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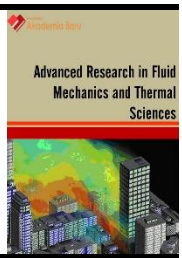

Study on Shape Geometry of Floating Oscillating Water Column Wave Energy Converter for Low Heave Wave Condition

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ABSTRACT

The Oscillating Water Column (OWC) is one of the most promising Wave Energy Converter (WEC) concepts in terms of practicality, survivability, and efficiency. One of the potential OWC types is the Backward Bent Duct Buoy (BBDB). The objective of this research is to investigate the performance of different BBDB shapes in low heave wave conditions. Three different bottom corner shapes were chosen for the experiments in a 3D wave basin. Wave height of 0.15m with period of 1s to 5s were used in regular wave conditions. Results show that different BBDB bottom corner shapes produce different pneumatic output characteristics. It was found that the highest primary conversion efficiency of the BBDB was produced by the BBDB with a round bottom corner shape with an efficiency of 1.47 follow by BBDB with a square bottom corner shape with an efficiency of 1.24 and BBDB with 45° bottom corner shape with the efficiency of 0.86. Thus, the round bottom corner shape is proposed to be the most efficient shape in low wave heave wave conditions.

1. Introduction

To tackle important global climate change issues and rising CO_2 levels, we need to reduce the dependence on fossil fuels and the focus on generating renewable energy. There are many types of renewable energy, such as wind, solar, wave and hydro [1]. Wave energy is one of the renewable energies that can be widely explored [2]. Ocean wave energy has the second-largest potential of all ocean renewable energy sources [3].

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Wave Energy Converter (WEC) is a device that converts wave energy into useful energy such as electricity. It can operate in any harsh environment, constraints in wave power inputs and massive loads experienced in extreme weather conditions [4]. There are more than a thousand different WEC in literatures from floating, oscillating, and bottom-standing to submerged types [5,6].

An oscillating WEC type such as Wavebob, Wavestar, OPT Powerbuoy, Archimedes Wave Swing, Pelamis, Aquamarine Power's Oyster and Oscillating Water Column (OWC) are being used according to the geometric suitability, environmental conditions, and the amount of output power required to accommodate local loads [7]. In addition, the buoyancy and economic costs of the buoys also become one of the considering factors for the selection of wave energy converter types.

The OWC type is a well-established wave energy device concept, which will continue to contribute greatly to the progression of wave energy [8]. An OWC device is an energy converting device that does not produce CO_2 as a by-product thus is deemed as a great alternative for “green” electricity power. In an OWC device, power is produced by the incoming plane surface waves that give rise to water-air column designed within the device [9].

The OWC device consists of a partially submerged chamber with open water bottom and duct that allows movement of air internally and externally from the environment into the chamber. The wave behaviour constantly changes the water elevation in the chamber, hence enabling the volume of air inside the column to be constantly being pushed and sucked through the orifice. Attached to an air turbine, the generator is being driven from the air movements in both directions [10].

Currently, four types of FOWCs have been developed, namely Forward Bent Ducted Buoy (FBDB), Backward Bent Ducted Buoy (BBDB), Centre Buoy Pipe and Sloped Buoy. In 3D wave tanks, the WEC Model BBDB were found to reach a peak of primary conversion efficiency of 1.72 under a regular wave and 0.52 under an irregular wave [11]. Due to the design of BBDB devices which typically have shallow drafts, they can be easily transported and installed. Centre Buoy Pipe and Sloped Buoy have in-depth drafts that require special equipment for transportation. These adjustments are also complicated and more time will be spent for installation purposes.

The oscillating water column (OWC) Backward Bent Duct Buoy (BBDB) was created following the most successful OWC navigation buoys in wave energy converter, with the target of building a large and efficient OWC wave energy converter for large-wave power production [12]. Compared to other WECs, BBDB has a simple single floating structure, low cost, and high conversion efficiency. Since Yoshio Masuda [13] first introduced the concept of BBDB converters in 1986, there have been many researchers from various countries who have conducted various types of experimental studies on this concept in 2D and 3D wave tanks. The previous studies about the conversion performance of the wave power to pneumatic power are summarised and listed in Table 1.

In addition, there have been several studies on the geometric shape changes made to these BBDB models by previous researchers. For the front buoy, three different shape geometries have been tested in a 2D and 3D wave tanks and a semi-cylindrical buoyancy module was found to give the best performance [14]. As for the length of the duct, the increase in the length of the duct decreases the primary conversion efficiency [15].

However, the authors found that the effect of different geometry of bottom corner shape of BBDB towards the performance has not been studied. The authors also believed that the design of the bottom corner shape contributes significantly towards the oscillation motion of the BBDB device and eventually affecting the performance output. Thus, the purpose of this study is to investigate the characteristics and performance of BBDB with different bottom corner shape designs at low heave wave conditions.

