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Wave Energy Conversion in Malaysia: A Focus on Bent Duct Buoy Configurations

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ABSTRACT

Ocean wave energy, a renewable and abundant resource, presents significant potential for sustainable power generation. The South China Sea, adjacent to Malaysia, demonstrates considerable promise in this domain. This study investigates bent duct buoy Oscillating Water Column(OWC), predominantly examined by researchers in its Backward Bent Duct Buoy (BBDB) configuration. This paper provides an in-depth analysis of fixed and floating for both backward and frontward configurations, and the output result will be shown in power output and efficiency; the result will be compared with all the configurations. This research provides valuable insights for selecting optimal configurations tailored to specific wave conditions in different geographical locations. Utilising a 3D Computational Fluid Dynamics (CFD) analysis methodology, four distinct configurations are fixed forward and backwards and floating forward and backwards to assess their performance with 0.75 m to 1.5 m wave heights. The study reveals that all the configurations show superior efficiency. In full-scale simulations, the fixed forward and backward configurations produced 10.8 kW of power with a significant wave height of approximately 0.75 m and an efficiency of 0.41. It shows the highest efficiency at low wave conditions. Similarly, a full-scale floating backwards bent duct buoy model, scaled up by a factor of eight, generated between 7.5 kW and 61.1 kW of power across wave heights ranging from 0.75 m to 1.5 m, achieving efficiencies of approximately 0.34 to 0.38. These configurations' results consistently indicate robust energy extraction across different wave conditions. The bent duct buoy OWC demonstrates significant potential as a wave energy converter under Malaysian wave conditions.

1. Introduction

Capturing wave energy typically involves various technologies and devices strategically placed in coastal areas or offshore locations. These devices are designed to convert the up-and-down motion

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of waves into usable electrical energy through mechanical or hydraulic mechanisms. The Bent Duct Buoy (BDB) Oscillating Water Column(OWC) wave energy converter is a promising technology designed to harness the power of ocean waves and convert it into usable energy [1]. This innovative device consists of a buoyant structure with a duct that extends downwards into the water, forming a backward-bent shape. As waves pass by the buoy, they cause the structure to move, generating hydraulic pressure within the duct. One of the notable advantages of the BDB design is its ability to efficiently capture wave energy across a wide range of wave conditions, from small ripples to large swells [2]. Its simple design and relatively low maintenance requirements make it an attractive option for renewable energy generation in coastal regions worldwide. However, like any emerging technology, the BDB wave energy converter also faces challenges, including the need for further optimisation to improve efficiency and durability and considerations regarding its environmental impact and integration into existing infrastructure [3].

The location chosen was Kapas Island, Malaysia, on the West Coast. Table 1 provides a summary of the wave conditions at Kapas Island, sourced from the Yaakob *et al*. study [4]. The wave conditions are categorised based on their frequency of occurrence, ranging from low to high waves.

Table 1
Wave height and wave period at Kapas Island, Malaysia

Wave Conditions	Wave Height, Hs (m)	Period, Tp (s)
Low	0.75	5.5
Medium	1.25	6.5
High	1.5	7.5

There are two types of OWC: fixed and floating [5]. These two types of OWC have different characteristics. From here, researchers can learn every mechanism that occurs in these two types of configurations. The significant difference is that the floating OWC type is in the middle of the sea, while the fixed OWC type is on the coast. Two criteria are studied to see the performance of the device, such as air chamber shape and duct entrance [6].

The design of the air chamber in an Oscillating Water Column (OWC) system is crucial for enhancing device efficiency. Previous researchers addressed this by constructing and designing the OWC with a circular shape to facilitate smoother airflow [7]. In the articles published, the authors investigate how chamber configurations of an OWC device affect its efficiency [8]. A curved entrance to the OWC chamber is recommended to enhance hydrodynamic energy extraction [6]. Ashlin *et al*. experimented on four different base profiles [9]. The result shows that OWCs with a circular lower profile curve perform better than OWCs with different lower profiles. Rosdzimin et al. also examined the lower corner of floating OWCs [10].

