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Siming Zheng

Study on Hydrodynamic Characteristics of the Raft-type Wave-Powered Desalination Device

Doctoral Thesis accepted by
the Tsinghua University, Beijing, China

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Supervisor's Foreword

Wave-powered desalination is a very promising option to ease water crisis which is striking worldwide and, with rising populations and increasingly rapid climate change, more probably looms in the near future. When we are faced with very severe water scarcity which appears in most islands, it is believed that this shortage could be relieved fundamentally provided that inexhaustible wave energy in waters surrounding these islands is utilized for powering desalination. Even though it has been under development since the 1970s and many concepts, including the DelBuoy, AquaBuoy, McCabe Wave Pump, OMI wave pump and CETO, have been proposed, so far no conceptual device has been commercialized. Nevertheless, more and more people believe that the abundance of untapped wave energy, with the further development of wave energy utilization technology, seems to be an ideal alternative for powering desalination.

Among the wide variety of desalination devices proposed thus far, a raft-type wave-powered desalination device would be one of the best solutions mainly because of its advantages which lie in (1) the fact that ocean wave energy appears to be ideally suited for coupling with desalination process because both the wave and seawater are available in the same place and (2) using wave energy to directly pressurize seawater flow through reciprocating hydraulic pumps in one direction to a reverse osmosis membrane for freshwater. This avoids the conversion of the energy from hydraulic to electrical and then back to hydraulic, consequently leading a more effective desalination powered directly by the hydraulics of the WEC; and (3) raft-type WECs are proven to have a high wave energy conversion efficiency and can be very complaint to the extreme waves for a good survivability. However, a model for raft-type wave-powered desalination has not been established which fully couples mechanical process of desalination by RO and wave energy conversion by WECs. Additionally, the details of how the maximum wave energy capture width ratio for the raft-type WECs and how the performance of WECs with adjustable gyration radius by using either internal oscillators sliding inside along raft body or water tank have not been described. These hinder the development of raft-type wave-powered desalination technology to some extent. In order to effectively desalinate seawater, there is a need to comprehensively understand mechanisms underlying wave energy conversion by WEC and desalination process by RO as well as mechanisms underlying interaction between WEC and RO. In order to promote the industrialization of wave-powered desalination technology, there is a need to further explore ways and methods to improve its performance.

This thesis looks at the issues of hydrodynamic characteristics of the raft-type wave-powered desalination device. To achieve a sustainable water supply, we need improved technologies that can be applied with high reliability and low cost-benefit ratio. Reverse osmosis (RO) technologies are a potential sustainable solution, if they can be applied with limited materials consumption and a small energy footprint, while wave energy conversion technologies have enough potential to play an important role in sustainable energy future. Mechanical process of desalination by RO is required to fully integrate with wave energy conversion by WECs with high capture width ratio. Modeling technologies must be able to fully reflect the physical characteristics of wave energy conversion and desalination process so as to make device designs scientifically. Understanding these characteristics and developing these technologies provide a possible pathway to a sustainable water supply in future. This thesis explores these technologies and mechanisms underlying these technologies through both analytical and numerical studies. It is a promising vision of the future, built around a particular technology whose time has perhaps come.

Beijing, China
August 2017

Prof. Yongliang Zhang

Abstract

The growing scarcity of freshwater is driving the implementation of desalination on an increasingly large scale. Using wave power as the driving force of reverse osmosis (RO) system gives a new way to reduce desalination plant costs by bridging the fields of renewable energy and desalination. Among the wide variety of devices proposed thus far, raft-type wave energy converters (WECs) are proven to have a high wave energy conversion efficiency. Therefore, the wave-powered RO system based on raft-type WECs is fundamentally attractive. In this thesis, both analytical analysis and numerical method are used to study the hydrodynamic characteristics of a raft-type wave-powered desalination device, in which the desalination system is assumed to be a power take-off (PTO) system of raft-type WECs first and then to be a RO convection-diffusion model for a detailed study on real desalination process.

