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DESIGN ENHANCEMENT OF AN OSCILLATING WATER COLUMN FOR HARNESSING OF WAVE ENERGY

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ABSTRACT

Renewable energy resources are in increased demand due to environmental and economic problems associated with the conventional energy resources like fossil fuels. In the past few decades, different ideas, designs and devices have been put forward to extract energy from sea waves. Oscillating water column (OWC) technology is one of these new tools being adopted for wave energy extraction. An OWC device converts wave energy into electricity using high speed air flow caused by fluctuations in water level induced by incoming sea waves. This paper briefly describes two main components of an OWC i.e. air chamber and power take off system. The air chamber, being the major component in energy conversion process, holds significant importance in research studies. Geometric components of an OWC chamber affecting the efficiency of an OWC are also discussed. Although studies have been done on improvement of air chamber designs; however, very few researchers have explored OWC applications under mild sea waves. This paper also addresses development of an OWC with a modified design with reference to the guidelines stipulated by previous researchers. It is anticipated that the proposed OWC model will have better energy extraction performance in the low wave energy climates.

Keywords: wave energy, air chamber, OWC prototypes.

INTRODUCTION

Energy is the central need and necessity of life for humans since ancient times. After industrial revolution, extensive consumption of fossil fuels led to the emission of greenhouse gases that accelerated climate changes. Conventional sources of energy are now being replaced by renewable sources to minimize their adverse effects. Oceans are also one of the sources of renewable energy. Ocean or marine energy can be extracted in the form of waves, tides, salinity gradient, and ocean temperature differences. Among marine energy resources, wave energy is gaining more attention as it is in abundance and more consistent. It has also greater power density (2–3 kW/m^2) as compared to wind (0.1-0.2 kW/m^2) and solar energy (0.4-0.6 kW/m^2) [1]. Wave energy converters (WECs) are used to harness wave energy. Based on their working principle, wave energy converters are classified as attenuators, surface point absorbers, oscillating wave surge convertor, oscillating water column, overtopping devices and submerged pressure differentials [2].

Among wave energy converters, oscillating water column (OWC) is the widely studied type of wave energy converters [3]. Oscillating water column device harnesses wave energy using oscillation of water inside an enclosed chamber due to wave action. An OWC consists of two essential components, an air chamber and a power take off (PTO) system as shown in Figure-1. Air chamber, also known as collector chamber, is a partly submerged hollow assembly made up of concrete or steel. The air chamber transforms wave power into pneumatic power in the form of air flow, which is produced by the oscillations of the water column. The power take-off system (PTO) system of an OWC consists of a turbine and a generator. The alternating air flow passing from orifice to turbine causes it to rotate, which is further connected to a generator to produce electricity.

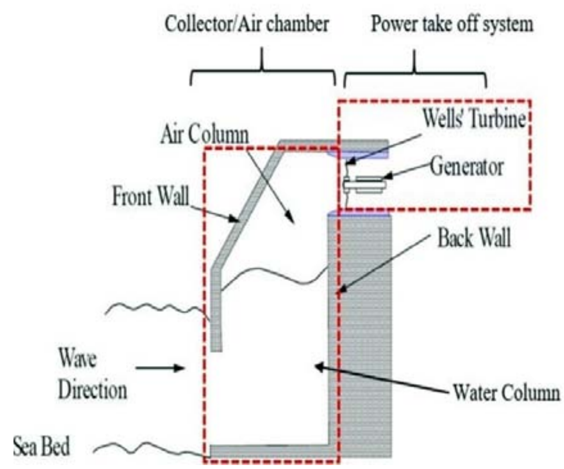

Figure-1. Typical OWC components [4].

Different types of OWC have been introduced and studied by previous researchers. OWCs are classified on the basis of locations and construction technique. According to locations, OWCs devices are classified as shoreline OWCs, nearshore OWCs, and offshore OWCs. Base on construction practice, OWC devices can divide into two main types; (1) fixed OWCs and (2) floating OWCs. Fixed OWCs are generally constructed near coastline or nearshore regions. They can be either fixed to coastline with rocky cliff or bottom mounted in near shore locations. Floating OWCs are like floating structures installed near shore or offshore locations where the wave intensity is high. Unlike fixed OWCs, floating OWCs are moored to the seabed. Among all types of OWCs, shoreline fixed OWCs have easy accessibility from land. Furthermore, survivability index of the shoreline OWC is higher than other locations [5].

