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Design an Optimum Air Duct for Oscillating Water Column Wave Energy Device

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ABSTRACT

Oscillating Water Column (OWC) is a technology that harvests wave energy to generate electricity. It works by harnessing the wave-induced pressure oscillation in the opening mouth of OWC. The oscillation of the pressurised air is extracted using a turbine placed at the top of the OWC structure. Although OWC has been studied for many years, designing an optimum air duct for such devices is still an open research area. The air duct plays a crucial role in the energy conversion process, as it is responsible for directing the airflow towards the turbine, and its design can greatly affect the performance and efficiency of the system. The article aims to study how the air duct design impacts the power output form. Moreover, the result will be compared with the conventional air duct design. The OWC performance is analysed using Computational Fluid Dynamic (CFD) software to identify which shape of the air duct has high efficiency. Autodesk Inventor is used to design the OWC devices modified from the basis design. Then these designs are imported into CFD software to simulate and obtain the energy extraction result. The CFD software is chosen to simulate the hydrodynamics problem. In this study, the oval design shows significant improvement in the energy extraction performance compared to the basis design. The oval design managed to produce 9.81, 10.02, and 11.66 J/kg of mechanical energy compared to 9.81, 9.82, and 10.04J/kg as prompted by the basis air duct design at the wave height of 0.2505, 0.75, and 2.25m, respectively. The result shows that the non-edge produces higher air pressure than the sharp edge of the air duct shape. Thus, the oval air duct design is more efficient, and it may increase the performance of the OWC wave energy converter device at a low wave height of 0.75 m.

1. Introduction

In the past few decades, rising renewable energy demand has been noticeable, leading to a thriving market and excellent prospects in some of the green energies. A fusion of emerging green energies and conventional technologies is employed, which may involve wind, solar, and geothermal

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energy. Among these, exploiting the vast potential of the ocean may be a viable way to fulfil renewable energy demand for electricity. Scientific advancement and market growth of renewable energy technologies, including marine energy technology, will contribute significantly to economic, environmental, and social development in the 21st century. Many governments have adopted new energy generation strategies and guidelines for an environmentally sustainable society. Perhaps, energies have been generated from the sea, tides, waves, salinity, temperature gradient, and ocean currents [1].

Oceans provide renewable and clean energy sources. As the waves move from deep to shallow waters, the dissipation of specific energy sources, such as potential and kinetic energy, predominantly occurs during their breaking phase. The degree of dissipation and the increment of magnitude depends on the key factors involving bathymetry, seabed friction, and obstructions. There are several types of wave energy converters (WECs), of which the OWC stands out as the simplest concept to harness wave energy [2,3]. OWC's concept was introduced by Yoshio Masuda [4], and its working principle is identical to an air pump because the chamber's water column oscillates up and down.

The efficiency of wave energy conversion dictates the amount of energy produced by the wave energy converters. The OWC operated with a pneumatic system has recently been widely used to convert wave energy. Its efficiency depends significantly on the effectiveness of the wave energy absorption in an air chamber. In OWC, wave energy converters utilise the resonance of an air chamber to enhance and optimise airflow, which is closely tied to the characteristics of the incident waves. However, to ensure that the operation runs efficiently, the shape of the air duct should be optimised by considering the wave climate at an installation site so that the flow of air extracted in the air chamber can be enhanced [5].

Thus, this paper presents the study to identify the optimal air duct design based on an existing design in UniKL MIMET. Once the design has been developed, a device's performance is accessed via CFD simulation using wave energy data specific to the Malaysian sea. This study focuses on improving the energy extraction amount, and thus, the new air duct design is proposed.

Wave energy has several advantages over other renewable energies, including predictability, abundance, high load factor, and low environmental impact. Ocean waves have the maximum energy density among renewable energy sources, making it possible to generate substantial energy from virtually inexhaustible energy sources in a relatively small area [6]. Wave energy has several extra advantages compared to other green energies, which comprise high availability, resource predictability, high power density, a relatively high utilisation factor, and a low environmental and visual impact [7].