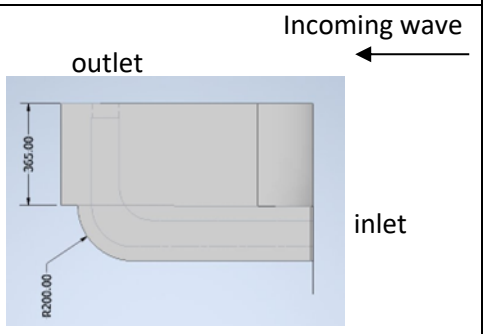
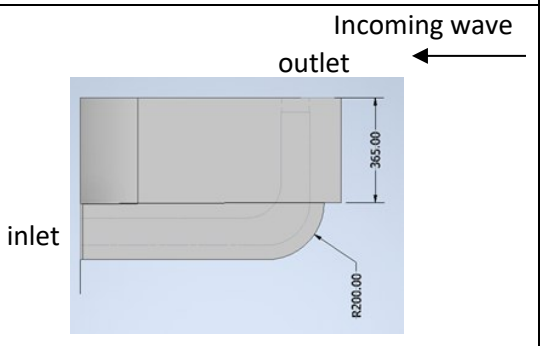
The conventional duct entrance of the fixed OWC faces the incident wave. While the floating BDB OWC and vice versa. According to Portillo *et al*. [11], analysis is carried out to study the BBDB backward and frontward configurations. The results show how the frontward inlet performs in the case study. Rezanejad *et al*. [12] investigated the combination dual chamber of BBDB. The experiment study shows the device can perform the most probable sea states in Portuguese oceanic areas with the proposed configurations. It is found that the BDB is more efficient than OWC in energy production, and this finding is suitable for all systems. Xu *et al*. [13] identified that the FOWC has the best energy production performance with the selected mooring system.

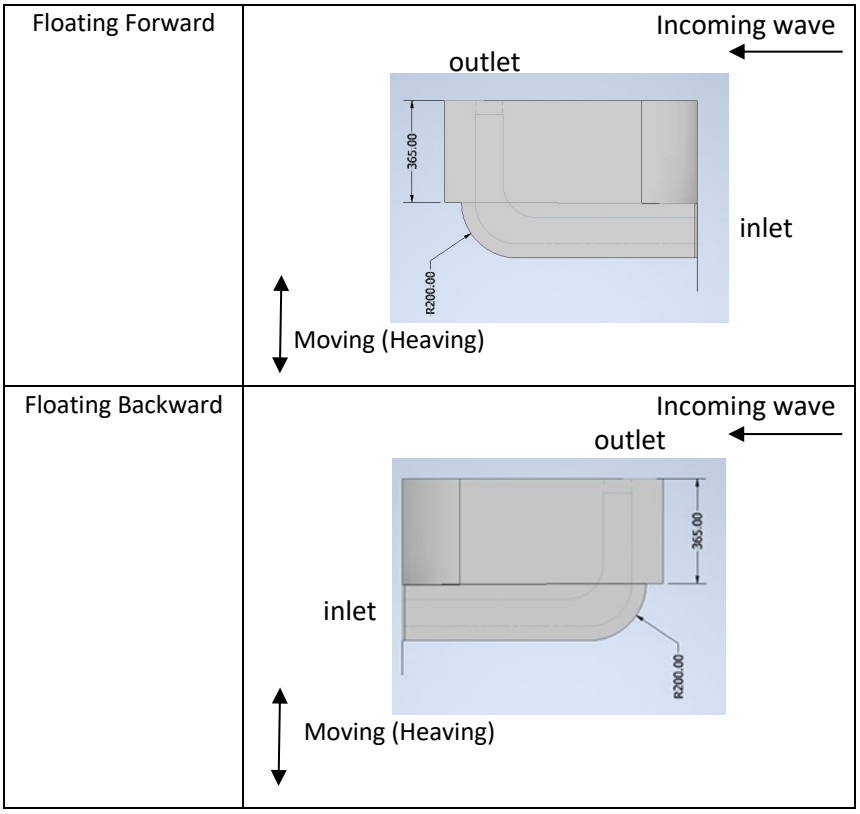
To add value to current knowledge, this study focuses on two primary research contributions: the exploration of fixed and floating configurations for BDB and the analysis of various incident wave interactions using the Computer Fluid Dynamic (CFD) method. Consequently, configurations tailored for low wave energy conditions are proposed.

2. Methodology

The process starts with designing a selected BDB OWC model scale. The research used the Froude scaling method and a downscale model at 1:8 ratios. The BDB design is chosen according to the dimension based on the research done by Jalani *et al*. [14]. The internal design is modified to improve the fluid flow. Table 2 shows the side-view design dimension of the modified internal geometry with an area of the inlet and outlet. Then, the design will be used to obtain analysis based on wave data in the Malaysian Ocean. The inlet and outlet areas for all the designs are 0.047 m^2 and 0.0071 $m^{2,}$ respectively. The design will be simulated with the selected location of the Malaysia Sea, namely around the coast, near the coast and offshore. The next part involved the simulation of the laboratory scale BDB model by using the CFD method. This methodology uses the CFD software to simulate the OWC model. Thus, the paper will show the power estimation and efficiency results of the BDB OWC device.

