TURBINE–CHAMBER COUPLING IN AN OWC WAVE ENERGY CONVERTER

I. Lopez[1], G. Iglesias[2], M. Lopez[1], F. Castro[3] and M.A. Rodríguez[3]

Oscillating Water Column (OWC) systems are one of the most popular technologies for wave energy conversion. Their main elements are the chamber with the water column and the air turbine. When studying the performance of an OWC system both elements should be considered together, for they are effectively coupled: the damping exerted by the air turbine affects the efficiency of the conversion from wave power to pneumatic power in the OWC chamber, which in turn affects the air flow driving the turbine. The optimum level of damping is that which maximizes the efficiency of the conversion from wave to pneumatic power. In this work the turbine-chamber coupling is studied through a combination of physical and numerical modeling.

Keywords: wave energy; oscillating water column; OWC

INTRODUCTION

Among the various wave energy converter (WEC) technologies, oscillating water column (OWC) systems constitute one of the most popular options. They consist of a chamber exposed to wave action through a submerged opening (Fig. 1) and a turbine-generator group. The lower part of the chamber is filled with seawater (the “water column”) and its upper part is connected to the atmosphere through a duct in which the turbine is installed. Waves cause the free surface of the water column to oscillate up and down, thereby forcing the air to flow through the duct alternatingly out of the chamber and into it; this airflow drives the turbine-generator group.

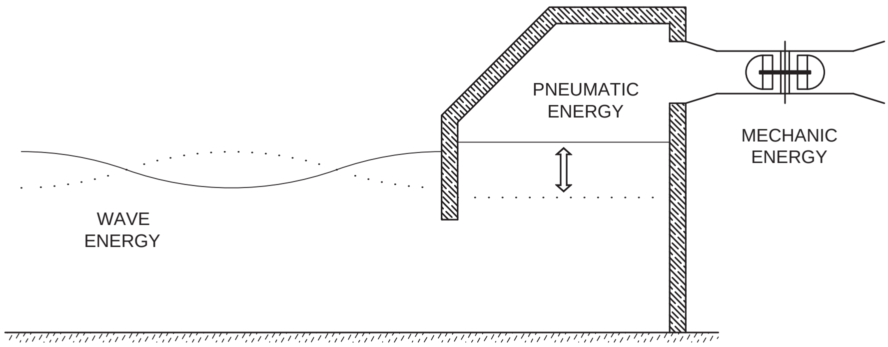

Figure 1. Scheme of an Oscillating Water Column (OWC) wave energy converter.

The main advantages of OWC systems over other WECs are two. The first is their technological simplicity; in effect, an OWC consists essentially of the aforementioned two elements: the chamber, which is generally made of concrete, and the turbine-generator group, with a self-rectifying air turbine. The second advantage concerns the maintenance costs, which are generally lower than in other WECs not only as a result of the aforementioned simplicity but also because there are no moving parts in direct contact with seawater.

In the design and optimization of this kind of wave energy converter, the coupling between the chamber and the turbine exerts a fundamental role (Curran et al. 1997; Pereiras et al. 2011). This coupling is very important because the performances of these two elements depend on each other: the turbine must provide the optimal pneumatic damping (pressure difference across the turbine) in order to achieve resonant or near-resonant conditions in the chamber, and the chamber, in turn, must provide the optimal pneumatic energy to maximize the turbine production.

Moreover, there are other aspects that should also be heeded when designing an OWC. First, the wave climate at the location of interest must be taken into account with a view to achieving resonant or near-resonant conditions for the free surface oscillation inside the chamber as often as possible and

[1] University of Santiago de Compostela, Campus Universitario s/n, Lugo, 27002, Spain.
[2] School of Marine Science and Engineering, University of Plymouth, Drake Circus, Plymouth PL4 8AA, U.K.
[3] University of Valladolid, Paseo del Cauce 59, Valladolid, 47011, Spain.

thus maximizing the power output. A second aspect to consider, which also affects the system's efficiency, is the relation between the dynamics of the air-water system and the turbine characteristics. Finally, the chamber—and the OWC system as a whole—must be able to withstand challenging environmental conditions, with high wave loads under storm conditions.

