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Validation Study of U-Oscillating Water Column Device Using Computational Fluid Dynamic (CFD) Simulation

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ABSTRACT

Renewable energy plays an important role in producing electricity, whereas fossil fuels slowly decrease worldwide. Oscillating water column (OWC) is a concept that has been widely used and has advantage as it is said to reach full scale model stage. It is found that the OWC device can be improved by integrating it with breakwater system for coastal protection. U-OWC device is another type of OWC with an additional vertical front wall which shows better performance than the classic OWC. This paper describes a CFD validation procedure for parametric study to further optimize the U-OWC device. The results will be validated by comparing with established experimental data. The study was based on two-dimensional and three-dimensional analysis using commercial FLOW-3D software. Some parametric analysis regarding geometrical modifications of U-OWC device has been suggested to obtain the optimal configuration of the device. Although this system operated in low amplitude, it is expected to generate and improve its efficiency level with some special tuning.
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Keywords: *Oscillating Water Column (OWC); U-OWC; FLOW-3D; CFD Validation; Geometrical Modifications*

1.0 INTRODUCTION

Malaysia as a developing country needs to maintain its energy demand instead of depending on fossil fuel. Energy consumption in Malaysia is estimated to increase around 6 to 8 percent annually based on the national economic growth [1]. Excess burning of fossil fuel as main energy source will threaten future energy supply and also environmental condition [2]. Besides that, the burning of fossil fuel will release greenhouse gases which eventually will give a huge impact on environment [3, 4]. Thus, it is important to search for other clean energy sources to reduce the negative impact on the environment. Malaysia is aware of its role in formulating national policies, cause and effect of development towards environment and is responsive in searching for renewable energy sources

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[5]. Ocean energy appears as a potential energy to be harvested in Malaysia as it is surrounded by ocean. The energy can be extracted in several forms which are thermal difference, tides, waves, ocean current and salinity gradient. Wave energy along east coast of Peninsular Malaysia has more potential than other regions with average significant wave height around 0.5m to 1.5m [6]. Since the wave power is low, some modifications to the wave energy device need to be developed to extract this energy [6].

One type of wave energy device is oscillating water column (OWC) which appears to be one of the most successful concepts that reached full scale prototype stage [7]. OWC device basically consists of a partially submerged chamber with an opening below the sea water level. When waves approach the device, water will push into the chamber and will help oscillate the air column at the upper part of the chamber. Water inside the chamber will act like a piston and the compressed air will be released into the atmosphere via turbine. OWC can act as dual function device if it is used at shoreline area. Instead of producing electricity, it will help to protect the coastal area from wave erosion. Shoreline devices have some advantages such as ease of maintenance and installation works [8, 9].

One modified type of OWC is U-OWC device which has an additional front vertical seaward wall. The additional front seaward wall creates a U-shape duct that appears to be more efficient than classical OWC device. The incoming waves hit the device and produce pressure fluctuation at the upper opening of the vertical duct. The vertical front wall results in higher pressure fluctuation which allows for better resonance with high frequency waves [10]. The U-OWC device also has less likelihood to draw air from seaward opening compared to classical OWC device.

Therefore, this paper presents a study to find the optimum geometrical configuration of U-OWC device. FLOW-3D program is used in this study to carry out a three dimensional numerical modelling of U-OWC device. This paper will describe the validation process of U-OWC device with the previous experimental work [11] for further optimization of geometrical modifications using CFD simulation.

2.0 U-OSCILLATING WATER COLUMN (U-OWC)

First analytical description of U-OWC concept was introduced by Boccotti [12] under linear wave theory. The work was further refined to get more accurate description of wave field and the dynamics of the device [13]. Previous study on U-OWC concept showed that it has resonance coefficient range larger than conventional OWC which gives better performance in swells and large wind waves [12]. Recent works focused more on validating the numerical models by using computational fluid dynamics (CFD) solvers [14, 15]. Study also showed that changing the geometrical configuration of the device can improve the device performance [16].

Vyzikas [11] reported that geometry of a device has significant effect on the device performance. The study compared the performance of a conventional OWC device with a U-OWC device. Results showed that the U-OWC device with toe protection structure worked better in terms of its efficiency in most of the cases compared to the conventional OWC.

In our paper, we use the U-OWC design based on previous study [11] for further geometrical optimization using CFD. Figure 1 shows the side, top and 3D view of the device. The principal dimensions of U-OWC device are tabulated in Table 1.