Table 2
Bent duct buoy design dimension

Design	Side View(mm)
Fixed Forward	
Fixed Backward	



2.1 Simulation Setup

The OWC model was investigated through numerical CFD software. The CFD software is based on features that can solve the fluid flow equation using Reynolds Averaging of the Navier–Stokes (RANS) equations. The solver can produce scalar quantities such as velocity and pressure. RANS equations are combined with the Volume of Fluid (VOF) method to monitor the location of accurate fluid surfaces [15,16].

This model was designed using AutoCAD software and uploaded to the CFD software. Next, the programme's meshing features were utilised to create the grid for the 3D model. A layered mesh approach was used for the meshing, allowing for local refinement within the region of interest. This method can reduce simulation times, which increases computational efficiency. In the simulation workspace, an open water state is used to mimic the actual circumstance (Figures 2 and 3).

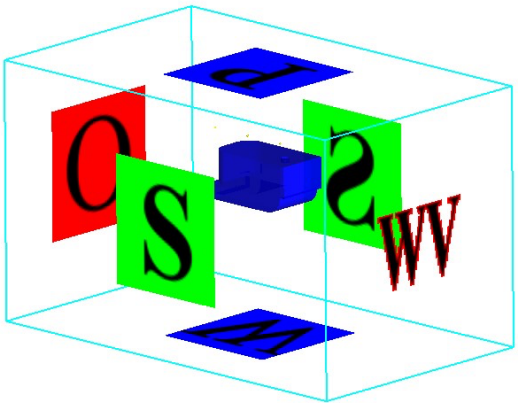


Fig. 2. Boundary conditions

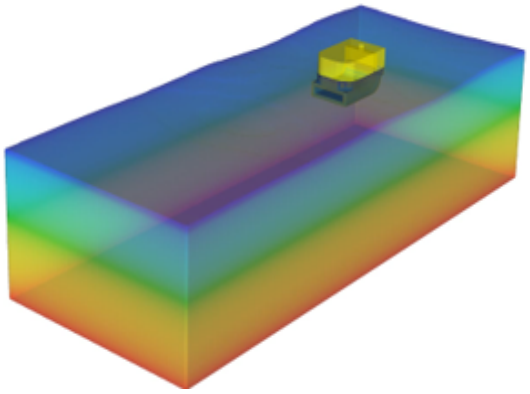


Fig. 3. Render of boundary and mesh conditions

2.1.1 Probe Location

Figure 4 shows three probes employed in this study at various sites: the OWC first front, which measures the incoming flow. The last probe was positioned at the OWC orifice, and the second was affixed to the inlet to measure the fluid velocity that struck it directly.

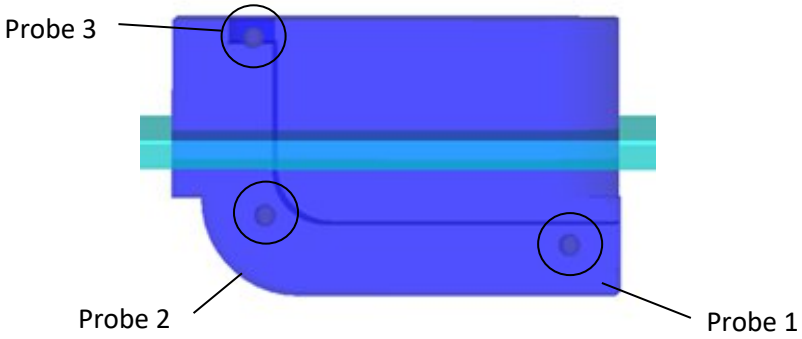


Fig. 4. Location of probe

2.1.2 Grid-Dependent Study (GDS)

The grid-dependent analysis found the best mesh element numbers for each OWC design. The simulation's element numbers match the meshing quality. A finer mesh will result in a longer simulation time. The information was displayed as a function of velocity.

The relationship between velocity magnitude and mesh size is depicted in Figure 5. According to the graphic, the velocity trend at the graph's start is unstable. The mesh size range in which the event happens is 0.2 million – 4.6 million total cells.

Low mesh element numbers lead to poor mesh quality, which is the source of inconsistent results. On the other hand, the curve starts showing consistency with a mesh size of 0.04 m, approaching 8.9 million total cells. The results show a good arrangement with the complexity of the proposed OWC design. The relationship between mesh number and velocity for an OWC is shown in Figure 5.