Table 1
Experimental studies on BBDB conversion efficiency

Year	Authors	Maximum Efficiency				References
		2D Regular waves	3D Regular waves	2D Irregular wave	3D Irregular wave	
1995	Liang *et al.,*	0.41				[16]
1997	Liang *et al.,*	0.73				[17]
1998	Liang *et al.,*		2.04		0.37	[18]
1999	Pathak *et al.,*		1.73	0.52		[19]
2000	Liang *et al.,*	0.79				[20]
2001	Liang *et al.,*		1.50			[21]
2008	Toyota *et al.,*	0.35				[22]
2011	Imai *et al.,*	0.70	0.78		0.49	[15]
2017	Wu *et al.,*	1.19	1.46		0.87	[23]

2. Description of Models

As BBDB technology relies on the movement of oscillating bodies to convert wave energy, it is essential to enhance the oscillation of the device to improve conversion efficiency. In this study, the shape of the BBDB model was changed from the initial flat bottom corner to different bottom corner shapes and from one buoy to two buoy system, similar to the study conducted by Bailey *et al.,* [24]. The purpose of incorporating both the front and rear buoys together is to reduce hydrodynamic resistance and consequently increasing the amplitude of the BBDB oscillation as shown in Fig. 1.

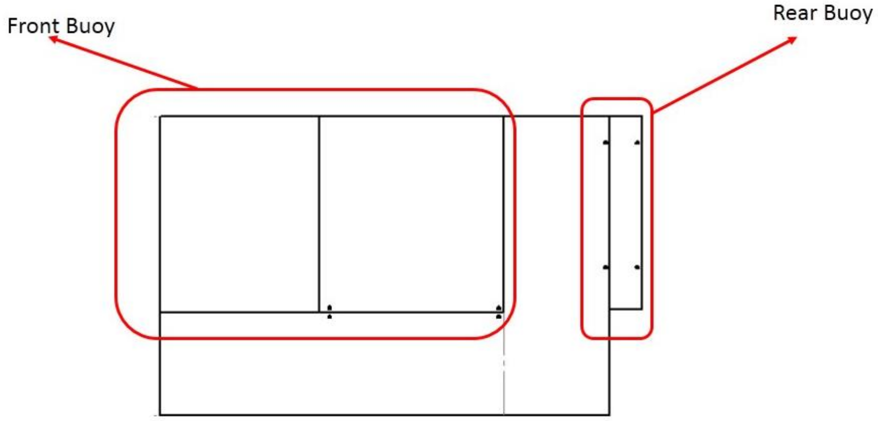

Fig. 1. Illustration of front and rear buoy (side view)

Three BBDB devices with different bottom corner shapes (Model A, B and C) were fabricated and tested in the experiments. All models have the same basic dimensions; horizontal water column of 0.85 m length, 0.565 m height and 0.6 m width, with a vertical water column of 0.6 m × 0.2 m size. The material used for the fabrication of all models are transparent acrylic boards with thickness 5mm. The diameter of orifice to allow airflow in the both directions is 40mm, located on top of the air column.

For Model A, a curved bottom corner with radius of 0.2m replaced the initial shape. The detail design of model A can be seen in Fig. **2**. Model B is similar to basic (baseline) model of the BBDB, with a rectangular shape of the bottom corner. However, the difference between Model B with the basic model previously tested by other researchers is the addition of the rear buoy. A detail design of model B can be seen in Fig. **3**. For Model C, the bottom corner of the model was designed to have an inclined edge at an angle of 45^0 as depicted in Fig. **4**.