The concept of wave energy conversion from sea waves using oscillating water column technology came through navigational buoys in Japan. Japanese naval officer, Yoshio Masuda, used navigational buoys to produce electricity from ocean waves [6]. Since then, many full scale OWCs prototypes have been installed and tested around the world. LIMPET is the first commercial OWC power plant powering more than 250 houses, located at island of the Islay, Scotland. Detailed review of the OWC prototypes installed around the world is given by Falcoa and Henriques [7]. Among different wave energy converters, OWCs are more promising wave extraction devices due to their simplicity as there is no moving part of an OWC in the water except blades of the turbines which are situated above the water level [8].

An OWC performance is assessed based on its energy extraction efficiency, also known as wave to wire efficiency. The actual measured wave to wire efficiencies of OWCs installed around the world are below their theoretical efficiencies [9]. The uninterrupted and maximum flow of air through the turbine is the key factor in defining efficiency of the OWC. Being the primary component in energy conversion stage, the air chamber of an OWC holds significant importance. Air losses inside the chamber and duct reduce the air flow rate, thus decreasing pneumatic power available to the turbine. Improper design of an OWC chamber is also one of the reasons for low performance of the device [10]. This point towards the importance of OWC chamber design and identification of the factors affecting its performance.

GEOMETRIC COMPONENTS AFFECTING OWC EFFICIENCY

The OWC chamber is the main component of an OWC device. Therefore, to design an efficient OWC, there is a need to have better understanding of air chamber components. The effects of geometric parameters of the air chamber on the efficiency of an OWC are studied by different researchers. The structural components of OWC chamber have significant effect on the performance of the OWC i.e. wall of air chamber, width, front wall thickness, bottom slope and orifice size. Thomas *et al.* [11] experimentally examined the effect of front wall geometry on efficiency of an OWC. They concluded that curved rather that rectangular opening shape of the immersed front wall enhanced hydrodynamic efficiency of the OWC. Zaouf *et al*. [12] reported in their study that L shape wall has more efficiency (24%) than simple vertical shape of front wall (20.4%). Bouali and Larbi [12] reported that the maximum OWC efficiency was achieved at front wall submergence depth of 0.45h (where h is water depth). Ning *et al.* [13] proved that hydrodynamic efficiency of an OWC tends to decrease by increasing front wall immersion depth in short waves.

Inclination of OWC chamber is another factor that effects oscillation characteristics of water inside OWC chamber. In general, the resonant period of an OWC device is considerably extended by inclination of the walls especially rear wall [14]. Ravinesh *et al.* [15] found that decreasing the angle of inclination of air chamber from vertical 90° to 55°, increased the dynamic pressure inside the air chamber by 200%. Dizadji and Ehsan [16] studied the inclination of back and rear walls and claimed that parallel inclined assembly of both walls of the OWC chamber had better performance.

The bottom opening of the OWC device is another parameter affecting the performance of OWC. Yaakob *et al*. [17] claimed that curve entrance and reflector at the bottom of the air chamber enhanced the efficiency when compared with typical OWC. Amin [18] also suggested the use of a curved entrance to the OWC chamber in order to increase its hydrodynamic energy extraction performance. Wilbert *et al*. [19] reported that energy conversion capacity of an OWC achieves maximum efficiency of 94% at Ho/h = 0.80 (where Ho= opening length, h = water depth). Ashlin *et al*. [20] carried out laboratory experiments on four unalike bottom profiles: (1) flat bottom, (2) round curve of radius 300 mm, (3) slope of 1:1 and (4) slope of 1:5. The OWC with circular curve bottom profile gave better performance compared to the OWCs with different bottom profiles.