Over the last few decades, several types of OWC devices have been developed, from offshore floating OWCs, e.g. the Mighty Whale (Washio et al. 2000) to onshore OWCs, like the well-known LIMPET (Boake et al. 2002; Heath et al. 2000) or the Pico OWC (Falcão et al. 1995; Falcão 2000) in the Azores Islands, to nearshore converters like the Port Kembla OWC (Alcorn et al. 2005). Among them, the breakwater-integrated OWC is a particularly interesting option due to its great advantages. First, the construction costs are shared between the breakwater and the WEC. Second, the environmental impact is similar to that of the coastal structure without the OWC device. Furthermore, the wave heights in front of the breakwater are reduced due to the absorption of wave energy by the WEC and the consequent reduction in reflected wave height; this constitutes an advantage relative to a conventional breakwater from the perspectives of maritime access to the port, wave loads on the structure and seabed scour.

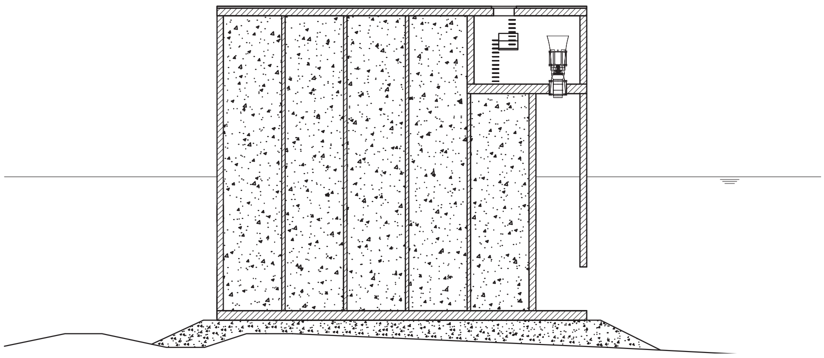

Figure 2. Breakwater-integrated OWC.

Many efforts have been devoted to the research of the wave energy converting efficiency and operating performance of the oscillating water column system. Wang et al. (2002) studied numerically and experimentally the hydrodynamic performance of an onshore wave power device for different bottom slopes. Josset and Clement (2007) applied the low order boundary element method (BEM) for efficient hydrodynamic modeling of generic bottom mounted OWC power plants. Morris-Thomas et al. (2007) studied experimentally the hydrodynamic performance of an OWC analyzing the influence of the lip configuration: depth, thickness and geometry. Marjani et al. (2008) presented a numerical model to predict the flow characteristics in the components of an oscillating water column (OWC) system used for the wave energy capture. Dizadji & Sajadian (2011) carried out a series of laboratory tests modifying the slope of the front and rear walls of a small-scale OWC model searching the more efficient geometry. Zhang et al. (2012) developed a two-phase level-set model with the global mass correction and immersed boundary method and studied the vortical motion around the front wall of the chamber and its impact on the energy efficiency of the OWC.

In parallel with these studies, a lot of works have been developed in the field of the self-rectifying air turbines. Setoguchi et al. (2001) reviewed the investigation on the impulse turbines for wave energy conversion with different shape parameters experimentally and numerically and comparison with the Wells turbines. Thakker et al. (2004) implemented a numerical quasi-steady, one dimensional model of the behavior of an axial impulse turbine and a Wells turbine. Takao et al. (2007) studied the performance of Wells turbine with end plates effects experimentally by the modeling test. Jayashankar et al. (2009) designed and studied the twin unidirectional impulse turbine topology for OWC devices.

In most studies so far, the two main elements of the OWC wave energy converter, the chamber and turbine, were investigated separately. This means, on the one hand, that the air turbine and its effects on the pressure difference and oscillations of the water column in the chamber are neglected in the analysis of the chamber and, on the other hand, that the oscillations of the water column and the pressure variations during the exhalation and inhalation processes are not considered in the analysis of the self-rectifying air turbines, whether Wells or impulse turbines.