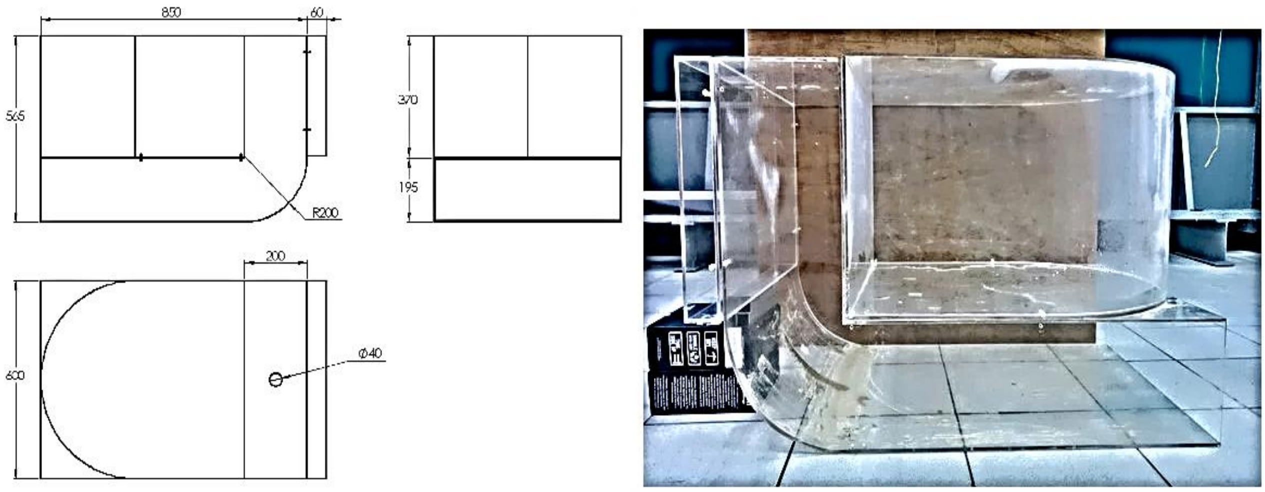

Fig. 2. Drawing (left) and picture (right) of Model A with a rounded corner

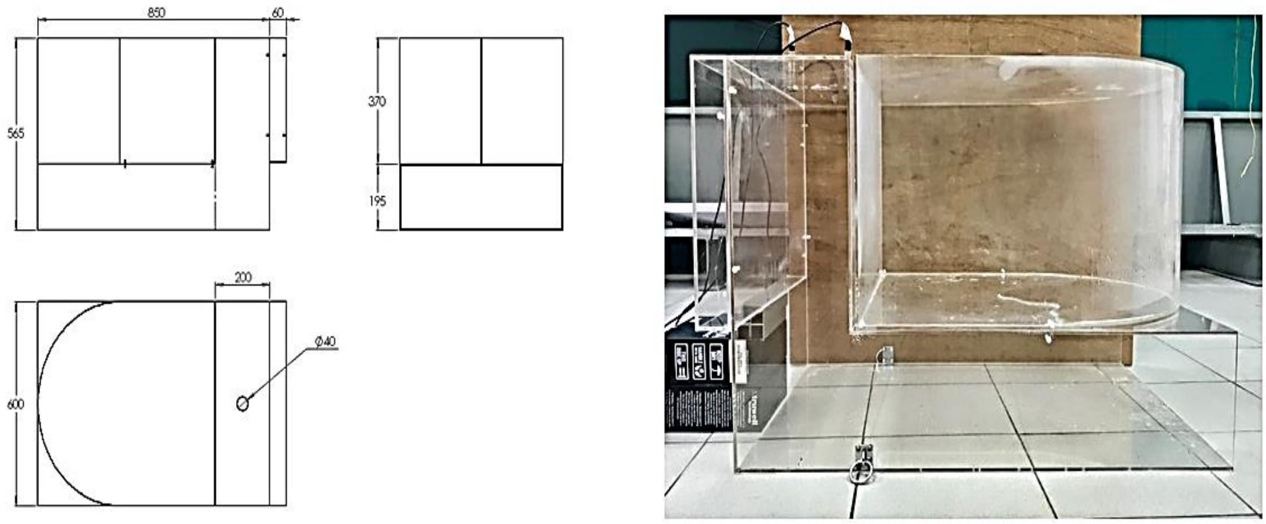

Fig. 3. Drawing (left) and picture (right) of Model B with a rectangular corner

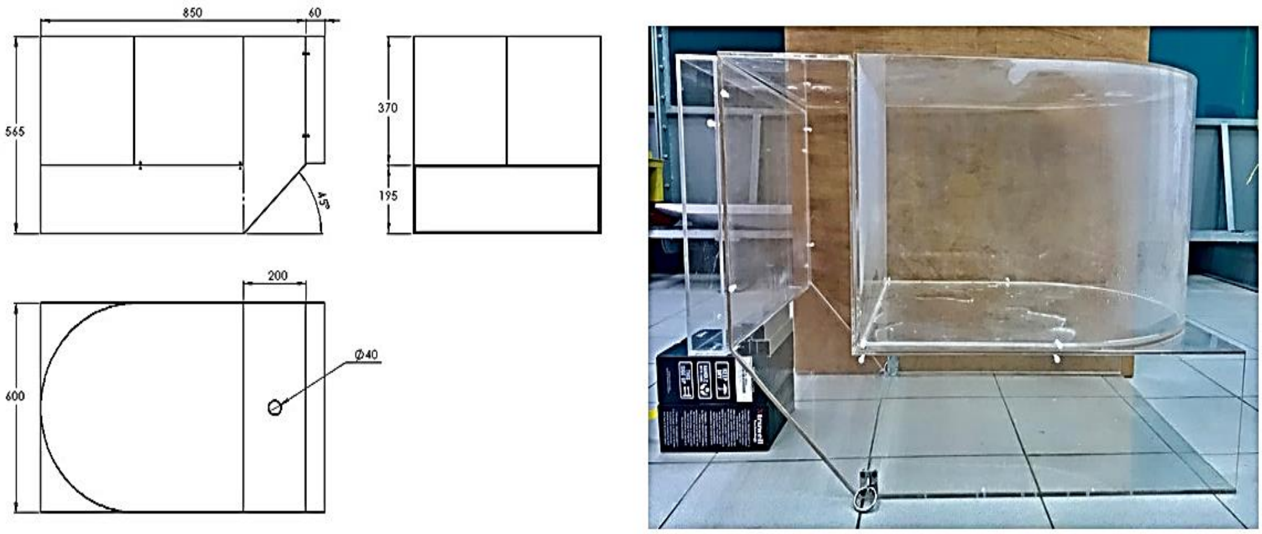

Fig. 4. Drawing (left) and picture (right) of Model C with a 45° edge

3. Experimental Set-Up

3.1 3D Wave Tank Test

The primary conversion efficiency of small scale BBDB models in regular waves was measured in a 3D wave basin. Experiments were carried out in the wave basin at the National Hydraulic Research Institute of Malaysia (NAHRIM) shown in Fig. **5**. The basin is 30 m long, 30 m wide and 1.2 m deep. Active absorbing wavemakers are located at the upstream of the basin. For this experiment, 0.05 - 0.15 m of wave height and 1 – 5 s of wave period were selected to match low heave wave condition.

Fig. 5. 3D wave basin at NAHRIM

3.2 The Primary Performance of OWC

The primary conversion efficiency η_1 is defined as the ratio of the energy of air to the energy of incident waves from Elhanafi *et al.,* [25].

$$\eta_1 = \frac{E_{air}}{E_{wave}} \tag{2}$$

$$E_{wave} = \frac{1}{2}\rho g \zeta_i^2 C_g B \tag{4}$$

