Applied Energy 168 (2016) 636–648

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

An experimental investigation of hydrodynamics of a fixed OWC Wave Energy Converter

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HIGHLIGHTS

- The hydrodynamic performance of a fixed OWC device is experimentally studied.
- There exists a critical wave slope at which hydrodynamic efficiency reaches the maximum.
- Slope angle has little influence on the resonant frequency.
- The water motion inside the chamber is highly dependent on the relative wave length λ/B.

ARTICLE INFO

Article history:
Received 24 July 2015
Received in revised form 25 January 2016
Accepted 28 January 2016

Keywords:
OWC
Wave energy
Model testing
Hydrodynamic efficiency
Water motion

ABSTRACT

The hydrodynamic performance of a fixed Oscillating Water Column (OWC) wave energy device under various wave conditions and geometric parameters was tested experimentally in a wave flume. The measured water surface elevation at the chamber center, the air pressure in the chamber of the OWC device and the hydrodynamic efficiency are compared well with the published numerical model results in Ning et al. (2015). Then the effects of various parameters including incident wave amplitude, the chamber width, the front wall draught, the orifice scale and the bottom slope on the hydrodynamic efficiency of the OWC device were investigated. It is found that the opening ratio ε ($\varepsilon = S_0/S$, where S_0 and S are the cross-sectional areas of the orifice and the air chamber, respectively) has a significant influence on the maximum hydrodynamic efficiency of the OWC device. The optimal efficiency occurs at the opening ratio of $\varepsilon = 0.66\%$. Although bottom slope has little influence on the resonant frequency, the optimal hydrodynamic efficiency increases with the increase of bottom slope. A proper bottom slope can provide a work space in the OWC chamber almost independent on the sea wave conditions. The spatial variation of the water surface inside and outside the chamber was also examined. And the results indicate that the water motion is highly dependent on the relative wave length λ/B (where λ is the wave length and B is the chamber width). Seiching phenomenon is triggered when $\lambda/B = 2$ at which the hydrodynamic efficiency is close to zero.

1. Introduction

To cope with the increasing costs of fossil fuels and the environmental problems derived from the extraction and the use of fossil fuels, renewable energy sources are believed to play a more and more important role to mitigate these effects [1]. Wave energy is certainly a significant component of the renewable energy [2] due to its high energy density [3] and less negative environmental impact [4,5]. More than one thousand wave energy converter patents had been registered by 1980 and the number has increased markedly since then [6], in which the OWC device has been extensively studied and implemented due to its mechanical and structural simplicity [7]. Generally, a land-fixed OWC device consists of two parts: a partially submerged land back chamber and an open below the mean sea level. They are used to trap a column of air above the free surface. As the waves impinge on the device, the oscillating motion of the internal water free surface makes the air to flow through a turbine that drives an electrical generator [8]. A number of full sized OWC prototypes have been installed and tested world widely, including Tofteshallen in Norway (500 kW), Sakata in Japan (60 kW), Pico in Portugal (400 kW), Limpet in Scotland (500 kW), and more recently Mutriku in Spain (300 kW) [9]. However, OWC technology has not been fully commercialized

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http://dx.doi.org/10.1016/j.apenergy.2016.01.107
0306-2619/

yet [10]. The main reason is that the hydrodynamics of the OWC devices has not been fully understood. Further hydrodynamic investigations on OWC device still need to be carried out theoretically, numerically and experimentally.

Although significant efforts have been made to investigate the hydrodynamic performance of OWC devices theoretically at the early stage, such as McCormick [11], Evans [12], Falcão and Sarmento [13], Evans [14] and Falnes and McIver [15], majority of OWC theories are based on linear wave theory and neglect the viscosity, spatial variation of water surface elevation in the chamber. The hydrodynamic efficiency is generally over-predicted based on the simple theoretical solutions [8,16,17].

Recent development of numerical techniques and increasing computer power has significantly increased the efficiency and accuracy of numerical studies of the hydrodynamic performance of OWC devices. Based on the potential flow model, Count and Evans [18] developed a numerical model by coupling the three-dimensional (3-D) boundary integral method outside the OWC device and with the eigenfunction expansion method in the rectangular inner region. Wang et al. [19] validated numerical computations with experimental measurements and found the topographical effects of bottom slope and water depth is important to the performance of an OWC. Delauré and Lewis [7] applied the first-order BEM to simulate the hydrodynamic performance of a 3D fixed OWC device and discussed its accuracy. Josset and Clément [20] developed a time-domain numerical model of OWC wave power plants to predict the annual performance of the wave energy plants on Pico Island, Azores, Portugal. Nunes et al. [21] analyzed an off-shore OWC device numerically and studied the techniques that could improve energy extraction efficiency. It was proved that it is possible to achieve a resonant response for sinusoidal waves with a frequency different from the device's natural frequency. Falcão et al. [22] analyzed the performance of an OWC spar buoy wave energy converter in the frequency domain for both regular and irregular waves. Iturrioz et al. [10] presented a simplified time-domain model for a fixed detached OWC device and validated numerical computations by comparison with experimental data. Gkikas and Athanassoulis [23] presented a nonlinear system identification method for modeling the pressure fluctuation inside the chamber of an OWC wave energy converter under monochromatic excitation. Ning et al. [16] developed a two-dimensional (2-D) fully nonlinear numerical wave flume (NWF) based on a time-domain higher-order boundary element method (HOBEM) and used it to investigate the hydrodynamic performance of a fixed OWC wave energy device. Rezanejad et al. [24] investigated the performance of dual chamber OWC devices in the stepped sea bottom condition.

