Renewable Energy 118 (2018) 727–741

Contents lists available at ScienceDirect

Renewable Energy

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

Geometric evaluation of the main operational principle of an overtopping wave energy converter by means of Constructal Design

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ARTICLE INFO

Article history:
Received 14 July 2016
Received in revised form
17 November 2017
Accepted 21 November 2017
Available online 22 November 2017

Keywords:
Wave energy
Constructal Design
Overtopping device
Geometric evaluation
Numerical study

ABSTRACT

Current work aims to study the geometry of an overtopping wave energy converter in real scale using Constructal Design. Problem studied here is submitted to two constraints (areas of wave tank and overtopping ramp) and two degrees of freedom: ratio between the height and length of ramp (H_1/L_1) (or ramp slope, β) and distance between the bottom of wave tank and the device (S). The effect of H_1/L_1 and S over dimensionless device available power (P_d) is evaluated for three different ramp area fractions (ϕ) and two different monochromatic waves. Conservation equations of mass, momentum and one equation for the transport of water volume fraction are solved with the finite volume method. To tackle with water-air mixture, multiphase model Volume of Fluid is used. Results showed the applicability of Constructal Design for improvement of device performance. For fixed magnitudes of S, the highest magnitudes of P_d are achieved for the lowest possible ratio of H_1/L_1. For smaller construction areas of the ramp, intermediate magnitudes of S led to the highest magnitudes of P_d, i.e., the sinking of device does not led necessarily to the best performance. Moreover, optimal shapes are not universal (the same) for the two wave conditions studied.

1. Introduction

Literature has evinced a wide variety of wave energy technologies, resulting in different ways of achievement of electric energy from the movement of sea waves. These technologies depend on several parameters as the water depth and the device location (onshore or shoreline, near-shore, offshore). Contrary to what has been seen for wind energy conversion, there is no dominant technology deployed for wave energy converters (WEC) [1]. In this sense, the improvement of WECs design parameters can also be considered an important subject.

Among different working principles for WECs, it is possible to mention the oscillating water column (OWC) (with air turbine), oscillating bodies (with hydraulic motor, hydraulic turbine, linear electric generation) and overtopping (with low-head hydraulic turbine) [1–4]. Latter device main operational principle is the scope of present work and consists on the water accumulation into a reservoir raised above the sea level. The wave water overtops the inclined ramp and enters into reservoir. The accumulated water returns to the sea passing through low head hydraulic turbines generating electricity [5,6]. Fig. 1 illustrates a schematic sketch with the main operational principle of the overtopping device.

At the authors knowledge, few works have been devoted to comprehension of overtopping device in comparison with the discussion about other WECs [5–8]. Moreover, the comprehension of fluid flow in the overtopping has been dominantly performed for wave flow over dams and breakwaters [9–12].

Concerning the Overtopping Wave Energy Converters (OWEC), some important works have been fulfilled in the development of experimental and numerical studies for evaluation of building parameters of offshore devices [5,7,13,14]. More precisely, Kofoed [7] performed an experimental study in model scale investigating the influence of some geometric parameters over the average volumetric rate of water that overtops the ramp. For the studied

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https://doi.org/10.1016/j.renene.2017.11.061

Nomenclature

A	area, m^2
A_r	ramp area, m^2
A_T	tank area, m^2
F	external forces, N.m^{-3}
g	gravitational acceleration, m.s^{-2}
h	water depth, m
h_a	height of water accumulated in the reservoir, m
H	wave height, m
H_1	ramp height, m
H_T	total tank height, m
H_R	reservoir height, m
k	wave number, m^{-1}
L_1	ramp length, m
L_R	reservoir length, m
L_T	total tank length, m
m	mass entering in the reservoir, kg
$\dot{m}$	mass flow rate of water per meter of wave front, kg.m^{-1}.s^{-1}
P_a	available power per meter of wavefront, W.m^{-1}
P_d	dimensionless available power, P_a/P_{wave}
P_{wave}	power contained in the wave per meter of wavefront, W.m^{-1}
p	pressure, N.m^{-2}
R	freeboard height ($R = S + H_1$), m
S	distance between the bottom of the wave tank and the device, m
t	time, s
T	wave period, s
u	velocity in x-direction, m.s^{-1}
v	velocity in y-direction, m.s^{-1}
$\dot{V}$	volumetric rate of water that overtops the ramp per meter of wave front, m^3.m^{-1}.s^{-1}
$\dot{V}_{avg}$	time-averaged volumetric rate of water that overtops the ramp per meter of wave front, m^3.m^{-1}.s^{-1}
w	velocity in z-direction, m.s^{-1}
x	horizontal direction, m
z	vertical direction, m

