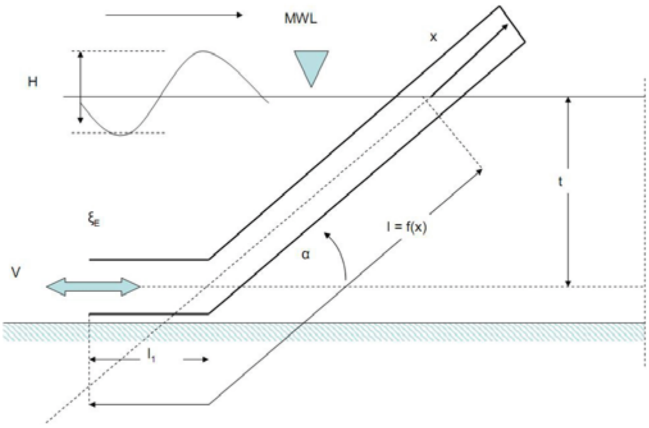

Fig. 4. Diagram of the OWC pump where l_i is the length of the input duct, l length of the input and output duct, t water depth and α angle to horizontal.

1.56 m. This is translated in real scale to waves with period of about 3.5 to 7 s. Analysis of the volume of water delivered per incoming wave is presented, along with studies of how removal of water affects resonance control.

4. WaveCatcher: pressure testing results

The scale model of the WaveCatcher was tested in order to determine the maximum pressure achievable, and the increase of pressure generated by each stroke of the piston. It was estimated by theoretical calculations that the maximum pressure achievable by the model was 0.48 MPa when considering the losses due to friction between the material and the limitations due to the dimensions of the parts. Friction losses are expected to reduce tenfold when at full scale; however, a precise estimation is not possible at the moment.

In order to determine the maximum pressure achievable, a 2l PET bottle was attached as a load, and water was supplied to the WaveCatcher at constant intervals. At each stroke the change in pressure was determined; the water collected in the tank released and the tank was driven back to the starting position with the use of a 3 kg counterweight. The continuous repetition of the procedure generates the build-up of pressure in the pressure vessel.

A decrease in the ratio of build-up in the storage tank was noticed, with the pressure reaching a stationary level after more than 300 strokes. This is explained by the fact that the pressure in the vessel had to be built up from zero; once the maximum pressure was reached the system losses could be estimated. After 350 strokes the pressure in the vessel stabilized at the maximum value of 0.42 MPa, achieving 85% of the theoretical pressure that could possibly be generated by the model. A plot of the increase of pressure in the pressure vessel can be found in Fig. 5.

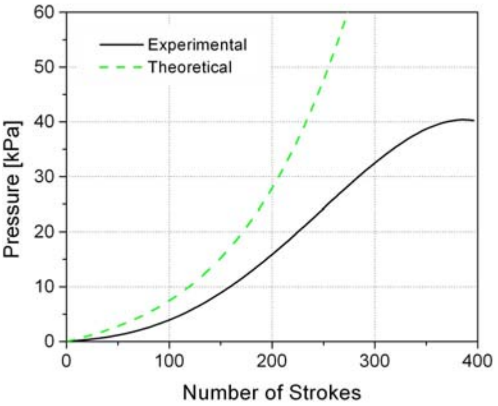

Fig. 5. Pressure build-up vs number of strokes compared with theoretical calculations.

5. OWC pump: testing and results

The correct functioning of the OWC pump is critical for the positive outcome of this research. Theoretical studies were therefore conducted before physical testing started. In particular, studies were conducted to determine the resonant frequency, and the effect of the output angle on resonance, and the overall delivery efficiency of the pump. The output angle of the pump acts as resonance control for the system. Resonance in the pump occurs when the natural frequency of oscillation of the pump ω_s is equal to the frequency of the incoming wave f [Eq. (2)] [8]:

$$\frac{\omega_s}{2\pi} = f \tag{2}$$

where ω_s is given by

$$\omega_s = \sqrt{\frac{g}{l + \frac{t}{\sin\alpha}}} \tag{3}$$

Here g is the gravitational constant, l the length of the input duct, t the water depth and α the angle of inclination of the output duct. When resonance is reached, lift heights considerably exceeding the wave height can be achieved [9].