$$E_{air} = \frac{1}{T}\int_0^T \Delta P(t)\, Q(t)\, \mathrm{dt} \tag{4}$$

$$C_g = \frac{\omega}{2k}(1 + \frac{2kh}{sinh(2kh)}) \tag{5}$$

$$\frac{\omega^2}{g} = ktanh(kh) \tag{6}$$

$$k = \frac{2\pi}{L} \tag{7}$$

3.3 Instrumentations

The complete setup of instrumentations is shown in Fig. **6**, consisting two digital ultrasonic water level sensors KEYENCE FW-H07 (±0.001 m accuracy) to measure the water level inside the water column, a pitot tube anemometer EXTECH HD-350 (0.0001 m^3/min accuracy) to measure the flow rate at the orifice and KEYENCE AP-10S (0.01 kPa accuracy) air pressure sensor to measure the air pressure inside the chamber. KEYENCE NR-500 was used as the data acquisition system connecting all sensors to the workstations.

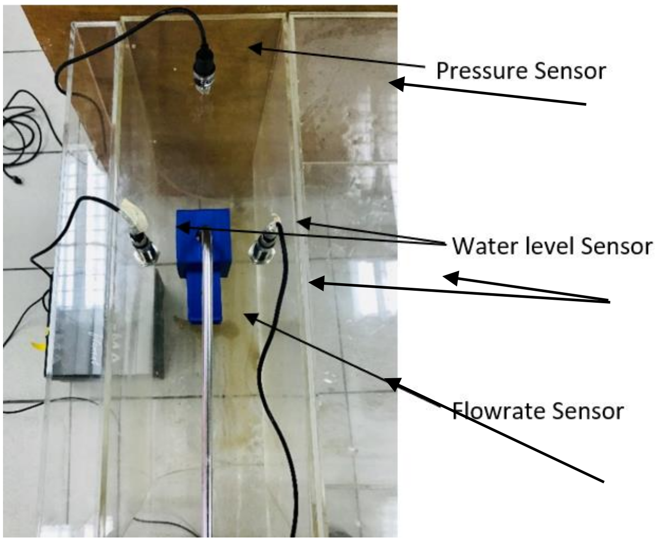

Fig. 6. Instrumentation setup onboard the BBDB models

The schematic diagram of the experimental setup is shown in Fig. **7**. The BBDB was attached to two mooring nylon lines at the bottom section. At the other end, the nylon lines were tied to 4 heavy concrete blocks at the bottom of the wave basin to prevent the device from moving during the experiments as shown in Fig. **8**.