This study was conducted on Kapas Island, Terengganu, facing the South China Sea. There are two side coasts to this Kapas Island. East Coast is primarily for tourism activities such as snorkeling and diving. Meanwhile, there is no sand beach on Kapas Island's west coast but only rocks, making it unsuitable for tourism activities. Moreover, Marang District Council has announced that Kapas Island will be closed to visitors from October to February due to the monsoon season. This statement implies that Kapas Island is expected to have rough wave conditions.

Table 1 summarises the wave conditions near Kapas Island. The data are extracted from the study by Yaakob *et al.,* [8]. The wave condition is chosen according to the frequency of occurrence during the calm, medium, and rough waves.

Table 1
Wave condition near Kapas Island

Wave condition	Amplitude (m)	Wave height, Hs (m)	Period, Tp (s)
1	0.00835	0.2505	3.5
2	0.025	0.75	5.5
3	0.075	2.25	8.5

1.1 Influence Criteria to OWC Performance

According to Abbasi *et al.,* [9], the performance of OWC is evaluated based on its energy extraction efficiency, also known as overall efficiency (wave-to-wire efficiency). There are a few criteria that may influence the OWC's performance.

1.1.1 Opening slope of air chamber

The inclination angle is designed to reduce wave reflection and increase turbine speed. Generally, Lino *et al.,* [10] stated that the OWC period of resonant is extended considerably by the wall's inclination, specifically the rear wall. Previous studies by Ram *et al.,* [11] have proven that reducing the air chamber incline angle from 90° to 55 ° would raise the air chamber's dynamic pressure by 200%. Dizadji *et al.,* [12] investigated the effect of the inclination of the back and rear walls and observed a performance improvement when both walls of an OWC chamber were assembled in a parallel inclined manner.

1.1.2 Bottom opening width of OWC

According to Yaakob *et al.,* [13], modifying the inlet curve and the reflector at the bottom of the air chamber could increase the effectiveness of the typical OWC. Amin [14] recommended the usage of a curved entrance to the OWC chamber to boost hydrodynamic energy extraction. Ashlin *et al.,* [15] conducted an experiment on four different base profiles. The result shows that OWCs with a circular bottom profile curve perform better than OWCs with different bottom profiles. Rosdzimin *et al.,* [16] also studied the bottom corner of floating OWCs.

1.1.3 Air chamber shape of OWC

In OWC design, the air chamber shape also plays an essential role in improving the device's efficiency. A previous researcher has experimented using an air chamber's rectangular shape. However, the result was unsatisfactory due to other supportive parts of the device and the chamber's shape [17]. Abbasi *et al.,* [9] constructed and designed OWC in a circular shape, which results in a smooth airflow. Liu Z. *et al.,* [18] confirmed that the wave incident period has discernible effects on the relative distribution of wave amplitude in the OWC chamber.

1.1.4 Depth of opening mouth

The depth of the opening mouth is another parameter that will affect the performance of the OWC device. Ashlin *et al.,* [15] mentioned that the depth of the opening mouth had become one of the key parameters to increase OWC's operation. Thomas *et al.,* [19] found that when the bottom opening decreases, the natural frequency of the OWC will decrease, contributing to its inefficiency in energy absorption. However, an increase in the bottom opening of an OWC is reported to correspond with an increase in its efficiency.

1.1.5 Air duct diameter

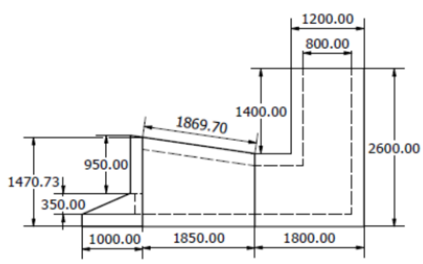
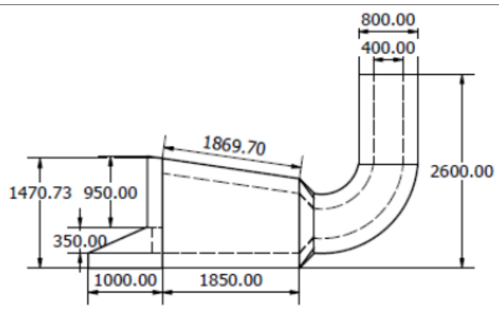
An air duct diameter is another criterion that must be emphasised to ensure optimal performance of the OWC device. The air chamber with a cylinder-type duct design can provide the turbine's maximum air flow rate [18]. Patel *et al.,* [20] stated that the nozzle of the air duct has two significant objectives: to accelerate the airflow velocity towards the turbine and to direct the airflow so that the maximum impact of air hitting the rotor blades will be achieved [21]. Therefore, the smaller diameter of the air duct will enhance the velocity of the airflow rate.