In Fig. 6 a plot of the relationship between ω_s and the angle α for different input pipe lengths is presented. One can notice how different configurations of the OWC pump can adapt to different wave frequencies, or different wave conditions. The adaptability of the OWC pump to promptly respond to a variation of the wave regime is of high importance allowing the WaveCatcher system to work independently from the variability of the renewable energy source.

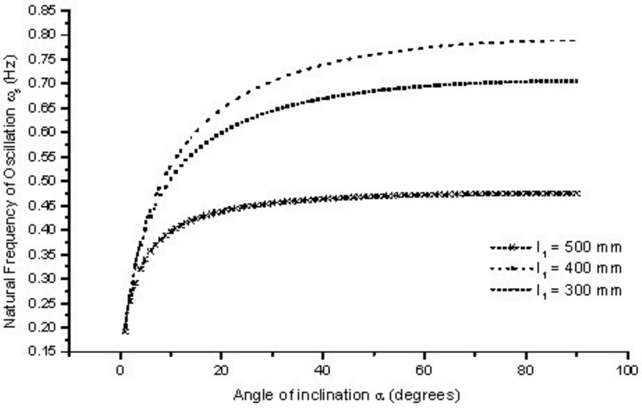

Fig. 6. Plot frequency vs angle for different input pipe lengths.

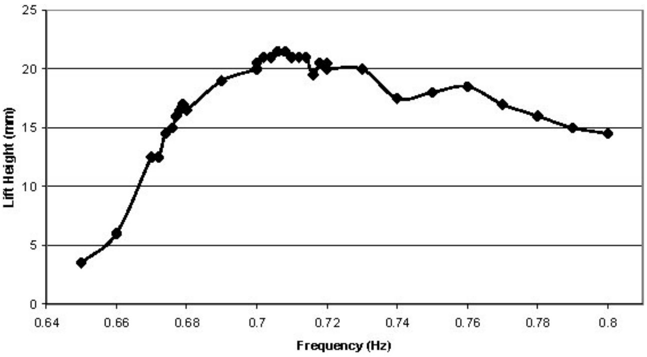

Fig. 7. Plot Lift heights by varying wave frequency near resonance for $\alpha = 30°$. Resonance is obtained when $f = 0.707$ Hz.

Physical testing of the OWC pump was conducted in the hydraulic laboratory at University of Southampton, initially at a scale of approximately 1:20. Limitations due to the scaling of the experiments affected the testing by increasing the damping. Damping was determined to reduce the natural frequency of oscillation, as in Eq. (4).

$$\omega_s = \frac{2\pi}{T\sqrt{1-D^2}} \qquad (4)$$

The damping coefficient D was estimated to be 0.76, affecting ω_s by increasing it by 54%.

Two types of investigation were carried out: first a series of tests was used to observe the average lift height; the lift height/wave height ratio was then determined. In Table 2 the ratio lift height/wave height for $\alpha = 30°$ is presented.

A second series of tests was conducted with a fixed wave height, while the wave period was varied in order to determine the range of frequencies where lift height and delivery is maximized. Fig. 7 presents the plot of the height achieved by varying wave frequency for $\alpha = 30°$.

Table 2
Lift height/wave height ratio determination for testing when $\alpha = 30°$ (average lift height/wave height ratio is 4)

Paddle stroke (mm)	Lift height, h_l (mm)	Wave height, H (mm)	Ratio h_l/H
10.6	0.0	1.8	0.0
13.8	2.0	2.3	0.9
15.8	7.5	2.7	2.8
18.2	14.5	3.1	4.7
23.2	17.0	3.9	4.3
23.6	**20.0**	**4.0**	**5.0**
26.0	**21.5**	**4.4**	**4.9**
30.6	23.5	5.2	4.6
33.8	25.0	5.7	4.4
37.1	26.5	6.3	4.2
41.3	28.0	7.0	4.0
45.9	31.0	7.7	4.0
45.89	31.5	7.7	4.1

From the physical testing of the OWC it can be noticed that the maximum lift height is approximately 4 to 5 times higher than the height of the incoming wave. This means that a volume of water ranging between 3 and 4×10^{-6} m^3 is conveyed by the pump during the tests, which at full capacity, and assuming a wave height of 1 m, translates to 0.14 m^3 of water being delivered to the WaveCatcher for each incoming wave. The delivery of water can be increased by varying the diameter of the OWC pump, since it does not affect the resonance control.