Recently, researchers have also developed viscous-flow model based on the N-S equations to analyze the OWC device. Marjani et al. [25] simulated the flow characteristics in the chamber of an OWC system using the FLUENT software. They found that the energetic performances are higher in the case of the inhalation mode than in the case of the exhalation mode. Zhang et al. [17] developed a 2-D two-phase numerical wave tank (NWT) using a level-set immersed boundary method to study the flow field, surface elevation and air pressure in an OWC chamber. They investigated the effects of the geometric parameters on the OWC power capture efficiency. Teixeira et al. [9] applied the Fluinco numerical model to simulate an OWC device and investigate the effects of the chamber geometry and the turbine characteristics on the device performance. López et al. [26] implemented a 2-D numerical model based on the RANS equations and the VOF surface capturing scheme (RANS-VOF) to study the optimum turbine-chamber coupling for an OWC. Luo et al. [27] developed a 2-D, fully nonlinear CFD model and analyzed the efficiency of fixed OWC-WEC devices with linear power take off systems. Iturrioz et al. [28] simulated a fixed detached OWC device using OpenFOAM to test capability of CFD simulations in analyzing the OWC device. However, it is still difficult to perfectly simulate the nonlinear wave interaction with an OWC device in any previous numerical models due to the complicated coupling process of air and water in the chamber.

In addition to the numerical modeling, a number of experiments have been carried out to study the performance of OWC devices. Tseng et al. [29] presented the concept of a breakwater and a harbor resonance chamber which can extract energy from the ocean and protect the shore at the same time. A 1/20 model of this type of system was constructed and tested in a wave tank and the experimental data were compared with the previous theoretical results. Afterward, Boccotti et al. [30] carried out an experiment to study the hydrodynamic performance of harbor resonance chambers. Morris-Thomas et al. [8] experimentally studied the energy efficiency of an OWC focused their study on the influence of front wall geometry on the OWC's performance. Gouaud et al. [31] carried out experiments to investigate the hydrodynamic performance of an OWC device and compared the experimental data to numerical results. Liu [32] studied the operating performance of an OWC air chamber both experimentally and numerically. Dizadji and Sajadian [33] carried out an experimental study on the geometrical design of an OWC system and optimized the set up for the maximizing the energy harness. He et al. [34] experimentally investigated an integrated oscillating water column type converter with floating breakwater and found that the integrated system can widen the frequency range for energy extraction. Imai et al. [35] studied the total conversion process of an OWC device with a turbine theoretically, and carried out experiment to validate the theoretical results.

Above literature review shows that a number of investigation methods have been developed and applied to study the hydrodynamic performance of the OWC device. Various numerical models have been established based on either potential-flow or viscous-flow model. However, the related experimental studies on land-fixed OWC devices are still limited, especially those on the influence of wave nonlinearity, turbine damping and bottom slope on the performance of the OWC devices. Moreover, no sufficient attention has been paid to the water motion in the chamber. The large difference between the internal and external surface elevations of the chamber can cause the dynamic pressure on the front wall, which may be a threat to the safety operation of the OWC device [36]. To complete the previous studies, the primary goal of this study is to experimentally investigate the effects of wave nonlinearity, the orifice scale and the bottom slope on the hydrodynamic efficiency of land-fixed OWC devices and the characteristics of water motion in the air chamber.

The rest of the present paper is organized as follows: The experimental procedure is described in Section 2. Experimental data is compared with the solutions of the higher-order boundary element method (HOBEM) in Section 3. In Section 4, the effects of the incident wave amplitude and geometric parameters on the hydrodynamic efficiency of the OWC device are discussed. In Section 5, the spatial variation of the free surface in the air chamber is analyzed. Finally, the conclusions of this study are summarized in Section 6.

2. Experiments

2.1. Experimental set-up

The physical model tests were carried out in the wave-current flume at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, China. The glass-walled wave flume is 69 m long, 2 m wide and 1.8 m deep as shown in Fig. 1(a).