Greek symbols

α	volume fraction
β	ramp slope
η	free-surface elevation, m
λ	wavelength, m
π	mathematical constant
ρ	density, kg.m^{-3}
σ	wave frequency, s^{-1}
$\overline{\overline{\tau}}$	stress tensor, Pa
Δt	time-step, s
μ	fluid dynamic viscosity, kg.m^{-1}.s^{-1}
ϕ	area fraction of the ramp (A_r/A_T)

Subscripts

$()_m$	once maximized
$()_{mm}$	twice maximized
$()_o$	once optimized
$()_{oo}$	twice optimized

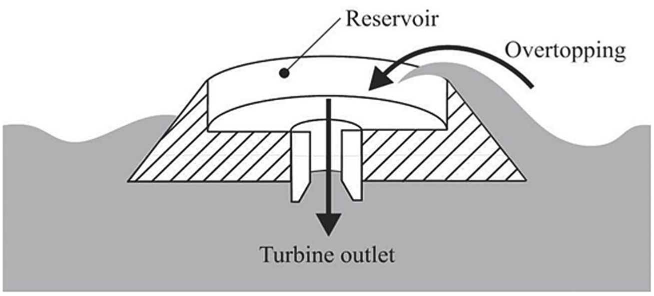

Fig. 1. Illustration of the main operational principle of overtopping device.

cases, the overtopping rate decreased with the increase of crest freeboard height and draught dimension (which was defined as the distance from the water depth and the inferior surface of the device). In addition, the slope of the ramp was varied from 20° to 60° and the optimal shape was reached for an intermediate angle of 30°. Afterwards, Kofoed et al. [5] realized extensive tests of a prototype with reduced scale of 1:50 inside a wave tank. It was also built a new prototype in reduced scale with 1:4.5 of a Wave Dragon (WD) device. This equipment was evaluated during three years being monitored parameters such as power, wave climate, forces in mooring lines and structure tension. The purpose was to determine the design for the structure, as well as, development of a plan to implement a unit for generation of 4 MW. More recently, Liu et al. [14] has experimentally studied an offshore overtopping wave energy converter (CROWN) which uses a circular ramp around the reservoir. Results showed that guide vanes and milder ramp slopes were found to significantly improve the overtopping discharge. Into the numerical framework, Liu et al. [13] evaluated an offshore overtopping device in model scale. Conservation equations were solved with the Finite Volume Method (FVM) and the Volume of Fluid (VOF) model was employed to track the free surface. Several conditions for incident waves and ramps with three different ratios between height and length (1:1, 1:2 and 2:3) were investigated. Nam et al. [15] had numerically evaluated an offshore device named Spiral-Reef Overtopping, which consists on devices with circular-shaped structures. The simulations were performed with FLOW3D, a code based on the Finite Difference Method (FDM). Two and three-dimensional simulations with the aim to evaluate the best geometry for accumulation of water inside the device reservoir were carried out. Afterwards, Iahnke [16] evaluated the ramp inclination of an overtopping device for a two-dimensional flow taking into account the wave conditions found in the southern coast of Brazil (Rio Grande city, placed in nearly geographical coordinates of 32°S and 52°W). Best performance was obtained for a ramp with an angle of 30°. Beels et al. [17] used a numerical model to solve the transient flow in a farm of Wave Dragon devices. For the evaluation of the farm arrangement it was tested different distances among different equipment: D, $2D$ and $3D$, being $D = 260$ m the distance between two points of Wave Dragon reflector. As a result, the authors concluded that a farm with five devices installed with a staggered arrangement is more efficient due to the best utilization of space associated with no significant interference of one converter in the others. Moreover, Jin et al. [18] performed a three-dimensional numerical study of a device similar to that studied in Nam et al. [15]. More precisely, it was made a comparison