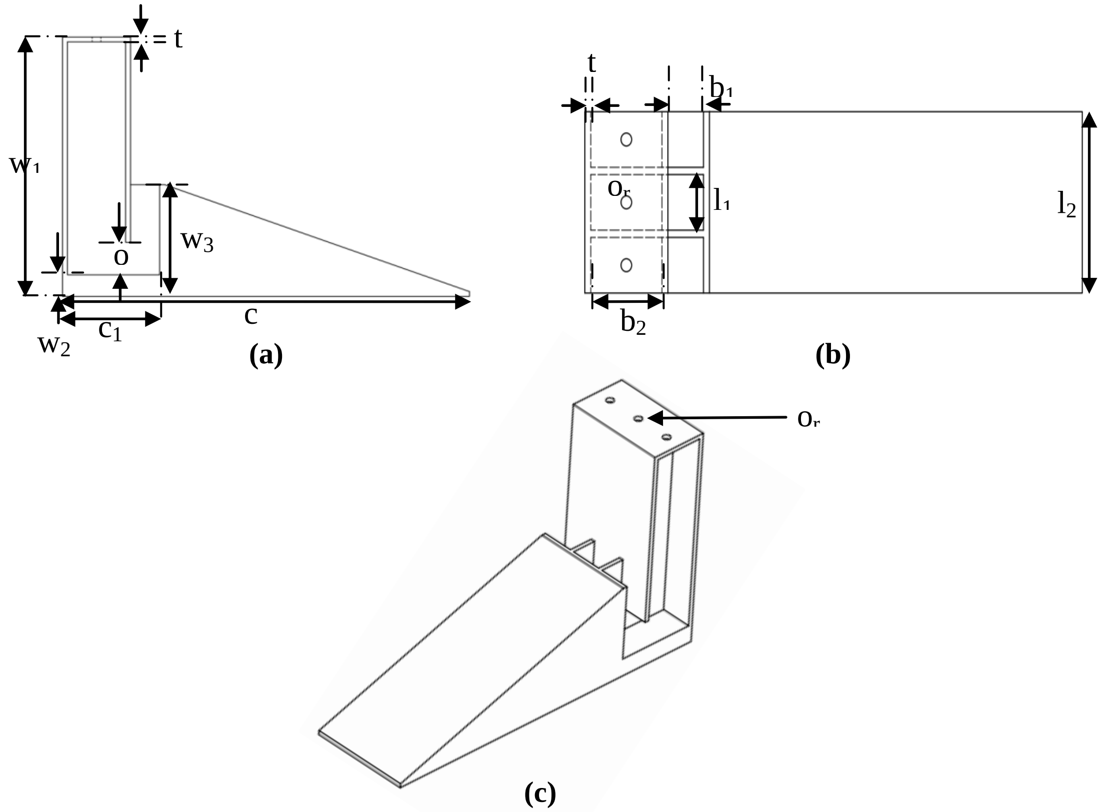


Figure 1: (a) Side view (b) plan view and (c) 3D perspective view of the U-OWC model [11].

Table 1: Dimensions of U-OWC model in meter [11].

w_1	w_2	w_3	c	c_1	o
1.268	0.107	0.554	2.000	0.644	0.161
b_1	**b_2**	**o_r**	**l_1**	**l_2**	**t**
0.143	0.286	0.015	0.184	0.6	0.024

2.1 Performance of U-OWC Device

General response of device can be observed by taking the surface elevation at specific location and normalizing it with the incident wave height. This general response is important to be used during the design process [11]. Commonly, non-dimensional ratio of amplitude known as response amplitude operator (RAO) is employed to measure the general response. RAO calculation will take into consideration only one degree of freedom (vertical oscillation) without considering the phases. The RAO can be written as

$$RAO = \frac{\Xi}{\alpha_w} \tag{1}$$

where Ξ represents response amplitude of wave inside the central chamber of the U-OWC device and α_w is amplitude of the incident wave.