Linear length of the collector chamber of an OWC in the direction of the wave propagation is described by the width B of the chamber. The resonant frequency reduces by increasing the width B of chamber; mainly due to increase in the mass of water column inside OWC chamber [13]. Gomes *et al.* [21] reported that the ideal width to height ratio of an OWC chamber is 0.84 and the worst is 0.14. Sameti and Farahi [22] found that the output power is directly proportional to wave height and chamber width. It was also reported that the optimum power output of OWC device (46 % efficiency) was achieved at B/L= 0.42 (where B= chamber width, L= wavelength). Ning *et al*. [23] showed variations of the OWC efficiency versus the chamber width normalized to water depth h. The maximum value obtained for the OWC efficiency was achieved for a chamber width of about 0.92h.

Efficiency of the OWC energy extraction also depends on the size of orifice. Ning *et al*. [13] found the for larger orifice ratio (ratio of the plan cross sectional area of the orifice to plan cross sectional area of the air chamber) internal air pressure decreases, while the extreme water surface elevation increases. He and Huang [24] carried out studies on different sizes of orifice and reported that the circular shaped orifice having orifice ratio of 0.625% could attain maximum air flow. Ashlin *et al*. [25] varied opening ratio ranging from 0.1% to 1.2% of plan area of the chamber. It was reported that opening ratio between 0.6 and 0.7% gives a maximum efficiency of about 64%.

Efficiency of OWC chamber is also reliant on wave parameters. The air pressure created inside the air chamber is the function of wave height. Larger the waves, larger will be the pneumatic power generated inside the air chamber. However the efficiency of the air chamber decreases with the increase in wave steepness. Turbulence, spillage and vortex shedding increase the energy losses in steeper waves [26]. López *et al*. [27] observed that the capture factor increases with the wave steepness at low wave frequencies and decreases at high wave frequencies.

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In summary, it can be deduced that chamber geometry and wave characteristics have significant effect on energy extraction efficiency of an OWC. To optimize existing OWC design, geometric factors like chamber width, wall height, orifice ratio, inclination angle and bottom profile, should be designed according to the guidelines set by previous researchers. Although, a lot of work has been done on various design studies of the OWC chamber, however, majority of the work is focused on harnessing energy from high energy waves. Very limited research is being done on OWC designs to extract energy from mild waves. For countries like Malaysia having mild wave conditions, there is a need to optimize existing OWC designs. This study is being carried out to develop a robust design of OWC to capture energy from the seas of mild wave conditions.

PROPOSED OWC MODEL

As discussed in literature review, OWC efficiency depends both on structural components and wave parameters. An OWC chamber model is proposed in this paper using the guidelines stipulated in previous studies. Wave climate varies from site to site. Wave parameters i.e. wave height, time period, celerity; wavelength primarily depends on the wave climate. It is anticipated that the newly developed OWC is to be installed in mild wave climate. As far as this study is concerned, the key geometric parameters considered for the proposed model are shape of chamber, inclination of the chamber and orifice size of the chamber. The efficiency of proposed OWC chamber can be ascertained by numerical or physical modelling.

Efficiency of OWC chamber

Overall efficiency of an OWC is sum of efficiencies of all three stages of energy conversion chain. Energy conversion chain of an OWC from wave power to electricity is a 3 step process (wave power to pneumatic power; pneumatic power to mechanical power; mechanical power to electricity). The expression for the overall efficiency (wave-to-wire efficiency) of an OWC is given by

$$\eta_{overall} = \frac{Power\ Output}{Wave\ Power} \tag{1}$$

It can also be defined as:

$$\eta_{efficiency} = \eta_{capture} \times \eta_{turbine} \times \eta_{generator} \tag{2}$$

In the above expression, is the capture efficiency of air chamber, whereas, and are the efficiencies of the turbine and the generator respectively.

Capture efficiency of air chamber is defined as the ratio of pneumatic power available inside the air chamber to the incident wave power.

$$\eta_{capture\ efficiency} = \frac{Pneumatic\ Power\ (Pu)}{Wave\ Power\ (Pw)} \tag{3}$$

OWC geometric design

The proposed OWC model in this paper has circular chamber as shown in Figure-2. Circular chamber will ensure smooth air flow inside the chamber. Unlike rectangular chamber, circular configuration of OWC chamber minimizes energy losses around corners and sharp edges. The effects of turbulence and sloshing results in energy loss at edges and corners of rectangular chamber when interacting with waves. The circular chamber of the proposed OWC design model consists of two section: (1) circular section and (2) conical section at the upper section. Conical section connects air chamber to the turbine section through a duct. The conical section starts from the point where one section of air chamber ends and converges to the turbine section. The purpose of using conical section is to gradually narrow the area of air flow from air chamber to turbine which will increase the air flow speed through the turbine, using the principle of fluid dynamics.

