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Comparison of numerical and experimental analyses for optimizing the geometry of OWC systems

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ABSTRACT

There is a considerable amount of wave energy that can be extracted from the oceans. This energy is largely untapped. Oscillating Water Column (OWC) is a mechanical system that utilizes fluctuating water level from sea waves to drive an air turbine which, in turn, provides electricity when transmitted to a generator. In this study, two sets of modeling, each involving a numerical modeling and a physical experimental modeling, were conducted in a wave flume to optimize OWC systems. By varying the length, width and angle of the air chamber, an OWC structure can be designed to obtain the maximum system power. The data used for designing the optimal geometry of the chamber that may yield the maximum conversion of wave energy to useful energy were provided from the interpretation of the measurements of these parameters. In this study, results of the numerical models were compared with the measured experimental values based on the Nash-Sutcliffe coefficient of efficiency (NSE) as performance evaluation criterion. The NSE values of both the classical and the modified OWC structures were obtained to be 0.97. It is observed that the results of the numerical models tend to follow much closer the results of the experimental model.

1. Introduction

Every living thing on Earth in some way depends upon energy, which is known to exist in a variety of different forms. The renewable energy resource in the oceans is classified into six main groups: Waves energy, Ocean currents energy, Tidal range (the vertical difference in height between the high tide and the succeeding low tide), Tidal currents (water flow resulting from the filling and emptying of coastal regions as a result of tidal rise and fall), OTEC (Ocean Thermal Energy Conversion) and Osmotic energy (derived from the difference in the salt concentration between seawater and river water). The transfer of kinetic energy of wind to the upper surface of the ocean is the driving factor for the creation of ocean wave energy. The theoretical potential resource of the world's wave energy is estimated to be 26,000 TWh/yr (Mark et al., 2010). Technology of Wave energy is rapidly growing and varies widely based on the types of conversion system. The wave energy technology presently available is categorized into four groups. These are attenuators, point absorbers, overtopping terminators, and oscillating wave column (OWC) terminators. The oscillating water column (OWC) system has been developed in recent years and it is the most extensively studied type of wave power plant. These structures are installed typically onshore or near shore. The OWC system consists of an air column that moves up and down by the motion of waves like a piston. Air is forced out of the column as the wave rises and fresh air is drawn in as the wave falls. This movement of air turns a weir turbine at the top of the column. Sarmento and Falcao (1985) attempted to develop a two-dimensional OWC wave energy system. The study demonstrated that air compressibility is important factor in OWC system. In addition, phase difference between pressure and flow rate at a turbine may be a method to reduce the dimension of the system and the size of turbines so that a negligible amount of system's energy is reduced. Falnes and McIver (1985) provided a system composed of oscillating bodies and oscillating pressure distributions. Lee et al. (1996) used three-dimensional radiation/diffraction code called WAMIT for analyzing an oscillating water column system. The models were developed in order to predict hydrodynamic performance of the OWC system. The dynamic boundary condition in the interior free surface was modified to account for the applied pressure in the chamber. The models were validated by checking radiation computations of WAMIT code versus the prediction values. Evans and Porter (1997) proposed a representative analytic solution of wave-structure-air interactions for OWC system. Thiruvenkatasamy and Neelamani (1997) conducted a laboratory investigation on the efficiency of power absorption of an array of Multi-resonant Oscillating Water Column wave-energy caissons. The study showed an increase in the efficiency of power absorption of the OWC up to (S/b)=3, where s stands for the