In the present study, the integrated system of chamber and turbine was studied through a combination of physical and numerical modeling. All the effects of the air turbine on the chamber performance or, in other words, the influence of the turbine-chamber coupling on the performance of the OWC were taken into account. Furthermore, the combination of physical and numerical modeling allowed to analyze in depth the hydrodynamic performance of an OWC. The physical model tests laid the foundations of the study, allowing to understand all the processes involved and to identify which parameters of the chamber are key to the efficiency of the OWC converter. Then, the numerical model, validated on the basis of the test results, allowed to delve into those aspects that were found to be most important.

This work constitutes the first stage of a research project, the final goal of which is the optimization of an OWC converter intended to be installed at a breakwater in NW Spain.

MATERIALS AND METHODS

Physical modeling

The physical model reproduces, at a 1:25 scale, the preliminary design of the OWC converter, with a rectangular-shaped vertical caisson with an opening in the front (Fig. 2). This small-scale model was designed as a 2D model for tests in a wave flume, in connection with a 2D numerical model with a relatively low computational cost—something essential in the initial stages of design where numerous tests have to be carried out. It was constructed in methacrylate due to the advantages of this material: first, its strength; second, its lightness; and finally, its transparency, that allows to observe the interior of the chamber at every moment. Moreover, not only the OWC itself but also its berm was modeled.

The main element of the physical model to be considered is that which simulates the damping of the turbine. Different solutions were adopted: an orifice (Wang et al. 2002; Morris-Thomas et al. 2007; Thiruvenkatasamy and Neelamani 1997; Gouaud et al. 2010), a bypass valve (Lopes et al. 2007) or a porous medium (El Marjani et al. 2008). In this work a slot was used, which constitutes the 2D version of the orifice.. The pressure drop induced by the slot is proportional to the flow rate squared, which emulates the behavior of an impulse turbine—the turbine type at the forefront of OWC turbine technology. In order to study the turbine-chamber coupling, turbines of different specifications were modeled by varying the slot width.

Figure 2. Laboratory wave flume (left) and OWC small-scale model (centre and right).

The model was tested in the wave flume of the University of Santiago de Compostela (USC). The flume, which is 20.00 m long, 0.90 m deep and 0.65 m wide, is equipped with a piston-type wave generation paddle. This wavemaker is controlled by an Active Wave Absorption Control System (AWACS) for the absorption of reflected waves. The model was placed at a distance of 10.35 m from the wavemaker.

The performance of an OWC device for a given incident wave depends on the pressure difference and flow rate between the intake and the exhaust of the turbine. The flow rate was calculated based on the displacements of the free surface within the chamber.

The following measurements were taken during the tests: the free surface displacements at eight positions along the flume and in front of the model (by means of conductivity wave gauges) and at two positions within the chamber itself (by means of ultrasonic sensors), and the differential pressure between the interior and exterior of the chamber (by means of a differential pressure sensor with two gauges). As regards the wave gauges, gauges WG1, WG2, WG3, WG4 and WG5 were placed on the centerline of the flume at 3 m, 6.15 m, 7.65 m, 7.95 m and 8.35 m from the wavemaker, respectively.

WG6, WG7 and WG6 were placed on the front wall of the model, so as to record any transverse oscillations of the flume that might occur. As there was no wave transmission across the OWC, no wave gauges were needed behind it.

As regards the wave conditions, both regular and irregular waves were used. For regular waves, thirty-five different wave conditions were used; the wave height was varied between 0.5 m and 2.5 m, and the wave period was varied between 7 s and 13 s. For irregular waves, the JONSWAP spectrum was used. In total, eight different irregular wave conditions were used; significant wave heights of 1 m and 2 m were selected, and the peak period was varied between 7 s and 13 s.