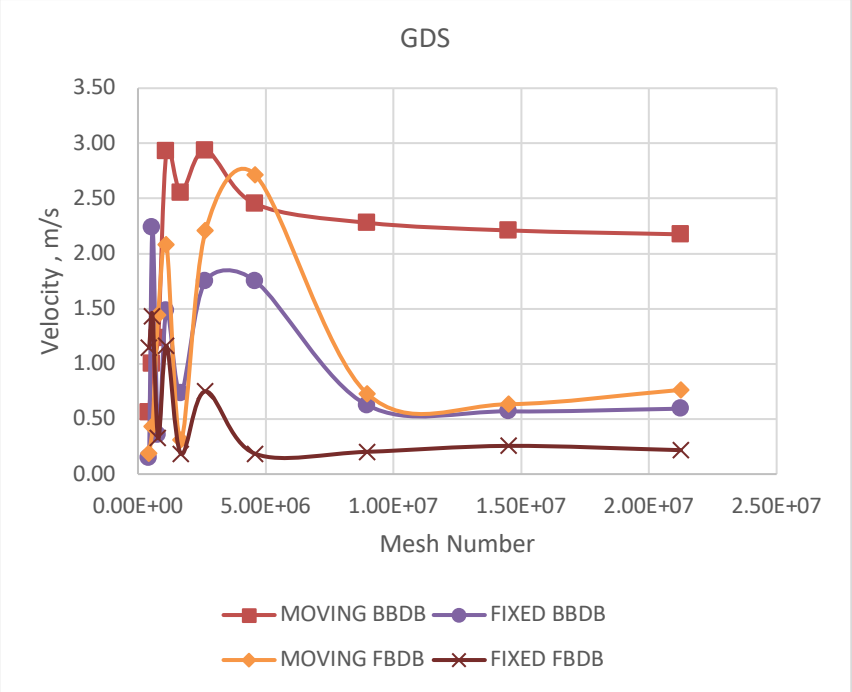


Fig. 5. GDS

3. Results and Discussion

This section will explain the results of OWC configurations by comparing them to pressure and velocity at the probe locations. The wave amplitude, 0.045 m to 0.09 m, and 1.91 seconds to 2.6 second peak period are used. The power estimation of each configuration will be shown at the end of this section.

The pressure results at Probe 3, identified as the optimal location for the turbine, reveal distinct performance differences across various wave conditions. Under low wave conditions (Figure 6), with a wave amplitude of 0.045 meters and a peak period of 1.91 seconds, the proposed design maintains a consistent pressure of around 22 Pa, while the moving backward design records a lower pressure of 17.64 Pa. In medium wave conditions (Figure 7), characterised by a 0.075-meter amplitude and a 2.25-second peak period, the fixed backward design achieves the highest mean pressure of 22.03 Pa, surpassing other proposed designs that hover around 16.00 Pa. All designs exhibit relatively low pressures during high wave conditions (Figure 8), with a wave amplitude of 0.09 meters and a 2.6-second peak period. However, the fixed backward design still leads with 15.72 Pa, followed by the moving backwards and fixed forward designs, which generate pressures of 14.95 Pa and 14.27 Pa, respectively.

