Numerical Study on an Integrated System of a Wave Energy Converter and a Breakwater

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***Abstract*—The study focuses on the characteristics of an integrated system that consists of a FOWC and a breakwater. A numerical wave tank (NWT) is designed based on Reynolds Averaged Navier-Stokes equation and overset mesh. A mesh study is conducted to determine the most accurate configuration whereas validation to numerical and experimental data is conducted to ensure the validity of the results of present study. A FOWC with and without breakwater was used in this study to compare their characteristics. Results show that the addition of breakwater enhanced the wave energy extraction at lower angular frequency. This finding may indicate favorable conditions that contribute to the higher energy extraction efficiency of the integrated system.**

Keywords—hydrodynamics, wave energy converter, breakwater, computational fluid dynamics

I. INTRODUCTION

As a signee of Conference of Parties 26 (COP26) declaration to go net zero-carbon by 2050, Malaysia faces an uphill task to convert its renewable energy mix of 7% at 2018 to 100% by 2050 [1]. A suitable candidate to help the country in achieving this goal would be the wave energy converter (WEC), given that the country has a long coastline of 4,675km [2]. The offshore wave energy generation is of particular interest, because of the large available offshore area and the more optimal parameters in this area for wave energy generation, such as a higher average wave height.

Oscillating water column (OWC), a form of WEC that rotates the turbine using air pressure generated by vertical movement of waves inside the column, is seen to be a technology where energy can be obtained economically at a good average wave height and wave period [2]. The form of OWC that is suitable for offshore energy generation is the floating oscillating water column (FOWC) due to its ability to float on the surface of the water, as opposed to the fixed OWC, that is typically built on the seashore.

Breakwater is traditionally used to protect coastal infrastructure from the constant pressure of incoming ocean waves. However, various studies [3]-[5] have found that it offers a complementary function of improving the efficiency of wave energy generation, when integrated with the WEC. A floating breakwater performs the same function in the offshore region, when integrated to the FOWC.

Several studies, such as Cheng et al. [5], have focused on the wave energy generation when the breakwater is placed upstream of the WEC, in the direction of incoming waves. One purpose of doing so could be to shield the WEC, so that the large incoming wave height gets minimized and the repair and maintenance work to FOWC is minimal. In the present study, the incoming wave is of low-heave, in-line with the condition off the coast of Malaysia, therefore the arrangement of interest is for the breakwater to be placed downstream of the FOWC, in the direction of the incoming wave, to reflect the waves back to the FOWC and thereby improving the efficiency of wave energy generation.

Computational Fluid Dynamics (CFD) solvers were traditionally seen to be less reliable compared to physical testing in replicating real-life conditions, especially in the ocean. For example, CFD results are not accepted as a mainstream way to assess ship performance [6]. However, as the various commercial solvers are constantly improving their products and services so that the design and simulation processes are more accurate, its benefits compared to physical testing are increasing in number overtime. If more work could be conducted numerically and less experimentally, this would serve as a huge time and cost-saving measure for the project, besides using less resources.

To replicate the heave movement of FOWC, body representation methods such as boundary fitted mesh, mesh distortion or overset grid features are necessary. Boundary fitted mesh (also known as dynamic layering), that adds or removes layers of cells adjacent to a moving boundary [7], the overset grids are two or more overlapping meshes that are internally static with fixed mesh connectivity but move relative to each other [8].

In model scale studies, it is essential to establish a similarity to full-scale condition [9]. To achieve full hydrodynamic similarity, some of the commonly used measurements and calculations in studies are the establishment of Froude and Reynolds number similarity between model and prototype. Froude similarity is used by Rezanejad et al. [10] and Zhou et al. [4], whereas Reynolds similarity is used by Celik and Altunkaynak [9]. The difference in scale also affects air compressibility inside an OWC chamber, therefore certain similarity calculations such as the Cauchy number or the scale ratio of air chamber volume is used to establish similarity [9]. When air compressibility is ignored during conversion from model to prototype scale, overestimation of results based on measurements inside the OWC is to be expected [11].