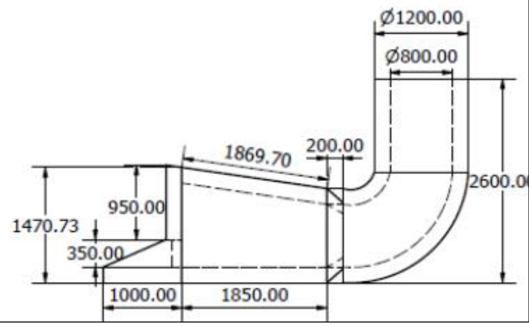
From the discussion above, a few criteria may influence the OWC's performance. Several studies have focused on improving the performance of OWC devices by optimising their geometry and operating at medium to high sea states. There is a lack of comprehensive research on the air duct design that connects the device to the turbine and operates at Malaysian low wave conditions. The research contribution from this study is to propose a new duct design integrated into the OWC device considering the air pressure with Malaysian seas. Therefore, the objective is to investigate the effect of the air duct design on its power output.

2. Methodology

The present work aims to find an optimum air duct design for the OWC WEC device. The numerical study was carried out using a downscale model at a 1:15 ratio. Table 2 shows the dimension and side view of the basis and the proposed designs for modification as oval and circle air duct. The basis design uses a square shape of the air duct. Then, the basis air duct is modified into another two shapes, which will enhance the power output. The main characteristic of the modified air duct is the absence of a sharp edge. All dimension for the case design is taken from the basis design, respectively. However, the air duct design exhibits slight differences in dimensions due to the changes in shape.

Table 2
Basis, oval and circle air duct design side view with dimension

Design	Side view(mm)	Height of air duct(mm)	Inner diameter (mm)
Basis Square Air Duct		2600	800
Oval Air Duct		2600	802.22 (horizontal), 400(vertical)

Circle Air Duct		2600	800

2.1 CFD Simulation

CFD simulates a fluid flow process using standard Naiver-Stokes and continuity equations for solving every computational cell. The setup and setting used in the CFD tool are equivalent to experimental work [22]. Thus, the configuration and setting of both the simulation and experiment are identical.

Hirt *et al.,* [23] stated that CFD uses the Volume of Fluid (VOF) method to monitor the fluid surface location. CFD is a multi-physical solver for solving a massive range of flow problems. The CFD software is configured with mass and momentum conservation equations in solving dynamic flow.

The cut-cell approach in CFD software identifies the cell-based area and volume fractions to represent obstacles. The cut-cell technique, consisting of mass and momentum, is integrated into the conservation equations. Implementing this method can significantly improve overall simulation efficiency by reducing the number of integrations compared to body-fit meshing. It also helps to limit the accuracy of mesh resolution. The CFD software is chosen to simulate the hydrodynamics problem.

2.1.1 Wave tank setup

The wave tank is designed using the Autodesk Inventor, and the size and shape are shown in Figure 1. The tank is built with a wave-breaking slope located at the tank's end. The purpose is to absorb the remaining wave and reduce the wave reflection effect that produces a standing if it is not well controlled. It is also built with a sidewall on both sides of the tank. The model is placed at the exact location, which is 17.55 meters away from the source of the incoming wave. The distance prescribed allows the wave to develop fully before reaching the OWC model.