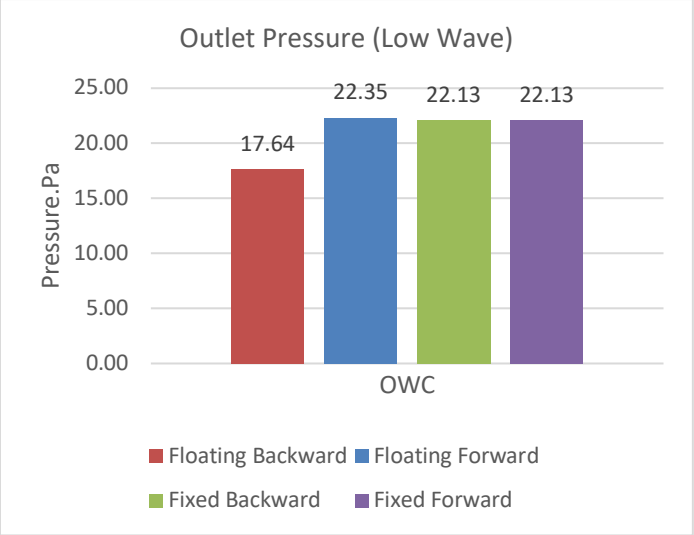


Fig. 6. Pressure at low wave condition

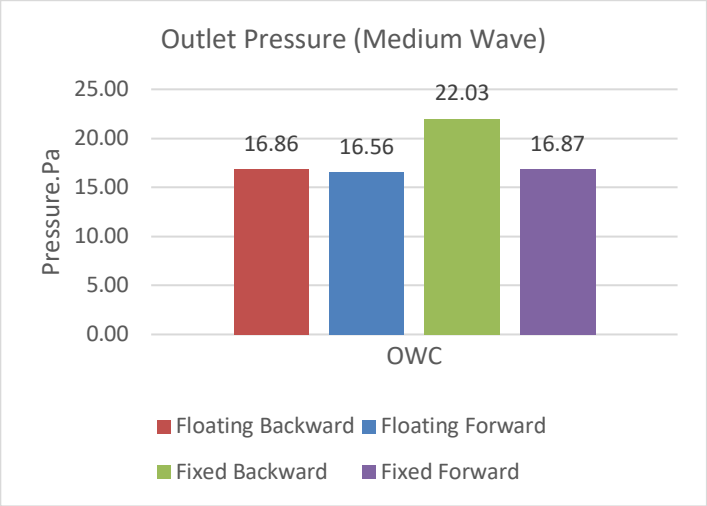


Fig. 7. Pressure at medium wave condition

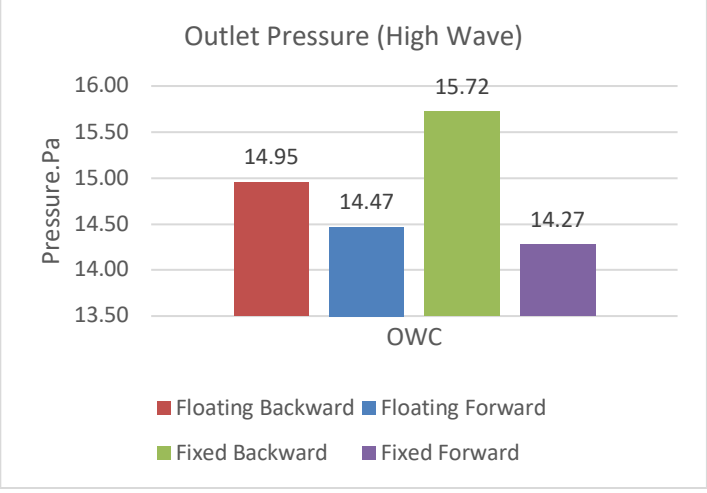


Fig. 8. Pressure at high wave condition

3.1 Power Estimation

The power estimation accounts for the velocities of all designs across three wave conditions, with mean velocities determined based on peak pressure times. Figures 9, 10, 11, and 12 illustrate these mean velocities for each respective condition, offering a detailed analysis of the performance under varying conditions. From Figure 9, the average velocities for high and medium wave conditions are 1.36 m/s. For low wave conditions, the average velocity is 0.53 m/s.

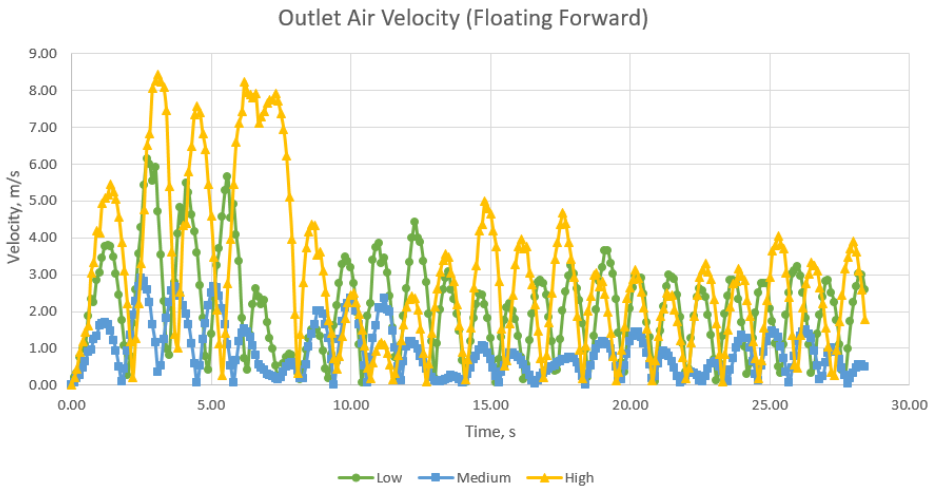


Fig. 9. Outlet air velocity for floating forward

From Figure 10, the highest average velocity value is in the high wave condition, which is 1.36 m/s. The average velocity in medium wave conditions is 0.36 m/s, and for low wave conditions, it is 0.15 m/s.