Sloshing occurs at the water surface of OWC and adversely influences the efficiency of the OWC. The desired motion of water surface inside the OWC chamber is in a piston-like motion. In contrast, sloshing occurs when there is irregularity in the vertical motion of water surface, at different locations inside of the OWC chamber. The sloshing mode is inefficient in terms of energy production [12]. According to Celik and Altunkaynak [9], as the incident wavelength becomes comparable to chamber length, full sloshing is generated in chamber.

Influence of the various properties of the WEC system serves as a means to understand the characteristics of the WEC system and to determine the setting that results in the optimal performance. Several properties that are commonly studied are the gap length between components of the WEC system, size of an individual component and incident wave period or frequency ranges used for the study. Zhang et al. [13] studied the influence of different WEC widths and drafts whereas Tan et al. [14] studied the influence of the body breadth ratio on the resonant characteristics. Jiang et al. [15] chose a range of wave angular frequency similar to present study, based on the resonance frequency of the narrow gap and as an extension of several other studies that used a similar range. Size of the orifice or top opening of the OWC is another property that is frequently studied, as conducted by Celik and Altunkaynak [9] and He and Huang [16].

Many types of hydrodynamic coefficients are used to compare the various cases of numerical models and measure the performance of the WEC system. Some common types are the reflection and transmission coefficients, used in various studies [5], [17]-[19] used conversion efficiency to measure the hydrodynamic efficiency of the system, where the average wave energy conversion power is divided to the incident wave power. For the OWC, measurement of air pressure inside the chamber is useful in predicting the performance of the device. Zabihi [20] studied the hydrodynamic efficiency of a fixed, bottom-detached OWC. Several studies such as Cheng et al. [5] and Rezanejad et al. [10] have looked into power take-off (PTO) damping as an indicator of OWC's performance.

The objective of this study is to investigate characteristics of an integrated FOWC-breakwater system. The significant finding of the study is the influence of breakwater on the performance of the FOWC.

II. NUMERICAL ANALYSIS

The CFD solver used for developing the numerical model is ANSYS Fluent. Reynolds Averaged Navier-Stokes and Volume of Fluid method were used for calculations. Eq. (1) to Eq. (3) show the mass continuity and Navier-Stokes equations [21].

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \tag{1}$$

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+2\mu\frac{\partial^2 v}{\partial y^2}+\frac{\partial}{\partial y}\left(\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)+F_x \tag{2}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial x}+2\mu\frac{\partial^2 u}{\partial y^2}+\frac{\partial}{\partial x}\left(\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)-\rho g+F_y \tag{3}$$

For mass equations, ρ is the fluid density, g is gravitational acceleration, u is velocity at horizontal direction, v is velocity at vertical direction, x and y are coordinate system directions, μ is the flow viscosity, and F_x and F_y are forces that affect fluid in the vertical and horizontal directions.

The model is developed based on Froude scale considerations. Length scale of model-to-prototype is 1/30, calculated based on Eq. (4). Froude number, as shown in Eq. (5), was found to be in the ranges of 0.49 – 0.86, which is very close to the ranges of 0.22 – 0.79, which is the Froude number calculated based on the wave parameters of the offshore region of Malaysian East Coast, based on the data by Muzathik et al. [22].

$$L_r=\frac{L_m}{L_p} \tag{4}$$

$$Fr=\frac{V}{\sqrt{gL}} \tag{5}$$

Where L_r is the length scale, L_m is the model scale, L_p is the prototype scale, Fr is the Froude number, V is the relevant velocity and L is the relevant length of the system.

Due to the small-scale nature of study, the air inside the FOWC chamber is deemed to be incompressible. Due to Froude similitude, overestimation of values based on measurements inside FOWC chamber is deemed to be minimal in effect, when model scale is converted to prototype scale.