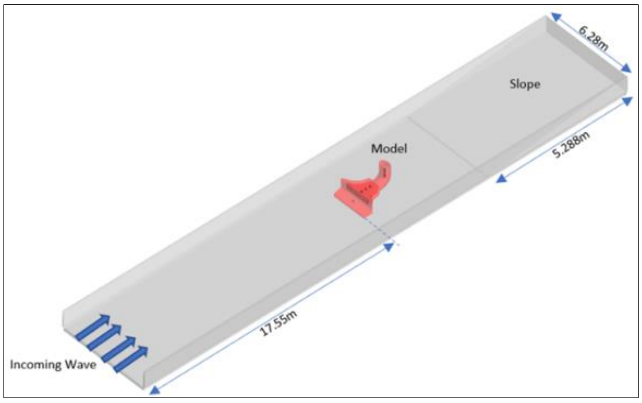


Fig. 1. Arrangement and measurement of wave tank

2.1.2 Wave boundary

The first step before defining the interaction between wave and structure is to set the working boundary, as shown in Figure 2. Every side of the boundary condition is set up accordingly, as described in Table 3.

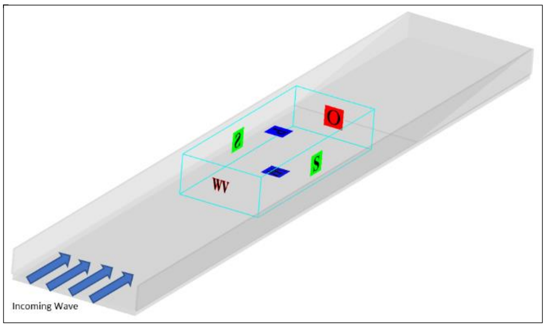


Fig. 2. Boundary condition for simulation

Table 3
Wave boundary condition justification

Boundary Condition	Justification	Symbol
Wave	Set at an incoming wave location	Wv
Wall	The bottom floor of the boundary	W
Symmetry	Sidewalls of boundary	S
Specified pressure	The top side of the boundary	P
Outflow	The back-side of the boundary with restriction to one-way fluid direction only	O

2.1.3 Location of probe

According to Figure 3, Probe 1 is placed in the inlet/mouth of OWC. The probe is put in to measure the power input. Then, Probes 2, 3, 4, 5, 6, and 7 are placed inside the chamber. Meanwhile, Probes 8–11 are put inside the air duct to obtain the output. It is essential to locate the probe precisely to compare the result at the end of this research study.

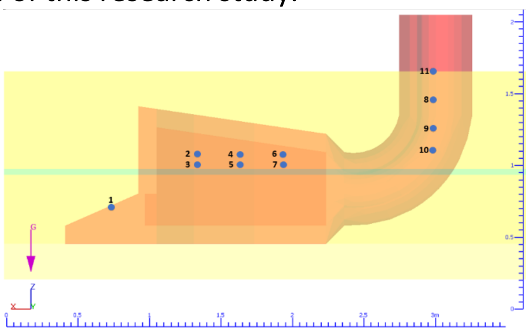


Fig. 3. Location of probe

2.1.4 Grid-Dependent Study (GDS)

The grid-dependent study process is one of the critical components of the entire study. The selection of the optimum mesh size is crucial before running the whole simulation. The smaller the mesh size, the longer the time for simulation, but with fair results. In the meantime, the larger the mesh size, the shorter the time taken for simulation, but it will give a coarse result. The mesh size is, therefore, chosen wisely to achieve an accurate output result for this study.

The graph of the grid-dependent study is generated from the result of each run using a different mesh size. The output result is extracted starting from the 4th wave and afterwards. This phenomenon happens due to the first three waves are not fully developed. The optimum mesh size is selected as the graph shows a consistent pattern. Continuing in mesh size reduction will no longer produce significant changes in the result.

The optimum mesh size for oval and circle designs is 0.062 (Figure 4) and 0.05 million (Figure 5), respectively. Thus, the entire simulation is run by using this optimum mesh size. The grid-dependent study is run for 20 seconds. However, the time for full simulation is longer because the peak wave point is taken after the 4th wave with ten fully developed peak waves.