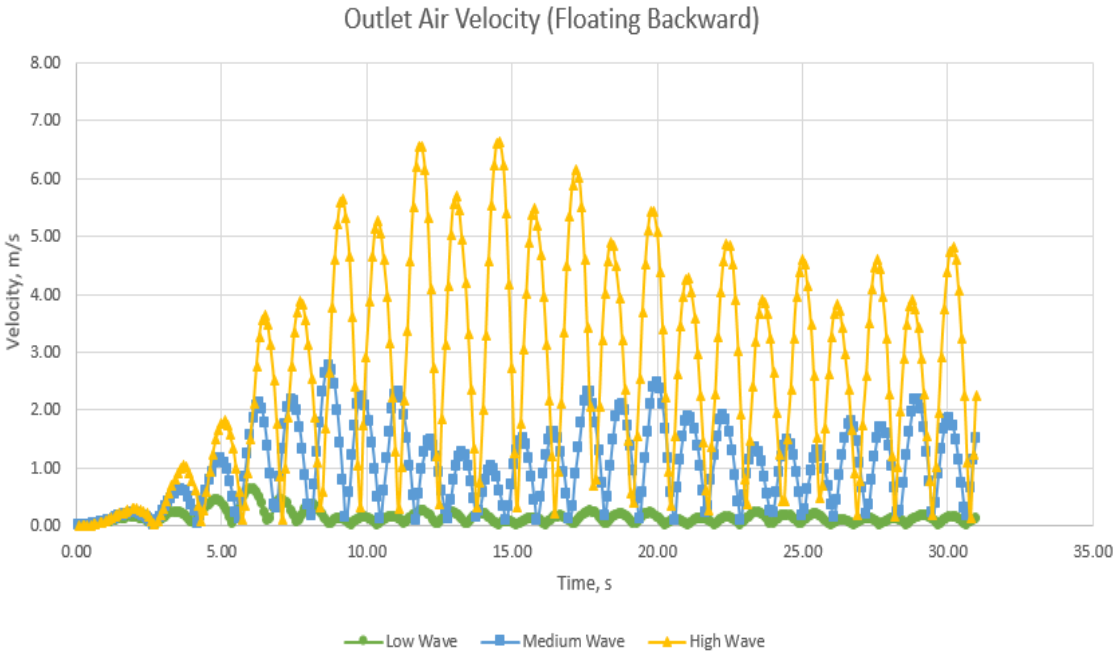


Fig. 10. Outlet air velocity for floating backwards

Figure 11 shows that the highest average velocity value is in a high wave condition, which is 1.64 m/s. The average velocity in medium wave conditions is 0.35 m/s. The maximum and average velocity in low wave conditions are 0.20 m/s.

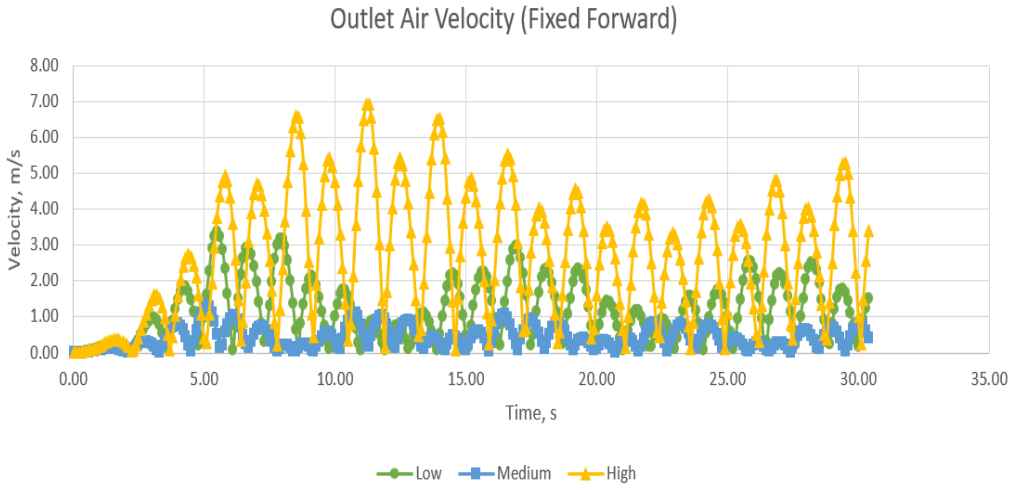


Fig. 11. Outlet air velocity for fixed forward

Figure 12 shows that the highest average velocity value is in high wave conditions, which is 0.95 m/s. The average velocity in medium wave conditions is 0.32 m/s, and for low wave conditions, it is 0.20 m/s.

The pressure and velocity results for the OWC model at probe 3 show the output results that can be used for further research. The combination of simulation data can be gathered at probe one and probe 3. Table 4 shows the energy estimation at full scale for all four configurations. The air density stands at 1.225 kg/m^3, and this calculation excludes the mass of air. Power measurements are conducted across all four conditions.