The hydrodynamic coefficients studied are calculated, with equations shown in Eq. (6) to Eq. (10).

$$\varepsilon=\frac{\bar{P}_0}{\bar{P}_i} \tag{6}$$

where,

$$\bar{P}_0=\frac{B}{T}\int_{t_0}^{t_0+T}(p(t)v(x,t))dt \tag{7}$$

$$\bar{P}_i=\frac{1}{4}\rho_{water}gA_i^{\,2}\frac{\omega}{k}\left(1+\frac{2kh}{\sinh 2kh}\right) \tag{8}$$

$$C_a=\frac{A_c}{A_i} \tag{9}$$

$$C_p=\frac{\Delta P}{\rho g A_i} \tag{10}$$

where ε is the energy-extraction efficiency, $\bar{P}_0$ is the pneumatic power extracted from the wave field, $\bar{P}_i$ is the wave power of the incident waves per unit crest width, B is the model width, T is the wave period, $p(t)$ is the instantaneous pressure of the air inside the chamber, $v(x,t)$

is the instantaneous vertical velocity of the surface oscillation at position x, ρ_{water} is the density of water, A_i is the incident wave amplitude and k is the wave number. C_s is the sloshing coefficient, η_{max} and η_{min} are the maximum and minimum values of wave elevation inside FOWC. C_g is the gap coefficient. Method I from Isaacson [23] was selected for the calculation of reflected waves in order to offset wave irregularity, as shown in Eq. (11) - (13):

$$A_i\exp(ikx_n) + A_r\exp[-i(kx_n-\beta)] = A_n\exp\left[i(\Phi_1+\delta_n)\right] \tag{11}$$

$$A_r = \frac{1}{2|\sin\Delta|}\sqrt{{A_1}^2+{A_2}^2-2A_1A_2\cos\left(\Delta+\delta\right)} \tag{12}$$

$$A_i = \frac{1}{2|\sin\Delta|}\sqrt{{A_1}^2+{A_2}^2-2A_1A_2\cos\left(\Delta-\delta\right)} \tag{13}$$

where x_n is the nth probe location, β is the phase angle, A_n is the measured amplitude of the nth record, Φ_1 is the phase angle at the first probe, and δ_n is the measured phase of the nth wave record relative to the first record, Δ is the dimensionless distance between two probes, A_1 is the measured amplitude of the first record, and A_2 is the measured amplitude of the second record. A 2-dimensional schematic of FOWC-breakwater system inside an NWT is shown in Fig. 1. The water depth was set to 0.5m and to replicate the damping effect of a seashore, a numerical beach was set in the range of 1.5m from the outlet.

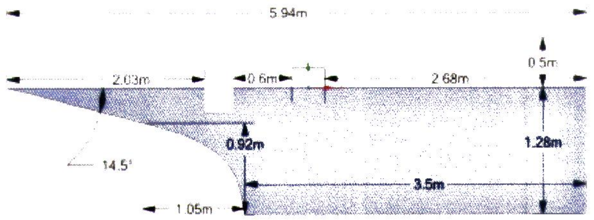

Fig. 1. Numerical design of wave tank with dimensions of boundaries and axes.

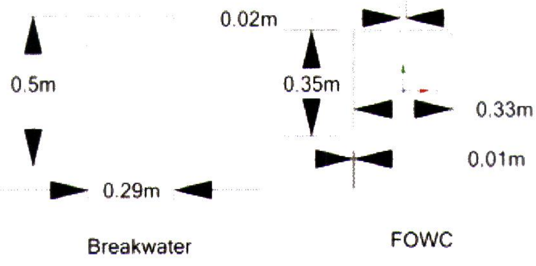

Fig. 2. Dimension of the FOWC and breakwater

TABLE I. BOUNDARY AND INITIAL CONDITIONS

Boundary conditions	Values
Wave height (m)	0.04
Wavelength (m)	2.63
Period (s)	1.3
Free surface level (m)	0
Bottom level (m)	-0.5
Wave theory	First-order Airy
Wave boundary condition option	Shallow/Intermediate waves

TABLE II. SIMULATION VARIABLES

Calculation Settings	Values
Courant number	1
Time stepping method	Fixed
Time step size (s)	0.001
Number of time steps	50000
Maximum iterations/Time steps	25

TABLE III. COORDINATES OF GAUGES

Gauge	x-coordinate (m)	y-coordinate (m)
WG	0	-0.1 to 0.1
PG	0	0.194
VG	0	0.194

III. RESULTS AND DISCUSSION

Results of numerical study were compared to previous experimental work with the same wave parameter and OWC design parameter setting. Results in Fig. 3 - 5 show a good agreement and high validity of numerical model.