Numerical modeling

The numerical model implemented solves the 2D Reynolds-Averaged Navier-Stokes (RANS) equations for an incompressible fluid, based on the decomposition of the instantaneous velocity and pressure fields into mean and turbulent components. The influence of turbulence fluctuations on the mean flow field is represented by the Reynolds stresses. To model this Reynolds stress tensor, the numerical model uses the concept of the turbulent viscosity; in particular, it uses the standard k-epsilon model. The movement of the free surface is tracked by the Volume of Fluid (VOF) method (Hirt and Nichols 1981). The VOF method introduces a VOF function F to define the fluid region. The physical meaning of the F function is the fractional volume of a cell occupied by the water. Thus, a unit value of F corresponds to a cell full of water, while a zero value indicates an air cell. A free surface exists in cells with F values between zero and unity.

A challenging task in numerical modeling—and in laboratory experiments as well—is to generate waves and absorb the reflected waves at the same time. In the laboratory this has been solved by the absorbing wave-maker (e.g. Schäffer and Klopman 2000), which adjusts its motion to minimize the re-reflection. In numerical modeling different methods have been employed (e.g. Troch and De Rouck 1999; Hafsia et al. 2009). In this work, waves are generated by means of the internal wave-maker method, proposed for RANS models by Lin and Liu (1999). This method consists of introducing a mass source function in the continuity equation for a group of cells inside the computational domain, which constitutes the source region. The free surface above the source region responds to a pressure increment defined within the source region cells, and a train of surface gravity waves is generated. The main advantage of this method is that the reflected waves do not interact with the source. Moreover, it enables the generation of regular and irregular waves. However, it has the drawback of generating waves in both directions, downstream and upstream.

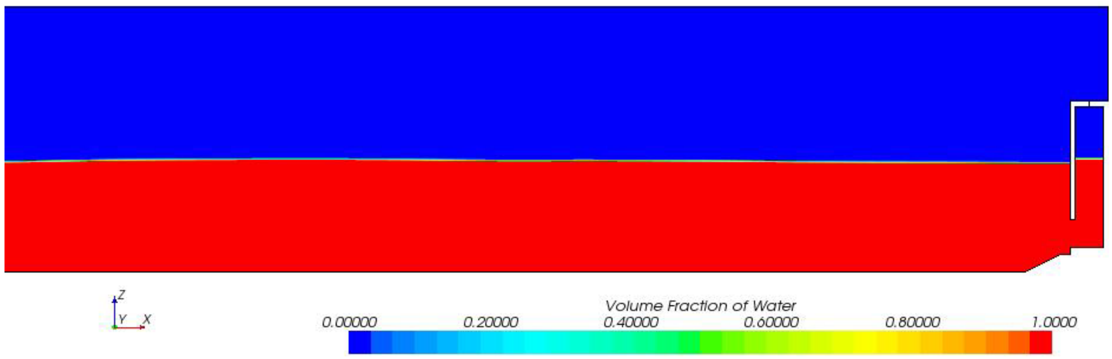

Figure 3. RANS-VOF numerical model of the oscillating water column.

The computational domain reproduces the experimental setup, both in terms of the dimensions of the flume of the USC and the location and geometry of the OWC model. Nevertheless, there are several details that differ between both models, physical and numerical. The main difference is the existence of an upstream wave dissipation ramp provided in order to absorb the waves reflected by the model and those generated by the internal source function in this direction. A second difference is that, given that there is no wave transmission through the rear wall of the OWC chamber, the remaining flume beyond the chamber is not considered by the numerical model. And, it goes without saying, the width of the numerical wave flume is one cell (2D model). As regards the source region, it has been designed applying the rules of thumb included in Lin and Liu (1999) and its center is located at the same distance from the first wave gauge as the wavemaker in the laboratory flume.

The influence of the turbine is commonly implemented in numerical modeling—as well as in physical modeling as it was aforementioned—using a device which simulates its influence on the conditions of oscillation of the chamber. Thus, following the same criteria used during the physical model tests, in the numerical model implemented in this work, the influence of the turbine is achieved by setting a variable slot which simulates different damping conditions.