Another important parameter to measure the hydrodynamic efficiency of U-OWC device is capture width ratio, C_w [11, 19]. C_w is defined as ratio of power absorbed by the device (P_{abs}) to the power of the incident wave (P_{inc}) as

$$C_w = \frac{P_{abs}}{P_{inc}} \quad (2)$$

The incident wave power is calculated by total incident wave energy across the tank width, W normal to wave crest of height, H and its celerity, C in water depth, d as follows

$$P_{inc} = \frac{\rho g H^2}{8}\frac{C}{2}\left(\frac{2kd}{\sinh 2kd} + 1\right)W \quad (2.1)$$

where k = 2π/L, and L is the wavelength of the incident wave. The power absorbed by the U-OWC device is calculated by the energy absorbed in one wave cycle of the wave period (T) through the section area of the orifice, S_c as

$$P_{abs} = \frac{1}{T}\int_0^T p(t)v(t)\, S_c dt \quad (2.2)$$

3.0 METHODOLOGY

Recent studies have shown that by adding additional front seaward wall to OWC device, a better performance can be obtained in both swell and large sea conditions. OWC concept has been widely explored through simulations, experiment and also the geometrical configurations. By furthering the study of U-OWC concept in terms of optimizing the geometrical configuration, it will improve the overall performance as wave energy extractor and also breakwater.

This research work involves CFD simulations to simulate the parametric study effect on the device performance. An appropriate CFD solver can simulate the real condition. The simulation is also able to predict some technical challenges conducting experimental works. There are three parts where U-OWC device must be optimized, which are the bottom profile shape, the bottom opening height and the shape of toe protection structure. In this paper, the authors report the validation of the simulations of U-OWC device with the experimental results by Vyzikas [11]. By comparing the simulation results with experimental data, further optimization process can be relied on.

3.1 CFD Simulation

The FLOW 3D software is used to carry out a three-dimensional modelling of U-OWC system. This software is chosen because it is able to perform well in solving hydraulic calculation for both free surface flow and pressure flow. The built in package allows to model the free surface by using Volume of Fluid (VoF) technique. The free surface is determined by using fluid fraction *(F)* which ranges from 0 to 1, where *F* is equal to 1 in the fluid state and equal to 0 when outside the fluid. It uses finite volume method to solve free surface flows, continuity equations and three dimensionless Reynolds Average Navier-Stokes (RANS) equations.

This simulation of U-OWC device was conducted under regular wave condition in a numerical flume tank domain. The U-OWC model consists of three identical chambers. The flume tank is 28m length, 0.6m width and the operating water depth for this device is at 0.75m. In this study, *k-ε* turbulence model is selected and the air is assumed to have constant properties of density,

ρ_a = 1.225 kgm^{-3} and viscosity, μ_a = 1.789 x 10^{-3} kgm^{-1}s^{-1} [20]. Data for this simulation is taken at the central chamber orifice for it free surface elevation inside the chamber, air velocity and pressure.

3.2 Boundary Condition

The upstream boundary condition X_{min} is considered as the wave generator while the other end X_{max} is considered as wall. Both boundary conditions for Y_{min} and Y_{max} refer to the wall according to the width of the model. The lower part boundary condition Z_{min} is taken as wall boundary condition while Z_{max} is taken as specific pressure boundary condition. The pressure is set to atmospheric pressure.

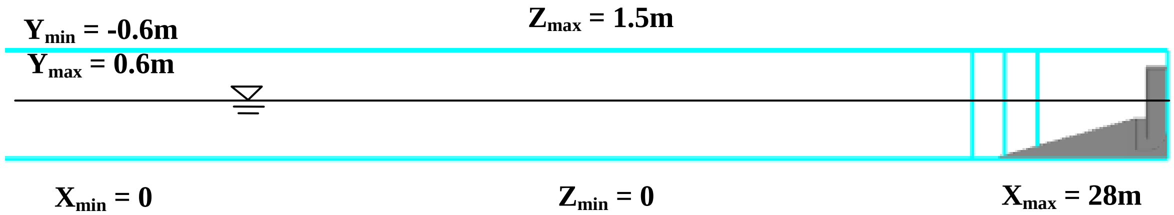


Figure 2: Simulation setup of the flume tank

3.3 Validation Process

Data from the simulation was compared with the experimental work by Vyzikas [11]. Validating this data with the experimental work can ensure the reliability for further geometric optimization. For the validation, the numerical model of U-OWC was tested using wave height of 0.088m to 0.159m with period around 2.6s to 1.7s, similar to those used by Vyzikas. However, for geometrical optimization of the device, the wave data was changed according to local condition. The wave data for local condition is around 0.5m to 1.5m wave height and with longer period which from 5s to 6s [7].