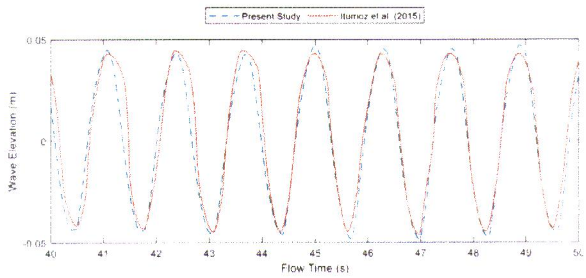

Fig. 3. Wave elevation

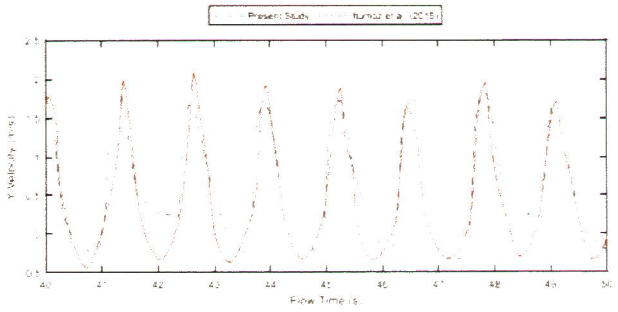

Fig. 4. Velocity in y-direction

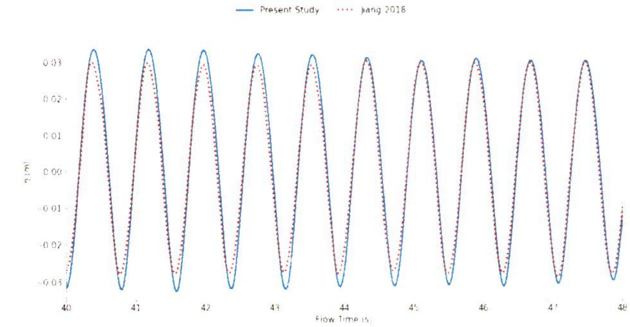

Fig. 5. Wave elevation

In Figure 6, it shows that the energy extraction efficiency of a wave increases as its angular frequency increases for floating oscillating water column without the presence of breakwater.