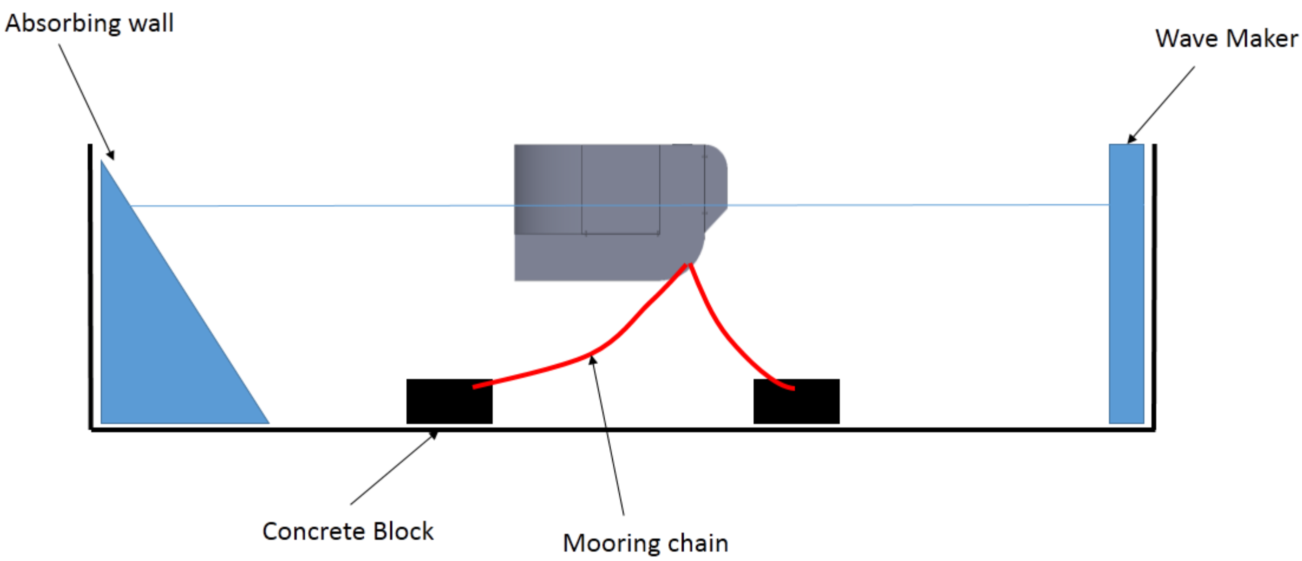

Fig. 7. Schematic diagram of the experiment setup

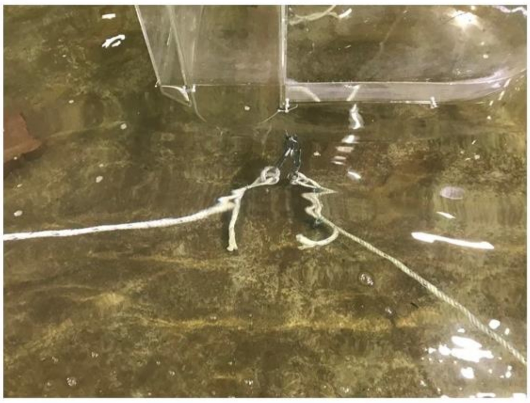

Fig. 8. Mooring connection for model (left) and concrete block (right)

4. Results and Discussion

The results of water elevation, pressure and flow rate inside the water column chamber are shown in Fig. 9 - 11, respectively. Fig. 9 shows the water elevation in the water column chamber for all models A, B and C. The horizontal axis is the ratio of the wavelength (λ) of the incident wave and the characteristic length of the BBDB (L) while the vertical axis represents the water elevation, ζ divided by the incident wave amplitude ζ_i. It was found that the trends of all models are slightly similar. Furthermore, at λ/L = 3.0, all model reaches a maximum value and model A gives the highest value compared to other models with a value of ζ/ζ_i = 1.98 at 0.15m wave height.