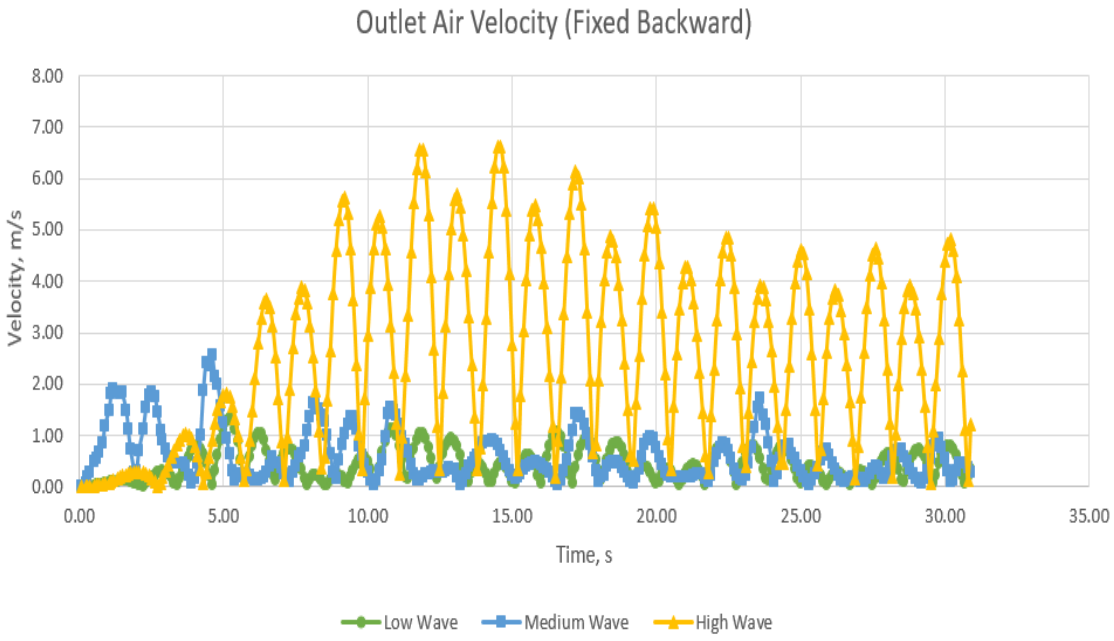


Fig. 12. Outlet air velocity for fixed backwards

The floating forward configuration results show a low efficiency of 0.27 at low wave conditions. The fixed forward and backward configurations achieved the highest efficiency of 0.41 at low wave conditions but showed inconsistent performance at medium and rough conditions. Floating backward shows consistency in performance in all wave conditions with an efficiency between 0.34 and 0.38.

Table 4
Power estimation of OWC device at full scale

Floating Backward	Wave Condition	Pressure in (Pa)	Pressure out (Pa)	Velocity in (m/s)	Velocity out (m/s)	Power (W)	Efficiency
	Low	34701	141	0.07	0.45	7488	0.38
	Medium	32261	135	0.20	1.05	19482	0.34
	High	33764	120	0.59	3.87	61177	0.34
Floating Forward	Wave Condition	Pressure in (Pa)	Pressure out (Pa)	Velocity in (m/s)	Velocity out (m/s)	Power (W)	Efficiency
	Low	39832	178	0.37	1.50	44988	0.27
	Medium	45286	132	1.27	3.85	175455	0.13
	High	65263	115	1.81	3.85	359343	0.06
Fixed Backward	Wave Condition	Pressure in (Pa)	Pressure out (Pa)	Velocity in (m/s)	Velocity out (m/s)	Power (W)	Efficiency
	Low	32923	177	0.11	0.57	10803	0.41
	Medium	35443	176	0.31	0.91	33596	0.23
	High	33884	125	0.48	2.69	49682	0.31
Fixed Forward	Wave Condition	Pressure in (Pa)	Pressure out (Pa)	Velocity in (m/s)	Velocity out (m/s)	Power (W)	Efficiency
	Low	32923	177	0.11	0.57	10803	0.41
	Medium	32219	134	0.26	0.99	24994	0.26
	High	32908	114	0.76	4.64	76640	0.31

4. Conclusion

This study investigates the performance of bent duct buoy OWCs in fixed and floating configurations under varying wave conditions. Four configurations have been proposed to see the device's performance under different wave conditions in Malaysia. The findings of this study can be summarised as follows:

i. The fixed backwards and forward duct buoy shows the highest efficiency at low wave conditions.
ii. Then, the floating forward bent duct buoy shows the lowest efficiency at low wave conditions.
iii. Finally, the floating backwards bent duct buoy performs consistent energy extraction at various wave conditions.

The literature also discussed this observation for the floating OWC with dual chamber case. Future work will explore further optimisation for broader wave condition adaptability, ensuring sustainable wave energy exploitation in Malaysia.

Acknowledgement
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References

[1] Mustapa, Mohd Azlan, O. B. Yaakob, Yasser M. Ahmed, Chang-Kyu Rheem, K. K. Koh, and F. A. Adnan. 2017. "Wave Energy Device and Breakwater Integration: A Review." *Renewable and Sustainable Energy Reviews* 77: 43–58. https://doi.org/10.1016/j.rser.2017.03.110.