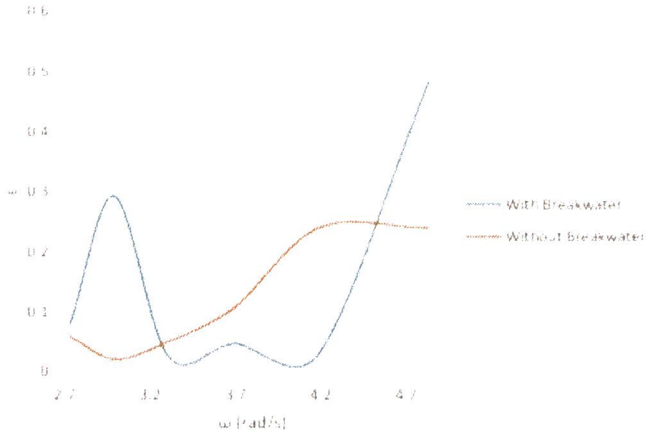

Fig. 6. Energy extraction at varying wave angular frequency

At the beginning, energy extraction efficiency decreases when the value of wave angular frequency is 2.7 rad/s up to 3.0 rad/s. Then, it increases until the wave angular frequency reaches a value of 4.2 rad/s. The value of energy extraction efficiency is then constant until the end of the experiment which is at 4.7 rad/s. Despite fluctuations between 1.3 and 1.9 seconds, there is an overall increase from 2.1 to 2.3 seconds when a breakwater is included, and it experiences a higher increase compared to the absence of breakwater. From the results shown in Fig. 6, it can be concluded that the highest energy extraction that can be obtained throughout the experiment is at a value of 0.4847 when the value of the wave's angular frequency is at 4.8332 rad/s with the presence of breakwater to the floating oscillating water column and the lowest energy extraction efficiency occurred when there is no presence of breakwater which is at the value of 0.0208 when the wave's angular frequency is at 2.9920 rad/s. Overall, it can be conclude that floating oscillating water column with the presence of breakwater enhance high energy extraction efficiency.

In Figure 7, the value of amplification coefficient for the oscillating water column without breakwater is decreasing from 2.7 rad/s to 3.0 rad/s, but then it increases to 4.1 rad/s before decreasing again until 4.7 rad/s. For the FOWC with the presence of breakwater despite fluctuations between 1.3 and 1.9 seconds, there is an overall increase from 2.1 to 2.3 seconds, and it experiences a higher increase compared to the absence of breakwater.

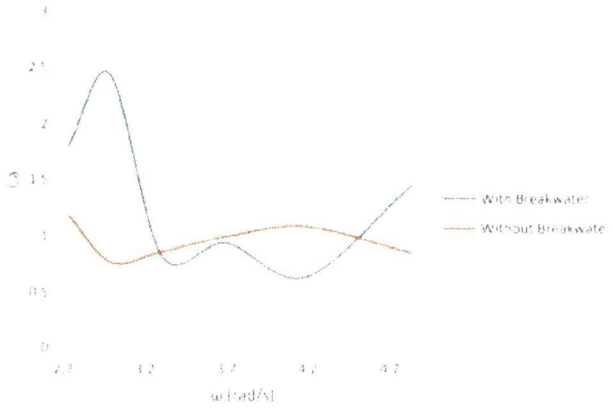

Fig. 7. Amplification coefficient at varying wave angular frequency

It can be concluded that the highest amplification coefficient that can be obtained throughout the experiment is at a value of 2.4 when the value of the wave's angular frequency is at 2.9 rad/s with the presence of breakwater to the floating oscillating water column. Meanwhile, the lowest value of amplification coefficient is 0.6 when the value of wave's angular frequency is 4.2 rad/s. The value of the amplification coefficient tends to be lower when an oscillating water column (OWC) wave energy converter system is equipped with a breakwater compared to an OWC system without a breakwater due to the influence of the breakwater on wave energy dynamics which includes pressure distribution. Breakwaters can also affect the pressure distribution around the OWC system. The breakwater can cause changes in wave reflection, refraction, and diffraction patterns, resulting in variations in the pressure acting on the OWC device. This altered pressure distribution may impact the amplification coefficient by influencing the efficiency of wave energy capture. Ultimately, the amplification coefficient plays a pivotal role in determining the performance and success of a wave energy converter system, contributing significantly to the advancement of sustainable and renewable energy technologies and it is shown that with the presence of breakwater to the FOWC, the objective can be achieved. Figure 8 shows that the pressure coefficient for the presence of breakwater to OWC is higher than the OWC without breakwater.

