Renewable Energy 96 (2016) 341–353

Contents lists available at ScienceDirect

Renewable Energy

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

Effects of bottom profile of an oscillating water column device on its hydrodynamic characteristics

S. John Ashlin, V. Sundar*, S.A. Sannasiraj

Department of Ocean Engg., Indian Institute of Technology Madras, India

ARTICLE INFO

Article history:
Received 11 July 2015
Received in revised form
11 April 2016
Accepted 29 April 2016

Keywords:
Oscillating water column
Optimum air damping
Bottom profile optimization
Hydrodynamic efficiency
Wave amplification
Pressure ratio

ABSTRACT

The oscillating water column, OWC device is one of the more promising devices for the extraction of energy from ocean waves. The present study mainly focuses on the influence of bottom profile configuration in the OWC on its hydrodynamic performance. Four different bottom profiles flat, circular curve of radius 300 mm, slope of 1:1 and 1:5 were tested in a wave flume. The said models were simultaneously subjected to both regular and random waves. The hydrodynamic performance was studied in terms of wave amplification factor, wave power absorption coefficient, hydrodynamic efficiency, lip wall pressure ratio (pressure at in front of lip wall/pressure due to incident wave) and air pressure ratio (air pressure/pressure due to incident wave). It is found that the natural period of the system was around 1.9 s. The OWC with circular curve bottom profile exhibited a better performance in terms of its effective wave energy conversion and wave amplification factor inside the chamber. The peak magnitude of hydrodynamic efficiency for circular curve bottom profile was 0.71. The performance of the OWC model is found to be better when closer to the natural period of the device.

1. Introduction

Among the renewable energy resources, ocean energy is the one, which is available in abundance around the globe. Ocean energy is available in the forms of ocean thermal energy (direct effect of solar radiation on the sea), wave energy (result of balancing nature between gravitational and wind force), tidal energy (due to the attraction between celestial bodies), ocean currents (due to the gradient of salinity, temperature, etc.), etc. The energy in the ocean waves is due to the imbalance between gravitational force and shear due to wind. It travels thousands of kilometers as a Swell wave without any energy loss from the place where the energy is imparted on the water surface. As the waves travel from deep to shallower water region, certain amount of energy (potential energy + kinetic energy) dissipates, particularly in the breaking zone. The level of dissipation as well as an increase in its amount depends on several parameters, of which the most important are seabed friction, bathymetry, and presence of obstructions. Nevertheless, the wave power available in the near shore is quite enough to produce electricity as it is directly proportional to the square of the amplitude of the wave and its wavelength.

Since the past several years, scientists and engineers have been working in the field for an effective device to extract the ocean wave energy. Wave energy convertors, WECs have been installed in countries like UK, USA, Norway, India and Japan. Considerable amount of literature on this topic have been reported by McCormick, Shaw and Ross [8,12,14]. Wave energy convertors (WEC), can be classified as per location, working principle as follows [1]:

(i) Based on its distance from coast as on-shore (less than 8 m in which case it facilitates integration with detached offshore breakwaters serving as coastal protection hard structure), near-shore (devices installed in depths between 8 and 20 m), and offshore devices (built in water depths greater than 20 m).
(ii) Based on its principle of operation, may be classified as point absorber buoy, surface attenuator, terminator, oscillating water column and overtopping devices.

Among the different types of WECs, the Oscillating Water Column (OWC) is claimed to be simple in its concept which has been installed and tested in a number of fields. A 125 kW OWC bottom-standing power plant situated in Kerala along the west coast of India [10] and a 75 kW LIMPET OWC power plant off the Island of

---

* Corresponding author.
E-mail address: vsundar@iitm.ac.in (V. Sundar).

http://dx.doi.org/10.1016/j.renene.2016.04.091

Islay, Scotland, UK [19] are a few important standing examples. Further, the 75 kW LIMPET was decommissioned in 1999 and led to the construction of a larger rated device of 500 kW in 2000. A summary of OWC's around the globe has been reported by Sundar et al. [13]. The OWC consists of a chamber with a partially submerged front wall that is continuously excited by the ocean waves. Due to wave excitation, during the instant of its crest inside the chamber the air column is compressed, whereas, the presence of its trough expands the air column. This leads to oscillation of air column and thus, the system acts like a pump which could be easily converted into meaning energy by driving a turbine on board the OWC. The turbine should be capable of rotating in the same direction irrespective of the reversible flow inside the chamber due to the passage of crest and trough. Wells turbine, is the most popular one handling this requirement with higher degree of efficiency. Since several decades, researchers have been involved in the improvement of the performance efficiency of OWC mostly tuning its configuration with respect to the wave climate.