4.0 RESULTS AND DISCUSSION

Meshing size of the element is an important aspect to give accurate results. For this particular study, the meshing size was determined by section plane of the x-axis direction. The meshing size was gradually decreased from X_{min} to X_{max}. As the U-OWC model located at the end of X_{max}, it is essential to have fine meshing at this area. Fine meshing gave the correct geometry shape of the model with smoother surface, whereas bad mesh will result in rougher and uneven surface of model that affect the simulation results. Table 2 shows the total number of mesh elements with the cell size, particularly at the U-OWC model, while Figure 3 shows the results for grid independence study.

Table 2: Number of mesh elements and its cell size in each direction.

No.	Total No. of Mesh Elements	Cell Size in each Direction			RAO inside Central Chamber
		x-direction	y-direction	z-direction	
1	855,000	0.02	0.02	0.02	0.84
2	**2,534,400**	**0.0125**	**0.0125**	**0.0125**	**1.24**
3	3,960,000	0.0123	0.01	0.01	1.21
4	4,320,000	0.01	0.01	0.01	1.23
5	5,400,000	0.00625	0.01	0.01	1.22

The U-OWC model was tested using the wave height of 0.0795m and at 2.6 s period. The wave condition was fixed for all the cases. The free surface elevation at the central chamber for each cases was obtained to calculate its RAO using Equation 1. The results show that the RAO value for the U-OWC model started to increase, reaching around 2.5 million mesh elements before some consistency is shown. Thus, total number of 2,534,400 mesh elemenets is taken to be used for this study as it will give an accurate and consistant result with less time consumption.

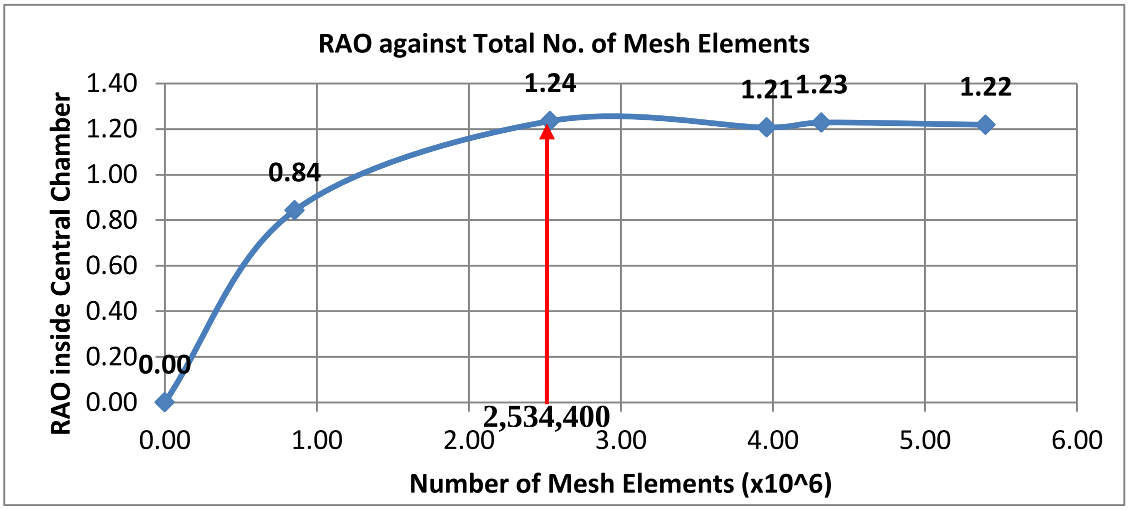
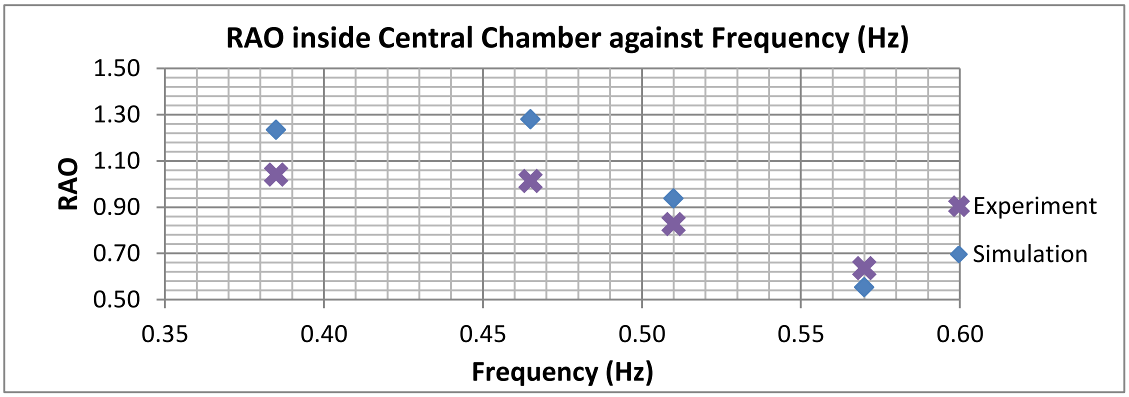