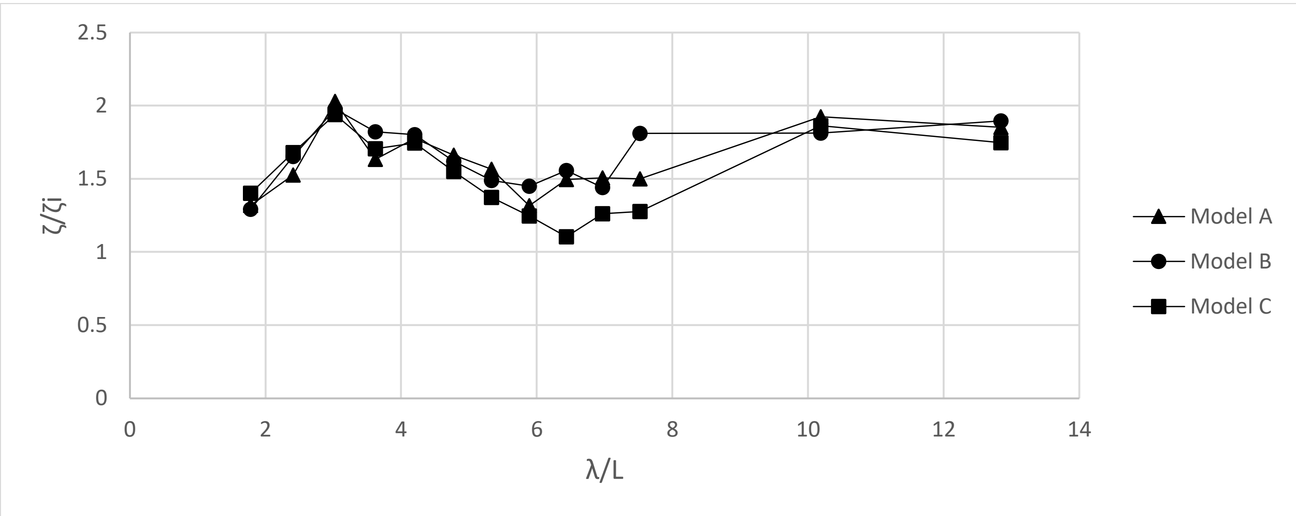

Fig. 9. Amplitude of wave inside water column chamber for all three models

The pressure inside the water column during the test we acquired and plotted in Fig. 10. The pressure is made dimensionless using ρ, g, and ζ_i. The pressure measurements for the three models shows similar trends. The pressure increases from λ/L = 2.0 to 3.0 and later it decreases to λ/L = 7.0. At λ/L = 8.0 to λ/L = 13.0 the pressure reaches a plateau. It was found that maximum pressure was given by Model A followed by Model B and C. Overall, by increasing the wavelength (by varying the wave period), the water column chamber pressure increases until reaches a peak. After the peak pressure, the chamber pressure drop sharply and later continue to increase at point λ/L = 6.0. After the point λ/L = 7.0, increasing the wavelength causes insignificant changes towards the pressure.

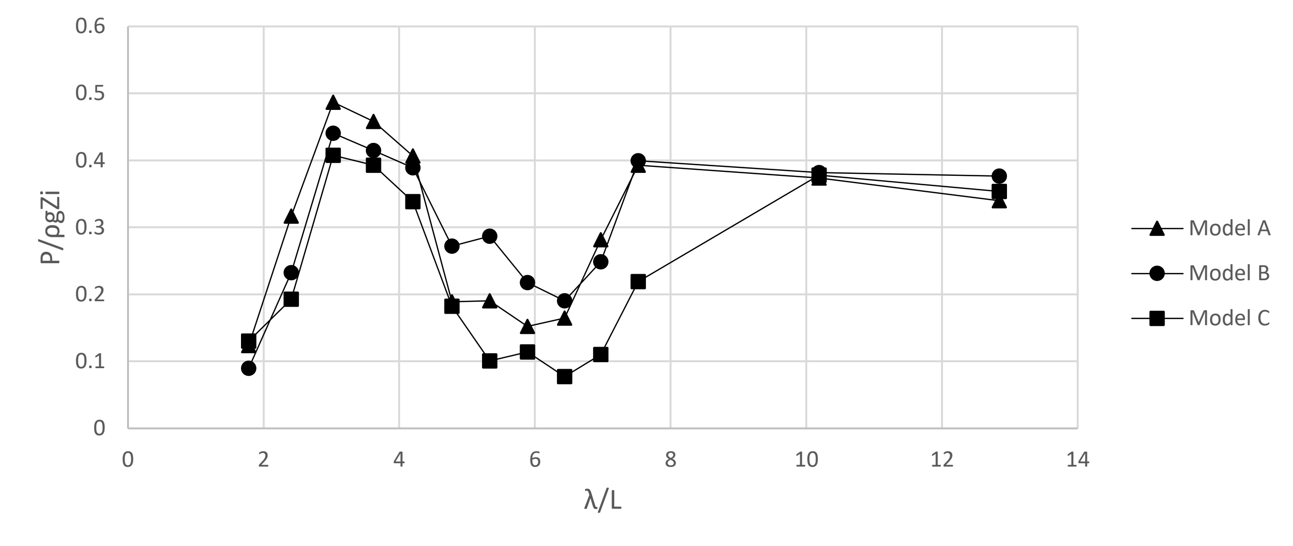

Fig. 10. Pressure inside water column for all models

It was observed at Fig. 11 that the air flow rate at the orifice of the air column increased up to a peak point and decreases after that at low λ/L between 1.9 and 5.0. At higher λ/L, the air flow rate is not significant. In all models, model A produces a higher airflow rate compared to other models. It also seen that the airflow rate of the model B and C is typical at low λ/L. A high air flow rate is favourable at the orifice in order to run the turbine system attached to the orifice in real case.