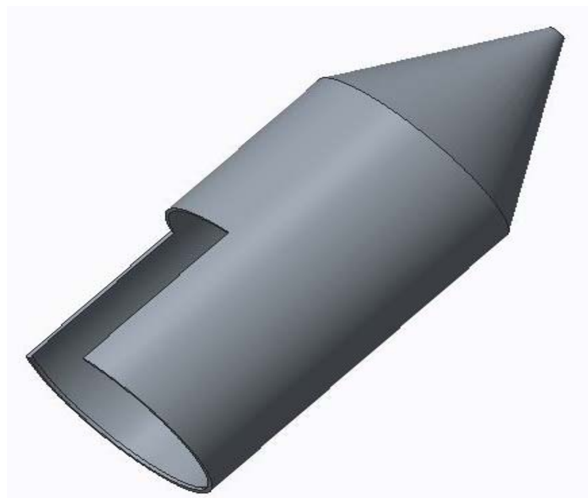

Figure-2. Proposed OWC model.

Unlike conventional OWC, proposed OWC air chamber is inclined at angle of 45°. Inclination angle of collector will gives an easier way for water column to ingress and egress which results in small turbulence and minimum energy dissipation. The conventional OWC are largely made of vertical air chambers. When a wave strikes the vertical wall of an OWC, most of the water particles reflect back from the vertical wall. During reflection from a vertical rigid wall, a partially standing wave is formed in front of the vertical structure, having combined amplitude of the incident and reflected waves. In most cases, the reflected wave superimposes the incoming wave and causes a net reduction in wave height. Inclined chamber is mostly suggested for OWCs which are to be installed in shallow waters where the horizontal part of wave motion is more dominant than the vertical motion.

The third parameter considered in proposed design is the orifice size. The size of the orifice of an OWC is be defined by the orifice ratio or opening ratio. The orifice provided in the model is of circular shape. Circular orifice has shown better performance than rectangular openings as suggested by Huang [24]. For this study, orifice is provided at the end of conical section. As recommended by previous researchers, the orifice ratio for the proposed model is set to 1%.

Introduction of conical section in air chamber and inclination of air chamber make the existing OWC model different from conventional OWCs. It is anticipated that the proposed OWC will be more efficient in extracting wave energy. The dimensions of the structural components of OWC chamber can be fixed depending upon the wave parameters for a specific location and sea characteristics. The recommended dimensions for structural component of an OWC design based on previous studies are summarized in Table-1.

Table-1. Recommended dimensions for OWC chamber.

Parameters	Symbol	Recommended
Width of chamber	*B*	*0.92h* (*h*= water depth) *0.42L* (*L*=Wavelength) *0.84Ha* (*Ha*=Height of Air chamber)
Height of air chamber	*Ha*	*1.2B*
Front wall Submergence Depth	*D*	*0.35-0.45h*
Opening length	*Ho*	*0.65-0.8h*
Inclination angle	*α*	45°-55°
Orifice Size ratio	*Ao*	0.60%-1.20%

CONCLUSIONS

Among different wave energy converters, oscillating water column is the simplest and most studied type of the wave energy conversion technology. The efficiency of an OWC power plant primarily depends upon the efficiency of OWC collector chamber as it is the first phase of wave energy conversion. Efficiency of the air chamber is reliant on the geometric design of the air chamber, sea characteristics and wave parameters. To develop an efficient OWC chamber, designer must consider and analyze all the geometric parameters. Based on the design guidelines developed for OWC, a new conceptual design of an OWC chamber is proposed in this study. The proposed OWC chamber is has two sections: (1) circular section and (2) conical section at the upper section. It is anticipated that inclined OWC chamber will increase the efficiency of an OWC device in mild wave climates.

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