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spacing between the caissons in an array and b represents the OWC width. In addition, it was observed that the efficiency decreased with increase in wave steepness (H/L) due to a greater blow up period for higher H/L values than for lower H/L values. The percentage of energy reflection decreased with increasing relative water depth (d/L) and the average energy reflection was found to be about 30%. Tseng et al. (2000) studied an OWC wave energy converter system that combines the concept of a breakwater and developed a harbor resonance chamber. In their study, the extraction efficiency of wave energy using a self-design oscillating column was investigated. The available power was increased when integrated along a certain length of shoreline or along an array of generators. According to Folley et al. (2006), the Limpet shoreline wave energy concept was commissioned in December, 2000 on the Island of Islay. A twin-rotor symmetrical wing turbine generator was used in this system. The objective behind the study was to replace fossil fuels by renewable energy resource and make Islay energy self-sufficient. According to the results of the study, a theoretical peak power of 500 kW was obtained by using a couple of counter-rotating Wells turbines, each of which drives a 250 kW generator. Martins et al. (2005) integrated an OWC wave energy plant in a caisson breakwater at a river in Portugal. They recommended that an alternative to a stand-alone OWC system for commercializing the technology is to reduce the cost of the pneumatic chamber by incorporating it into a breakwater. A Physical model having various bottom slopes was developed and tested by Wang et al. (2002) in a wave tank under regular wave conditions. Theoretical and experimental predictions were also validated. In addition, the topographical effects of bottom slope and water depth on the performance of the OWC system were investigated. The study showed that these parameters are very important to the overall efficiency of the system. The effects of several shape parameters on the wave energy absorbing capability of the OWC chamber were studied by Hong et al. (2007). In 2007, Boccotti (2007) patented an innovative OWC plant, called REWEC3 (taken from REsonant Wave Energy Converter), which has an advantage in obtaining an impressive natural resonance without any device for phase control. The REWEC3 is designed based on the principles of caisson breakwater involving an OWC system, where a small opening connects the OWC to the sea. El Marjani et al. (2008) studied the pneumatic energy in the air chamber of an oscillating water column system and FLUENT software was used to solve a turbulent 3D model. They presented their work performed on numerical modeling in wave energy conversion systems. The numerical model was developed to estimate the flow characteristics in the components of an oscillating water column (OWC) system. In the study of Liu et al. (2008), a computational modeling of an OWC system with different geometries and with different characteristics of waves was performed. The multiphase Volume of Fluid (VOF) model was used in the treatment of water-air interaction. The experimental results were used for the validation and comparison of the experimental method with the numerical results obtained from the proposed method. Senturk and Ozdamar (2012) conducted a linear theoretical analysis of a rectangular OWC system in which they add a fully submerged barrier with a gap to the usual partially submerged front wall in order to test the efficiency of the system depending on the size of the gap. Zhang et al. (2012) studied wave interaction with a semi-submerged OWC chamber by using a model called 2D-RANS. In addition, the vertical motion around the front wall of the chamber and its impact on the energy efficiency of the OWC system was investigated. Texeira et al. (2013) analyzed front wall depth, length and height of oscillating water column chamber and turbine characteristics. They performed numerical simulations by means of Navier-Stokes (NS) equations and applied semi-implicit two-step Taylor-Galerkin method. It is observed that there is a good agreement between the Fluinco and the commercial FLUENT model results.

The effects of geometry and dimensions of the OWC chamber on the efficiency of the OWC system were investigated and the geometry of the system was optimized to achieve the maximum power by Bouali and Larbi (2013). ANSYS-ICEM CFD was used for determining the geometry and meshing. Using the ANSYS-CFX software, flow field equations were solved. The best shape regarding the unit efficiency was obtained at the air chamber front wall at 180° angle in the counter flow direction. As a result of this study, the optimal value of the front wall immersion depth was found to be between 0.38 and 0.44 times the water depth and the best dimension were found to be between 0.8 and 1 times the water depth. Ramandan et al. (2014) developed a numerical model for a wave energy conversion system. In the study, a new float was designed and its performance was analyzed analytically. The float was made from a hollow cylinder and inverted cup. MATLAB program was used for simulating the energy conversion system. The developed model results were tested by experimental results using the same data sets. The new float was compared with the conventional float in terms of mechanism of transmission and power generation. It is concluded that the new float was found to produce higher power than the conventional float. According to the study, the optimum float diameter was found to be 0.7 m with mass of 90 kg. It was observed that, using these parameters, the maximum power could be yielded. The peak time wave period and the wave amplitude where the maximum power could be found were 3 s and 0.6 m, respectively. Mahnamfar and Altunkaynak (2016) carried out an experimental study to investigate the effect of chamber geometry and wave parameters on the yield of energy of an oscillating water column (OWC) system. By carrying out 20 experimental sets using a piston-type wave maker, the authors indicated that, considering the opening height, the maximum wave power was found at the opening height of 0.51 m under the characteristics of regular wave series number 4, H=23.37 cm, T=1.42 s and L=280 cm. In addition, the authors concluded that, in order to achieve high energy conversion efficiency by the OWC system, both the chamber geometry of the OWC system and wave parameters need to be optimized simultaneously.

From the above given review of previous works, one can understand that the studies generally focused on analyzing just numerical or experimental models with limited geometry of OWC structure. This calls for the need to study the design of a new modified OWC system with different geometry and compare experimental and numerical models. The present study was, therefore, initiated to investigate the chamber geometry of two OWC systems through a combination of physical and numerical modeling. The objectives of this study were 1) to optimize an OWC system by changing the geometry of the structure expressed in terms of the opening height or angle of the front plate of system under different wave heights and wave periods; 2) to improve the OWC system based on numerical models and physical experimental models and 3) to compare the results of the numerical models with the experimental models results.

2. Numerical simulation of the OWC system

In this study, the oscillating water column (OWC) was designed to have different geometries with the objective of investigating the performance of the system and the velocity distribution in the outlet tube of the system. The FLOW 3D program was used to carry out three-dimensional numerical modeling of the OWC system. The FLOW-3D computer software allows civil engineers to perform hydraulic calculation for free surface flow and pressure flow. The software was chosen in this study because free surfaces are modeled with the Volume of Fluid (VOF) technique, which is built in the FLOW 3D model. Due to the program's success in solving free-surface flows, continuity and 3-dimensional Reynolds Averaged Navier-Stokes (RANS) equations were solved by using the finite volume method. The program works on rectangular cells which were used in order to obtain a non-uniform mesh for computations. The most important advantage of rectangular grids is that they can be generated and stored very easily as a result of their regular or structured nature. Different blocks of cells can be