Meshing of the computational domain has been made by means of hexahedral elements. The domain is divided in different sub-mesh regions, which allows to choose different cell sizes in order to define a finer grid for the representation of specific study zones. Assuming a coordinate system where $x = 0$ at the center of the source region, with x increasing along the flume towards the model, and $z = 0$ at the free surface, with z increasing towards the top of the flume, the mesh is uniform in the x-direction, but non-uniform in the z-direction, with the finer sub-mesh region around the free surface. Moreover, another finer sub-mesh region is established including the whole OWC model.

RESULTS AND CONCLUSIONS

In this work a physical model of a breakwater-integrated OWC was constructed and tested in a wave flume under regular and irregular waves. In addition to the wave conditions, turbines of different specifications were tested by modifying the damping characteristics of the model. Both the oscillations of the water column inside the chamber and the pressure drop were measured, together with the free surface elevations along the flume. For illustration, different results from a regular and an irregular wave test are presented in Figures 4, 5 and 6, respectively.

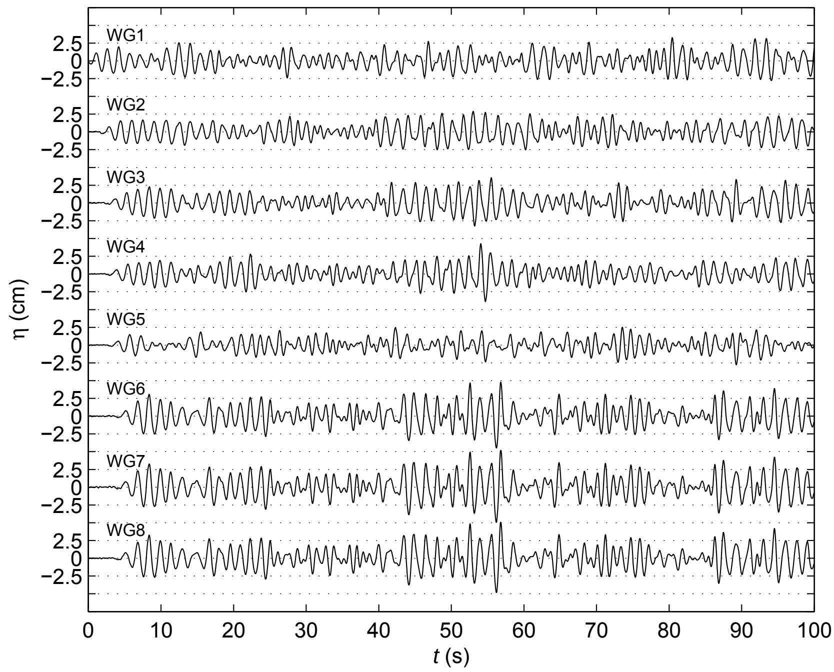

Figure 4. Free surface evolution for an irregular case (H_s = 4 cm, T_p = 1.54 s).

The next step in this research will be the data processing, in which the results of the physical model tests will be analysed to obtain the incident wave power and the pneumatic power captured by the chamber. On these grounds, the hydrodynamic efficiency of the OWC converter for each test will be determined.

As regards the numerical model, it has been implemented and is currently being calibrated and validated using the data provided by the physical model tests. For this purpose, the tests carried out in the laboratory are being reproduced in the numerical model—with the same wave conditions and turbine damping.

This study is an early stage within a wider research project whose final goal is the optimization of a breakwater-integrated OWC prototype. A series of laboratory tests have been successfully conducted taking into account the integrated system of chamber and turbine. Preliminary observations carried out during the experiments indicate the importance of the turbine-chamber coupling in the OWC performance. Much work remains to be done, among which the in-depth analysis of the results of the physical tests—which is expected to be available in upcoming publications— and the validation of the numerical model on the basis of the laboratory tests.