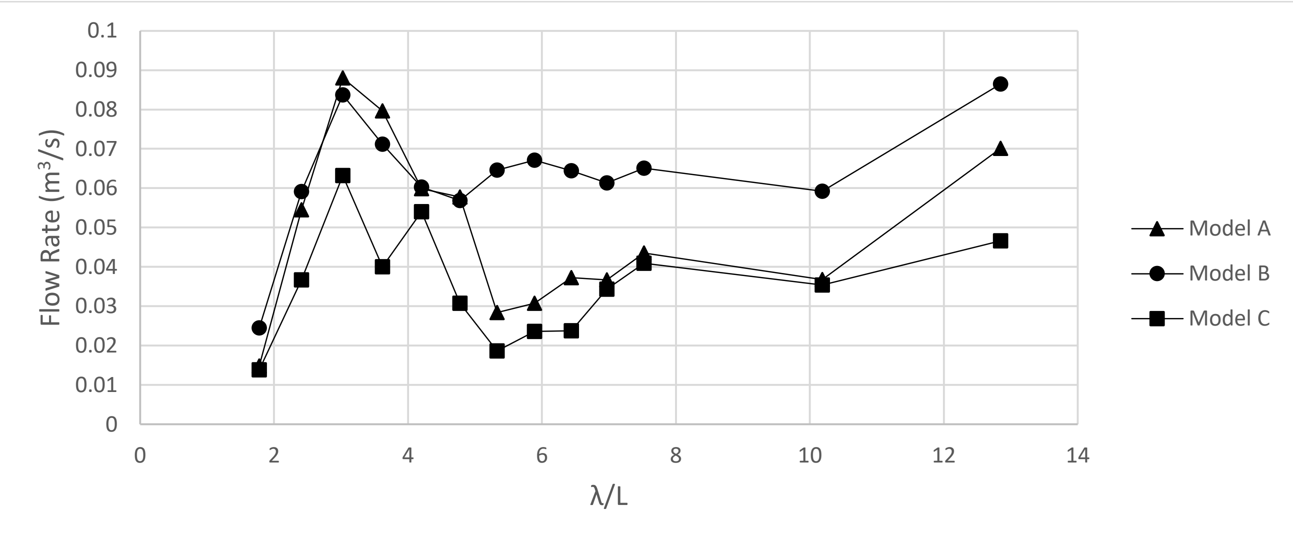

Fig. 11. Air flow rate at the nozzle outlet for all model

Fig. 12 shows the incident wave energy (E_{wave}) and pneumatic energy from the water column chamber for all three models. It appears that the wave energy increases significantly following the increase in λ/L. This is because the wave energy is affected by the wavelength (λ), which is one of the components in calculation of group velocity (C_g) in the wave energy formula. Based on Fig. 12, Model A reaches maximum pneumatic energy at 22.5 kgm^2/s^2. For all models, the pneumatic energy is not significant at λ/L = 4.0 and onwards. Therefore, all model produces higher air energy at low λ/L, which shows the suitability of the BBDB for low heave wave conditions.