It was inferred by Malmo and Reitan [7] that the natural frequency of an OWC system primarily depends on its front lip depth. McIver and Evans [9] observed that the reaction of OWC system depends on the extent of the dynamic pressure and its excitation period, whereas, Zheng et al. [22] proved that flared harbor walls in an OWC enhanced its efficiency compared to the one with rectangular walls. Evans and Porter [2] considered the air chamber length (b), water depth (d) and the submergence of lip wall (s) to be the main parameters dictating the efficiency of an OWC. It was inferred that for lower values of the ratio, b/d, and the behavior of fluid like a rigid body inside the OWC air chamber. It was also reported that for higher values of s/d, the frequency band of efficiency was becoming narrow. In this study, the thickness of lip wall is not considered. Through a detailed experimental study on OWC, Thiruvenkatasamy and Neelamani [15] found that an increase in wave steepness causes a decrease in its performance in terms of its efficiency and for a/A (ratio of air hole area (a) to plan area (A)) larger than 0.81%, a considerable reduction in energy absorption capability of the device was reported. Tseng et al. [17] reported that the experimental investigation on multi-resonant oscillating water column yields only 28.5% of efficiency because of high-energy loss. Wang et al. [18] studied analytically and experimentally the change in bottom slope in front of the shoreline mounted OWC model and observed that an increase in the slope of the bottom leads to a shift in the capture-width ratio at lower frequencies. The capture width is defined as the ratio of averaged output power from the system to the input power offered by waves. The thickness of the front wall did not have any influence on energy conversion capacity of the device as is claimed by Thomas et al. [16] through an experimental study. It was stated by Folley et al. [4] that the potential of near shore exploitable wave energy source is as similar to offshore sites. Zhang et al. [21] observed that the efficiency of OWC centered on a resonant frequency. This clearly shows the importance of phase lag between the dynamic excitation pressure and the corresponding air pressure being developed. Wilbert et al. [20] have considered the parameters such as water depth inside the wave energy converter (d) and opening at its base (o) and reported that effective energy conversion capacity of OWC was found to be increasing with an increase in its bottom opening, o/d. It reached a maximum efficiency of 94% closer to the natural frequency for $o/d = 0.80$. However, at the same time, the peak efficiency was found to shift towards the higher frequency with an increase in opening depth. Rezanejad et al [11] studied about change in stepped sea bottom effects on the efficiency of the OWC device based on the two dimensional linear water wave theory. It was reported that introducing step outside the chamber have significant effects on increasing its efficiency.

Sundar et al. [13] presented a comprehensive review on the possible approaches of integrating OWC with breakwaters for the harbor formation and coastal defense systems. The concept of integration of OWC with breakwaters that can reduce the total cost significantly to bring forth economic security in project planning was highlighted. Even though there have been considerable studies on optimizing OWC, the effect of bottom profile inside the chamber on its efficiency is an area that is yet to be explored. Hence, in the present study, an attempt is made to understand the effect of the bottom profile of the OWC on its efficiency which could be integrated with breakwaters. The idea of this study is to replicate such a condition in the laboratory, and hence, the OWC models were subjected to wave action without side clearance or otherwise not allowing waves to pass around the structure. The details of the OWC models, experimental set-up, wave characteristics, experimental procedure, results and discussion are reported in this paper.

2. Dimensions of the OWC

In the design of OWC, there is a hidden assumption that its performance mainly depends on the pressure excitation and natural frequency of the chamber. According to this, the dimensions are fixed to harness maximum efficiency. The key parameters of OWC is the depth of its front lip wall immersed in to the water, length, width of the chamber and optimum air damping to the system. According to Thomas et al. [16] a decrease in the bottom opening ‘o’, (increasing lip wall depth) reduces the natural frequency of the OWC leading to its ineffectiveness in absorbing energy, in which case, the bandwidth of the efficiency peak becoming narrower and thus decreasing the effective area under the efficiency curve. Wilbert et al. [20] reported the efficiency of an OWC increases with an increase in the bottom opening. For the considered o/d of 0.15, 0.30, 0.45 and 0.80 observed that a higher efficiency for o/d of 0.80. Since, the waves in nature are random, larger bottom opening can result in the trough propagating much below the tip of the lip wall leading to the penetration of air into the OWC chamber that would cause stalling of the turbine. To avoid such a precarious situation, in the present study the ratio of bottom opening to the water depth (o/d) is fixed as 0.6. The claim of Thomas et al. [16] that the bottom edge of the front lip wall of the OWC instead being sharp if curved leads to an increase in its efficiency was also incorporated in the models considered in this study. Wilbert et al. [20] through laboratory studies, suggested that the ratio of the length of the chamber (b) to the design wave length (L), (b/L) should be in between 0.09 and 0.1. If the predominant wave period along the coast is known to harness maximum wave energy, the length of OWC ‘b’ (along the wave direction) could be fixed. As the present study, considers a wave period ranges from 0.8 s to 3.0 s that correspond to ‘L’ ranging between 1 m and 6.5 m, ‘b’ was fixed as 0.3 m. The efficiency of the OWC also depends on the optimum air damping represented by ratio of area of the air hole in the air chamber in the OWC, a to the plan area of the air chamber, A.

3. Experimental setup

The experimental investigation was carried out in a wave flume of 72.5 m long, 2 m wide and 2.5 m deep in Indian Institute of Technology Madras, India. Four different 1:12 scale devices of OWC's (characterized by four different bottom profiles: flat bottom, circular curve bottom of radius 300 mm, bottom with a slope of 1:1 and 1:5)) were subjected to wave action. For simultaneous testing of these four OWC models and to avoid the phenomena of interaction due to radiation waves, the flume was divided into four equivalent parts and dividers extended 15 m from each of the