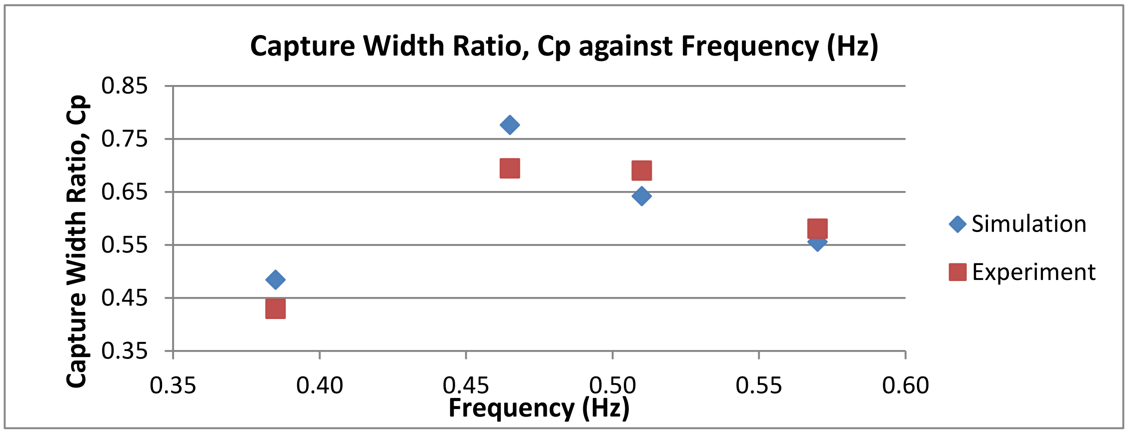
Figure 3: Grid Independence Study for U-OWC model using FLOW 3D software.

The comparison between simulation results and experimental data done by Vyzikas [11] are shown in Figure 4. Figure 4(a) compares the results for RAO in the central chamber. Both results show the same trend with slightly larger simulation values of RAO at the low frequency range. The NSE is 0.68, which is still considered as acceptable. The RAO for the simulation data show maximum values at the frequency of 0.465Hz showing resonance. Based on the data, U-OWC model will have larger values for RAO when it is exposed to low frequency waves.

Figure 4(b) shows the hydrodynamic efficiency of U-OWC model at four different frequencies. It seems that the simulation results of U-OWC model tend to follow the pattern of experimental data. The range of error is from 4% to 12% which are considered acceptable. The NSE is 0.74.



a)



b)

Figure 4: a) RAO inside central chamber and b) Capture width ratio, Cp

From the results, there are some technical issues that may affect the simulation data. The minimum possible number of mesh elements is 2,534,400. According to grid independence study, number of mesh elements larger than 2.5 million give results which are consistent, independent of the number of mesh elements. The meshing size used is much smaller at the end of flume tank where U-OWC model is located. This helps to form a more complete shape of model resulting in more precise and accurate data.

In addition, both simulation results increase when exposed to frequency of 0.456Hz. This is where resonance phenomena which is close to model natural frequency is expected to occur. Later, geometrical configurations of U-OWC model will be optimized so that the resonance region can be brought closer to the dominant period of waves in the Malaysian sea.

5.0 CONCLUDING REMARKS

The simulation model of the U-OWC model has been validated. Both trend for simulation data and experimental data seem to be similar. The NSE value calculated for both conditions are in the acceptable range. Further study regarding geometrical configuration of U-OWC model will be done to improve the hydrodynamic performance. The optimization will be carried out by changing the bottom profile shape and bottom opening height. These parameters will optimize the internal geometrical configurations for U-OWC device. Next is to change the slope of toe protection structure and its effectiveness to channel water into U-OWC device.

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