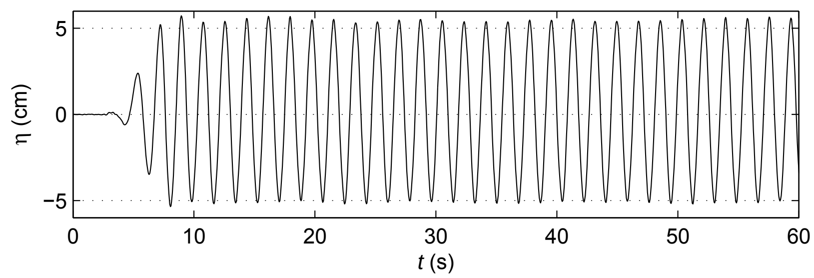

Figure 5. Oscillations of the water column inside the chamber for a regular case (*H* = 6 cm, *T* = 2 s).

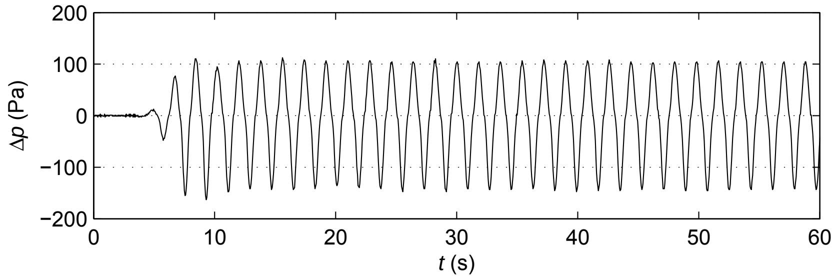

Figure 6. Pressure drop for a regular case (*H* = 6 cm, *T* = 2 s).

In conclusion, this work highlights the importance of studying the coupling between the chamber and turbine of an OWC, which translates in practice into adapting the turbine specifications to the chamber geometry and wave climate. The interest of this work lies not only in the particular project with which it is concerned, but also in the optimization methodology that is presented to take into account the turbine-chamber coupling through a combination of physical and numerical modeling. This methodology can be applied to OWC projects elsewhere.

ACKNOWLEDGMENTS

This research is part of the project DPI2009-14546-C02-02 supported by Spain's Ministry of Science and Innovation (Ministerio de Ciencia e Innovación).

REFERENCES

Alcorn, R., Hunter, S., Signorelli, C., Obeyesekera, R., Finnigan, T., and Denniss, T. 2005. Results of the testing of the Energetech wave energy plant at Port Kembla. *Energeth Report*.

Boake, C.B., Whittaker, T.J.T., Folley, M., and Ellen, H. 2002. Overview and initial operational experience of the LIMPET wave energy plant. *Proceedings of the 12th international offshore and polar engineering conference,* 586-594.

Curran, R., Stewart, T., and Whittaker, T.J.T. 1997. Design synthesis of oscillating water column wave energy converters: performance matching. *Proc.Inst.Mech.Eng.A: J.Power Energy,* 211(6), 489-505.

Dizadji, N., and Sajadian, S.E. 2011. Modeling and optimization of the chamber of OWC system. *Energy,* 36(5), 2360-2366.

El Marjani, A., Castro, F., Rodriguez, M.A., and Parra, M.T. 2008. Numerical modelling in wave energy conversion systems. *Energy,* 33(8), 1246-1253.

Falcão, A.F.O., Sabino, M., Whittaker, T., and Lewis, A. 1995. Design of a shoreline wave power pilot plant for the island of pico, azores. *Proceedings of the 2nd European Wave Power Conference, Lisbon, Portugal,* 87-93.

Falcão, A.F.d.O. 2000. The shoreline OWC wave power plant at the Azores. *Proceedings of the 4th European Wave Power Conference,* 42-48.

Gouaud, F., Rey, V., Piazzola, J., and Van Hooff, R. 2010. Experimental study of the hydrodynamic performance of an onshore wave power device in the presence of an underwater mound. *Coastal Engineering,* 57(11-12), 996-1005.