[2] Ismail, Nur Izzati, Muhamad Aiman Jalani, Mohd Rosdzimin Abdul Rahman, and Mohd Rashdan Saad. 2020. "Backward Bent Duct Buoy (BBDB) of Wave Energy Converter: An Overview of BBDB Shapes." In *Proceedings of International Conference of Aerospace and Mechanical Engineering 2019*, edited by P. Rajendran, N. M. Mazlan, A. A. A. Rahman, N. M. Suhadis, N. A. Razak, and M. S. Z. Abidin, 541–549. Lecture Notes in Mechanical Engineering. Singapore: Springer. https://doi.org/10.1007/978-981-15-4756-0_48.

[3] Jalani, Muhamad Aiman, Mohd Rashdan Saad, Mohamad Faizal Abdullah, Mohd Azzeri Md Naiem, Mohd Norsyarizad Razali, Noh Zainal Abidin, and Mohd Rosdzimin Abdul Rahman. 2023. "A Statistical Analysis for Optimisation of a Hybrid BBDB-PA in Mantanani Island, Sabah." *Journal of Marine Science and Engineering* 11 (2): 386. https://doi.org/10.3390/jmse11020386.

[4] Yaakob, O. B., Y. M. Ahmed, M. N. B. Mazlan, K. E. Jaafar, and R. M. R. Muda. 2013. "Model Testing of an Ocean Wave Energy System for Malaysian Sea."

[5] Doyle, S., and G. A. Aggidis. 2019. "Development of Multi-Oscillating Water Columns as Wave Energy Converters." *Renewable and Sustainable Energy Reviews* 107: 75–86. https://doi.org/10.1016/j.rser.2019.02.021.

[6] Yacob, D. H., S. Sarip, H. M. Kaidi, J. A. Ardila-Rey, and F. Muhammad-Sukki. 2022. "Oscillating Water Column Geometrical Factors and System Performance: A Review." *IEEE Access* 10: 32104–32122. https://doi.org/10.1109/ACCESS.2022.3160713.

[7] Abbasi, S. S., T. H. Min, S. H. Shafiai, S. Y. Theng, and L. C. Heng. 2017. "Design Enhancement of an Oscillating Water Column for Harnessing of Wave Energy." 12 (16): 5.

[8] Medina Rodríguez, A. A., J. M. Blanco Ilzarbe, R. Silva Casarín, and U. Izquierdo Ereño. 2020. "The Influence of the Chamber Configuration on the Hydrodynamic Efficiency of Oscillating Water Column Devices." *Journal of Marine Science and Engineering* 8 (10): 751. https://doi.org/10.3390/jmse8100751.

[9] John Ashlin, S., V. Sundar, and S. A. Sannasiraj. 2016. "Effects of Bottom Profile of an Oscillating Water Column Device on Its Hydrodynamic Characteristics." *Renewable Energy* 96: 341–353. https://doi.org/10.1016/j.renene.2016.04.091.

[10] Abdul Rahman, Mohd Rosdzimin. 2022. "Study on Shape Geometry of Floating Oscillating Water Column Wave Energy Converter for Low Heave Wave Condition." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*.

[11] Portillo, J. C. C., P. F. Reis, J. C. C. Henriques, L. M. C. Gato, and A. F. O. Falcão. 2019. "Backward Bent-Duct Buoy or Frontward Bent-Duct Buoy? Review, Assessment and Optimisation." *Renewable and Sustainable Energy Reviews* 112: 353–368. https://doi.org/10.1016/j.rser.2019.05.026.

[12] Rezanejad, K., J. F. M. Gadelho, S. Xu, and C. Guedes Soares. 2021. "Experimental Investigation on the Hydrodynamic Performance of a New Type Floating Oscillating Water Column Device with Dual-Chambers." *Ocean Engineering* 234: 109307. https://doi.org/10.1016/j.oceaneng.2021.109307.

[13] Xu, S., K. Rezanejad, J. F. M. Gadelho, S. Wang, and C. Guedes Soares. 2020. "Experimental Investigation on a Dual Chamber Floating Oscillating Water Column Moored by Flexible Mooring Systems." *Ocean Engineering* 216: 108083. https://doi.org/10.1016/j.oceaneng.2020.108083.

[14] Jalani, Muhamad Aiman, Nur Izzati Ismail, Mohd Rashdan Saad, Mohd Kamarul Huda Samion, Yasutaka Imai, Shuichi Nagata, and Mohd Rosdzimin Abdul Rahman. 2022. "Experimental Study on a Bottom Corner of the Floating WEC." *Ocean Engineering* 243: 110237. https://doi.org/10.1016/j.oceaneng.2021.110237.

[15] Hirt, Cyril W., and Billy D. Nichols. 1981. "Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries." *Journal of Computational Physics* 39 (1): 201–225. https://doi.org/10.1016/0021-9991(81)90145-5.

[16] Ferziger, Joel H., Milovan Perić, and Robert L. Street. 2020. *Computational Methods for Fluid Dynamics*. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-99693-6.