Firstly, an analytical model for the analysis of hydrodynamic characteristics of two-dimensional raft-type WECs is proposed based on linearized velocity potential theory. The unknown coefficients of velocity potentials are determined by utilizing eigenfunction expansion matching method. The analytical model is utilized to examine the effect of PTO damping coefficient, raft draught, spacing between adjacent rafts, raft numbers, raft length and raft length ratio on power absorption efficiency, and wave transmission coefficient. The results show that a raft-type WEC consisting of two rafts with different lengths is capable of capturing more power from waves compared to that with two same rafts.

The thesis also presents a dynamic analysis of a raft-type WEC, which consists of two hinged cylindrical rafts of elliptical cross section, based on the three-dimensional wave radiation–diffraction theory and boundary element method (BEM). The effect of raft length, linear damping and spring coefficient in the PTO system, axis ratio, and raft radius of gyration on wave power capture factor has been investigated in the frequency domain, while the effects of a nonlinear Coulomb damping, raft radius of gyration, and latching control have been studied in the time domain. The difference in the performance of a raft-type WEC obtained using a linear damping and a Coulomb damping is also illustrated. It is revealed that with the consideration of the mass non-uniform distribution along rafts, the phase lags between pitch excitation moments and pitch velocities can be reduced, leading to a much larger power capture factor.

The maximum mean power that can be absorbed by the raft-type WEC cannot be obtained accurately or rapidly by using numerical model. In addition, in practical applications, most WECs have physical limitations placed upon their excursions due to restraints such as mooring lines or pump stroke. To evaluate the maximum mean power that can be captured by the raft-type WEC under motion constraints, two mathematical models are presented by directly calculating time-averaged power absorption of PTO system and considering power absorption as the difference between excitation and radiated power without consideration of PTO system, respectively: The former one is mainly used for two interconnected rafts with relative pitch motion constraint; the other one can be applied for multiple connected floating rafts under a weighted global constraint.

Two power extraction enhancing strategies, one with the utilization of a spring-damping-mass oscillator system inside each raft and the other with the employment of a water tank, are also proposed. Effects of damping of PTO system, mass, damping and stiffness of the oscillator system, the size and position of the tanks on dynamics of the raft-type WECs mainly in terms of wave energy absorption are all investigated by using numerical models.

For wave-powered RO device, the pressure required for RO comes from the ocean waves, leading to a non-steady-state process with the feed pressure and flow rates varying with time. Therefore, a transient model accounting for the time variation of desalinating process is required to simulate the behavior of wave-powered desalination device. In the end of this thesis, a numerical model based on BEM and finite volume discretization is proposed to solve the hydrodynamics of raft-type WEC and the concentration variation in the RO polarization layer. The model considers the interaction between raft-type WEC, high-pressure accumulator, and RO module and accounts for the time variation of permeate flux and concentration. Results indicate that there is a proper RO width and a proper wave period to maximize averaged permeate water flux and to minimize the averaged permeate concentration as well.

Keywords Wave energy · Raft-type wave energy converter · Desalination · Hydrodynamics · Wave power capture factor

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2. Zheng SM, Zhang YL (2016) Wave diffraction and radiation by multiple rectangular floaters. Journal of Hydraulic Research, 54(1):102-115.
3. Zheng SM, Zhang YH, Zhang YL et al. (2015) Numerical study on the dynamics of a two-raft wave energy conversion device. Journal of Fluids and Structures, 58:271-290.
4. Zheng SM, Zhang YL, Sheng WA (2016) Maximum wave energy conversion by two interconnected floaters. Journal of Energy Resources Technology, 138 (3), p. 032004.
5. Zheng, SM, Zhang YL, Sheng WA (2016) Maximum theoretical power absorption of connected floating bodies under motion constraints. Applied Ocean Research, 58:95-103.
6. Zheng SM, Zhang YL, Sheng WA (2015) Numerical study on the dynamics of a novel two-raft wave energy absorption device. 11th European Wave and Tidal Energy Conference, 6-11 September, Nantes, France. 07C1-3.

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Finally, the author would also like to dedicate this dissertation to his wife, Lingling Zhang, and his parents, Meng Zheng and Shuzhen Qin, for their love and support all the time throughout his Ph.D. program.

Contents

Abbreviations

BEM	Boundary Element Method
PTO	Power Take-Off
RO	Reverse Osmosis
WEC	Wave Energy Converter
WPRO	Wave-Powered Reverse Osmosis