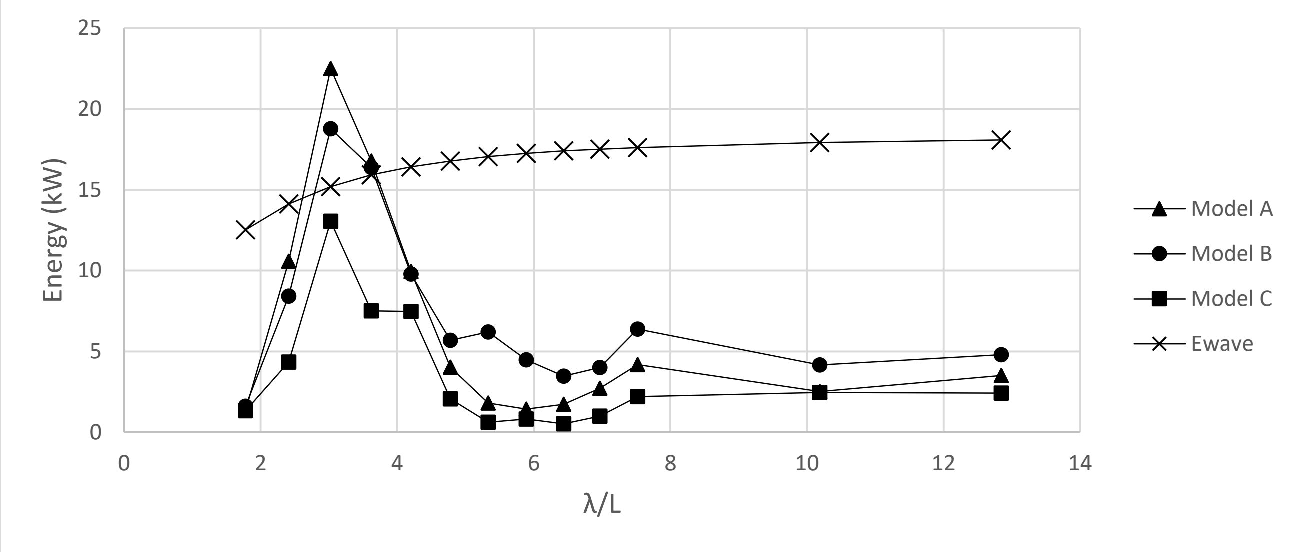

Fig. 12. Wave energy and air energy from the water column

Results in Fig. 13 shows the primary conversion efficiency of all three BBDB models tested. Model A performed the best by exhibiting the highest efficiency compared to all three models, at 1.47. This was followed by Model B is at 1.23 and Model C producing below 1.0. Overall, it can be seen that all models produced higher primary conversion efficiency at low λ/L conditions. The worst wave conditions were found to be between λ/L 5.0 until 7.0, which clearly shows the design region that needs to be avoided for BBDB.

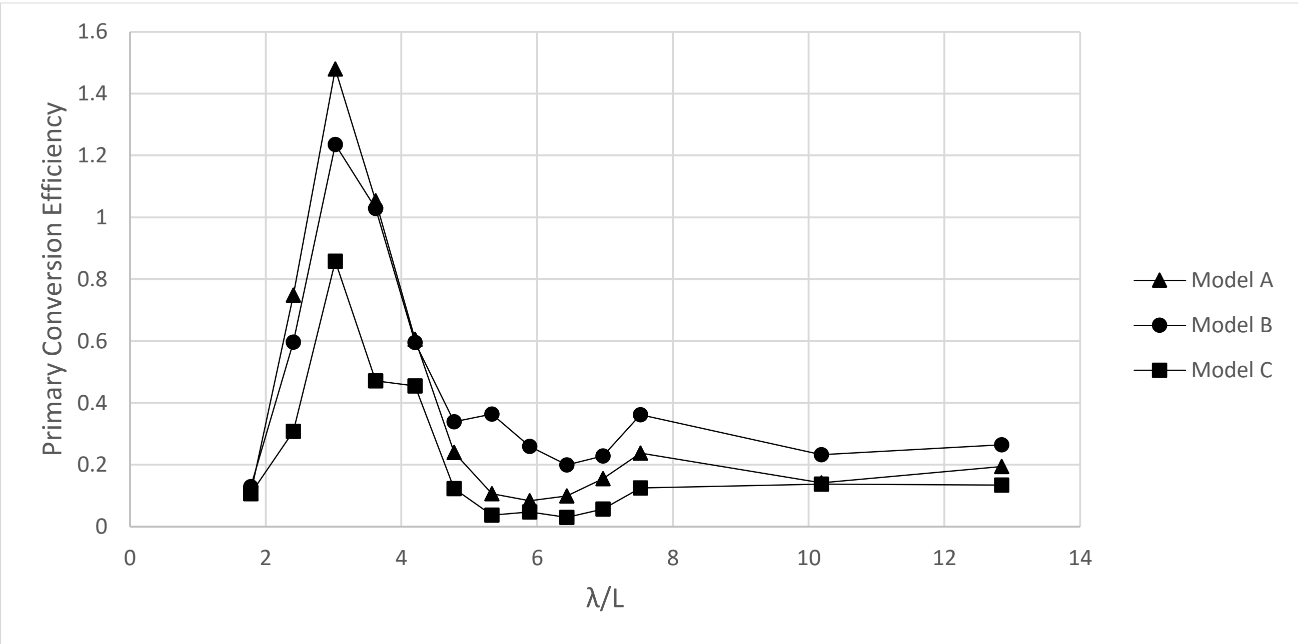

Fig. 13. Primary conversion efficiency

5. Conclusion

This study investigates the characteristics and performance of different shape backward bent-duct buoys. The three models of BBDB having different bottom corner shapes were tested in a 3D wave tank by applying regular waves. The finding of this study can be summarized as follow

i. Water column chamber pressure and elevation are significantly influenced by the wave period at the low value of λ/L.
ii. The effect of the variation in water column chamber pressure and elevation produces a higher airflow rate at the nozzle outlet.
iii. Model A gives higher performance compared to other models with primary conversion efficiency higher than 1.0 at a low value of λ/L.
iv. Overall the BBDB produces higher primary conversion efficiency at low λ/L regardless of different bottom corner shapes.

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