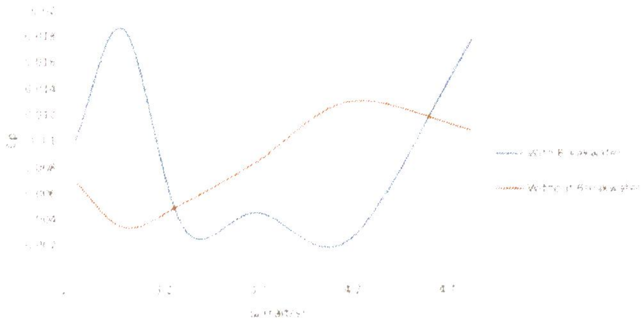

Fig. 8. Pressure coefficient at varying wave angular frequency

Apart from that, the highest-pressure coefficient for the OWC without breakwater decreases from 2.7 rad/s to 3.0 (rad/s), but then it increases to 4.1 rad/s before decreasing again to 4.7 rad/s. It observed that the highest-pressure coefficient that can be obtained at the value of 0.0185 when the value of the wave's angular frequency is at 2.9920 rad/s with the presence of breakwater to the FOWC and the lowest value of amplification efficiency which is 0.0025 when the value of wave's angular frequency is 4.1888 rad/s. The value of the pressure coefficient tends to be lower when a floating oscillating water column (FOWC) wave energy converter system is equipped with a breakwater compared to a FOWC system without a breakwater due to the influence of the breakwater on wave energy dynamics which includes pressure attenuation. The breakwater can create a partial shadowing effect behind it, causing the wave pressure to be reduced in the vicinity of the FOWC system. Consequently, the pressure differential between the incident waves and the FOWC chamber is decreased, which contributes to a lower pressure coefficient. Apart from that, wave reflection also could be the reason for the lower pressure coefficient for the FOWC with breakwater. It is because breakwaters can also reflect a portion of the incident waves away from the OWC system. This wave reflection reduces the wave energy available for capture, further contributing to a lower pressure coefficient. However, it is shown that the objective has been achieved where higher-pressure coefficient will be gained with the presence of Breakwater to the FOWC system. Accurate assessment and control of the pressure coefficient enable the development of innovative and effective WEC devices, contributing significantly to the advancement of sustainable and renewable energy technologies and providing a promising avenue for generating clean and renewable electricity from our oceans.

IV. CONCLUSIONS

The addition of a breakwater to a Floating Oscillating Water Column (FOWC) in the wave energy converter system has demonstrated significant improvements in hydrodynamic performance. This conclusion is drawn based on the higher maximum value for all three hydrodynamic coefficients studied. The higher amplification coefficient indicates that the presence of the breakwater enhances the system's ability to amplify wave energy, leading to increased power generation potential. This amplification effect contributes to higher energy extraction rates and, consequently, better overall system efficiency. The breakwater's presence effectively modifies the wave characteristics, resulting in more favorable conditions for energy conversion. Moreover, the pressure coefficient, which represents the pressure distribution around the system, shows distinct influences when a breakwater is included. The breakwater-WEC system experiences fluctuations in pressure coefficients at different time intervals, reflecting the dynamic interactions between the waves, breakwater, and WEC devices. These fluctuations may indicate favorable pressure conditions that contribute to the higher energy extraction efficiency of the hybrid system.

ACKNOWLEDGMENT

The authors would like to acknowledge the Universiti Pertahanan Nasional Malaysia for their support. This study also was performed under the Cooperative Research Program of IOES, Institute of Ocean Energy, Saga University, Japan (#23B10) (UPNM/2023/SAGA UNIVERSITY/TK/02).

REFERENCES

[1] National Energy Policy, 2022-2040, Economic Planning Unit, (2022), pp.17&35

[2] Samrat, N.H., Ahmad, N.B., Choudhury, I.A. and Taha, Z., March. Prospect of wave energy in Malaysia. In *2014 IEEE 8th International Power Engineering and Optimization Conference (PEOCO2014)* (2014) (pp. 127-132). IEEE.

[3] Howe, D., Nader, J.R. and Macfarlane, G., Experimental investigation of multiple Oscillating Water Column Wave Energy Converters integrated in a floating breakwater: Energy extraction performance. *Applied Ocean Research*, *97* (2020), p.102086.

[4] Zhou, Y., Ning, D., Chen, L. and Iglesias, G., Nonlinear hydrodynamic modeling of an offshore stationary multi-oscillating water column platform. *Ocean Engineering*, *227* (2021), p.108919.

[5] Cheng, Y., Fu, L., Dai, S., Collu, M., Cui, L., Yuan, Z. and Incecik, A., Experimental and numerical analysis of a hybrid WEC-breakwater system combining an oscillating water column and an oscillating buoy. *Renewable and Sustainable Energy Reviews*, *169* (2022), p.112909.