Hafsia, Z., Hadj, M.B., Lamloumi, H., and Maalel, K. 2009. Internal inlet for wave generation and absorption treatment. *Coastal Engineering,* 56(9), 951-959.

Heath, T., Whittaker, T.J.T., and Boake, C.B. 2000. The design, construction and operation of the LIMPET wave energy converter (Islay, Scotland). *Proceedings of the 4th European Wave Energy Conference,* 49-55.

Hirt, C.W., and Nichols, B.D. 1981. Volume of fluid (VOF) method for the dynamics of free boundaries. *Journal of Computational Physics,* 39(1), 201-225.

Jayashankar, V., Anand, S., Geetha, T., Santhakumar, S., Jagadeesh Kumar, V., Ravindran, M., Setoguchi, T., Takao, M., Toyota, K., and Nagata, S. 2009. A twin unidirectional impulse turbine topology for OWC based wave energy plants. *Renewable Energy,* 34(3), 692-698.

Josset, C., and Clément, A.H. 2007. A time-domain numerical simulator for oscillating water column wave power plants. *Renewable Energy,* 32(8), 1379-1402.

Lin, P., and Liu, P.L.F. 1999. Internal wave-maker for Navier-Stokes equations models. *Journal of Waterway, Port, Coastal and Ocean Engineering,* 125(4), 207-217.

Lopes, M., Ricci, P., Gato, L., and Falcão, A.F.O. 2007. Experimental and numerical analysis of the oscillating water column inside a surface-piercing vertical cylinder in regular waves. *Proceedings of the 7th European Wave and Tidal Energy Conference, Porto, Portugal.*

Morris-Thomas, M.T., Irvin, R.J., and Thiagarajan, K.P. 2007. An investigation into the hydrodynamic efficiency of an oscillating water column. *Journal of Offshore Mechanics and Arctic Engineering,* 129 273.

Pereiras, B., Castro, F., El Marjani, A., and Rodriguez, M.A. 2011. An improved radial impulse turbine for OWC. *Renewable Energy,* 36(5), 1477-1484.

Schäffer, H.A., and Klopman, G. 2000. Review of multidirectional active wave absorption methods. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 126 88.

Setoguchi, T., Santhakumar, S., Maeda, H., Takao, M., and Kaneko, K. 2001. A review of impulse turbines for wave energy conversion. *Renewable Energy,* 23(2), 261-292.

Takao, M., Setoguchi, T., Kinoue, Y., and Kaneko, K. 2007. Wells turbine with end plates for wave energy conversion. *Ocean Engineering,* 34(11–12), 1790-1795.

Thakker, A., Usmani, Z., and Dhanasekaran, T.S. 2004. Effects of turbine damping on performance of an impulse turbine for wave energy conversion under different sea conditions using numerical simulation techniques. *Renewable Energy,* 29(14), 2133-2151.

Thiruvenkatasamy, K., and Neelamani, S. 1997. On the efficiency of wave energy caissons in array. *Applied Ocean Research,* 19(1), 61-72.

Troch, P., and De Rouck, J. 1999. An active wave generating–absorbing boundary condition for VOF type numerical model. *Coastal Engineering,* 38(4), 223-247.

Wang, D.J., Katory, M., and Li, Y.S. 2002. Analytical and experimental investigation on the hydrodynamic performance of onshore wave-power devices. *Ocean Engineering,* 29(8), 871-885.

Washio, Y., Osawa, H., Nagata, Y., Fujii, F., Furuyama, H., and Fujita, T. 2000. The offshore floating type wave power device "Mighty Whale": open sea tests. *Proceedings of 10th International Offshore Polar Engineering Conference, Seattle, 2000, 1,* 373-380.

Zhang, Y., Zou, Q.-P., Greaves, D. 2012. Air–water two-phase flow modelling of hydrodynamic performance of an oscillating water column device. *Renewable Energy*, 41, 159-170.