6. Discussion and conclusions

This paper presents the first results of the investigation into an off-grid, wave energy driven desalination system. The main emphasis has been placed on the development of a stand-alone system that can be used for primary desalination needs in rural communities. Among the main advantages of the WaveCatcher is the fact that no electricity is required to drive the RO cell; therefore, the system is employable in any location with proximity to a shore or a cliff.

The WaveCatcher has been designed to be user-friendly being a full mechanical system that can be easily maintained without training required.

Tests showed that a 1:6 scale model of the WaveCatcher can generate a maximum pressure of 0.42 MPa from an initial head difference of 2 kPa (or 42 m w.c. from 0.2 m w.c.), translating into a full scale pressure of 2.52 MPa. This pressure can be maximized: with respect to the value reported in Table 1, if the piston diameter D of the prototype is reduced to 8.43 mm, the pressure generated should rise to 0.6 MPa at model and 6 MPa at full scale.

The system also has a number of practical advantages: the driving water does not have to be even cleaned, it can contain sand or biological components; only the feed water needs filtering. Due to the proximity with the shore, brine can be easily disposed of into the sea, while pressurized water can either be stored or directly used.

The WaveCatcher needs to be supplied with water from wave action in order to function correctly. The necessary amount of water to drive the WaveCatcher is supplied by an OWC water pump.

Studies have shown that an OWC pump, fitted with resonance control can lift the incoming wave of up to five times the initial wave height. The volume of water carried with each wave is then the accumulated in the collection tank of the WaveCatcher.

In order to expand the research presented here further work is required to reduce friction losses in the WaveCatcher mechanism. Studies on a group of OWC pumps working in parallel are underway in order to increase the volume of water delivered to the WaveCatcher and to stabilize the resonance control for random sea conditions. These studies will be carried out at a 1:10 scale in order to be directly comparable with the WaveCatcher needs.

Finally the systems will be coupled with a RO membrane. Pretreatments will be investigated when the OWC pump and WaveCatcher are fully operative.

Acknowledgments

This project could not have been carried out without the help of William Delabre, Pascal Galloway, Robert Hooper and Rob Winkel, who worked with dedication on the design of the WaveCatcher, achieving full functionality of the system.

References

[1] P.A. Davies, Wave-powered desalination: resource assessment and review of technology. Desalination, 186 (2005) 97–109.
[2] E.M. Nfah, J.M. Ngundam, M. Vandenbergh and J. Schmid, Simulation of off-grid generation options for remote villages in Cameroon. Renewable Energy, 33(5) (2008) 1064–1072.
[3] M. Qadir, B.R. Sharma, A. Bruggeman, R. Choukr-Allah and F. Karajeh, Non-conventional water resources and opportunities for water augmentation to achieve food security in water scarce countries. Agricul. Water Manage., 87(1) (2007) 2–22.
[4] E. Fosberry, Z.L. Gunton, G.M.P. Hawkswood and H. Radford, The WaveCatcher: A Micro-Renewable Energy System for the Generation of Fresh Drinking Water, University of Southampton, 2007.
[5] W. Delabre, P.W. Galloway, R. Hooper and R. Winkel, The WaveCatcher — A Wave-Powered Desalination System, University of Southampton, 2008.
[6] S.P.R. Czitrom, R. Godoy, E. Prado, P. Perez and R. Peralta-Fabi, Hydrodynamics of an oscillating water column seawater pump. Part II: tuning to monochromatic waves. Ocean Eng., 27(11) (2000) 1181–1198.
[7] S.P.R. Czitrom, R. Godoy, E. Prado, A. Olvera and C. Stern, Hydrodynamics of an oscillating water column seawater pump: Part I: theoretical aspects. Ocean Eng., 27(11) (2000) 1199–1219.
[8] D.V. Evans, Power from water waves, in: Annual Review of Fluid Mechanics, Vol. 13, Annual Reviews, Palo Alto, CA, 1981, pp. 157–187.
[9] R. Godoy-Diana and S.P.R. Czitrom, On the tuning of a wave-energy driven oscillating-water-column seawater pump to polychromatic waves. Ocean Eng., 34(17–18) (2007) 2374–2384.