[6] When will CFD replace towing tanks? *The Naval Architect* (2020), Feature 5, pp. 52-54.

[7] Luo, Y., Wang, Z., Peng, G., Xiao, Y., Zhai, L., Liu, X. and Zhang, Q., Numerical simulation of a heave-only floating OWC (oscillating water column) device. *Energy*, *76* (2014), pp.799-806.

[8] Windt, C., Davidson, J. and Ringwood, J.V., High-fidelity numerical modelling of ocean wave energy systems: A review of computational fluid dynamics-based numerical wave tanks. *Renewable and Sustainable Energy Reviews*, *93* (2018), pp.610-630.

[9] Çelik, A. and Altunkaynak, A., An in depth experimental investigation into effects of incident wave characteristics front wall opening and PTO damping on the water column displacement and air differential pressure in an OWC chamber. *Energy*, *230* (2021), p.120827.

[10] Rezanejad, K., Gadelho, J.F.M., Xu, S. and Soares, C.G., Experimental investigation on the hydrodynamic performance of a new type floating Oscillating Water Column device with dual-chambers. *Ocean Engineering*, *234* (2021), p.109307.

[11] Elhanafi, A., Macfarlane, G., Fleming, A. and Leong, Z., Scaling and air compressibility effects on a three-dimensional offshore stationary OWC wave energy converter. *Applied energy*, *189* (2017), pp.1-20.

[12] Baudry, V., Babarit, A. and Clement, A.H., An overview of analytical, numerical and experimental methods for modelling oscillating water columns. In *EWTEC* (2013).

[13] Zhang, H., Zhou, B., Zang, J., Vogel, C., Fan, T. and Chen, C., Effects of narrow gap wave resonance on a dual-floater WEC-breakwater hybrid system. *Ocean Engineering*, *225* (2021), p.108762.

[14] Tan, L., Tang, G.Q., Zhou, Z.B., Cheng, L., Chen, X. and Lu, L., Theoretical and numerical investigations of wave resonance between two floating bodies in close proximity. *Journal of Hydrodynamics*, *29*(5) (2017), pp.805-816.

[15] Jiang, S.C., Bai, W. and Tang, G.Q., Numerical simulation of wave resonance in the narrow gap between two non-identical boxes. *Ocean Engineering*, *156* (2018), pp.38-60.

[16] He, F. and Huang, Z., Hydrodynamic performance of pile-supported OWC-type structures as breakwaters: an experimental study. *Ocean Engineering*, *88* (2014), pp.618-626.

[17] Zhang, H., Zhou, B., Vogel, C., Willden, R., Zang, J. and Geng, J., Hydrodynamic performance of a dual-floater hybrid system combining a floating breakwater and an oscillating-buoy type wave energy converter. *Applied energy*, *259* (2020), p.114212.

[18] Poguluri, S.K., Kim, J., George, A. and Cho, I.H., Experimental and numerical investigation of a surface-fixed horizontal porous wave barrier. *Ocean Systems Engineering*, *11*(1) (2021), pp.1-16.

[19] Ram, G., Saad, M.R., Abidin, N.Z. and Rahman, M.R.A., Hydrodynamic performance of a hybrid system of a floating oscillating water column and a breakwater. *Ocean Engineering*, *264* (2022), p.112463.

[20] Zabihi, M., Mazaheri, S. and Namin, M.M., 2019. Experimental hydrodynamic investigation of a fixed offshore Oscillating Water Column device. Applied ocean research, 85, pp.20-33.

[21] Fluent, A.N.S.Y.S., ANSYS fluent theory guide 15.0. *ANSYS, Canonsburg, PA*, *33* (2013).

[22] Muzathik, A.M., Nik, W.W., Ibrahim, M.Z. and Samo, K.B., June. Ocean wave energy along Terengganu coast of Malaysia. In *Conf.: 2nd Int. Conf. on Production, Energy & Reliability (ICPER) 2010*. Malaysia: Universiti Teknologi Petronas (2010).

[23] Isaacson, M.; Measurement of regular wave reflection. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 1991, *117*(6), pp. 553-569.