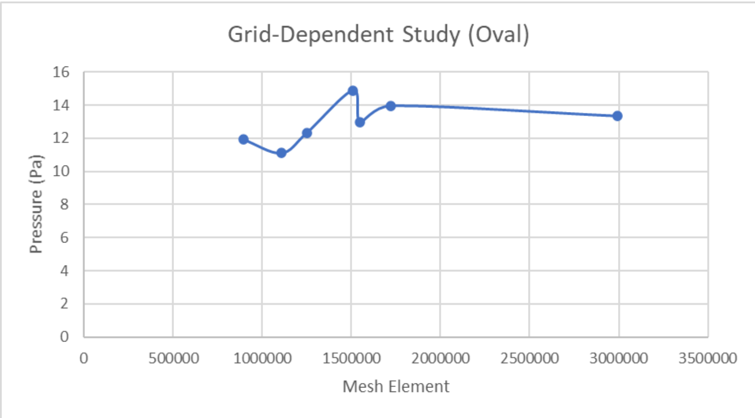


Fig. 4. Graph of GDS for oval shape

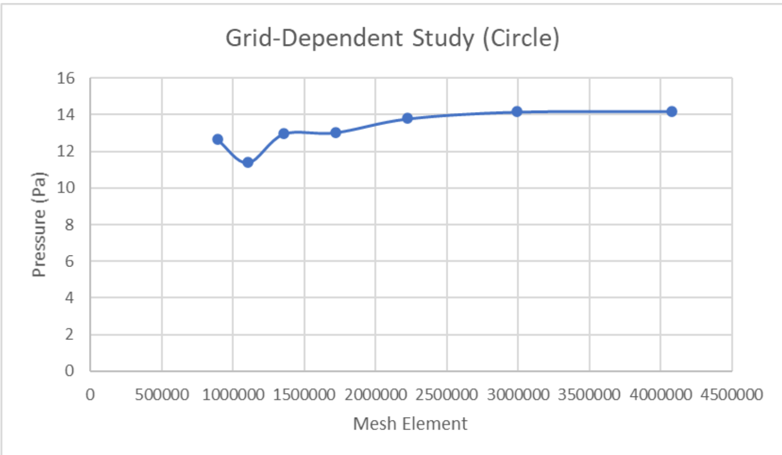


Fig. **5**. Graph of GDS for circle shape

For this study, selecting the optimal mesh size is performed only once since the quality of meshing is already ensured through the grid-dependent study. An example of grid line size configuration for an oval-air duct is shown in Figure 6.

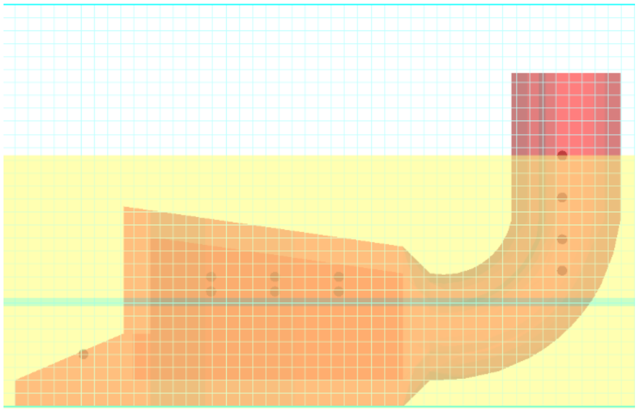


Fig. 6. Configuration of grid line size (Oval)

3. Results and Discussion

The proposed oval and circular air ducts are expected to improve the OWC's efficiency compared to the previous researcher's application of a square air duct. The result will be presented, discussed and visualised in this section.

3.1 Pressure Result Overview at Probe 8

Figure 7 shows the mean pressure graph at the first condition, which has a 0.00835 m wave amplitude and 0.9037 s peak period. The result is taken at Probe 8 because Probe 8 is expected to be the most compatible location for the turbine. In the proposed design, the oval air duct has the highest pressure of 11.57 Pa. Meanwhile, the basis design has only 11.55 Pa, while the circle air duct has 11.26 Pa.

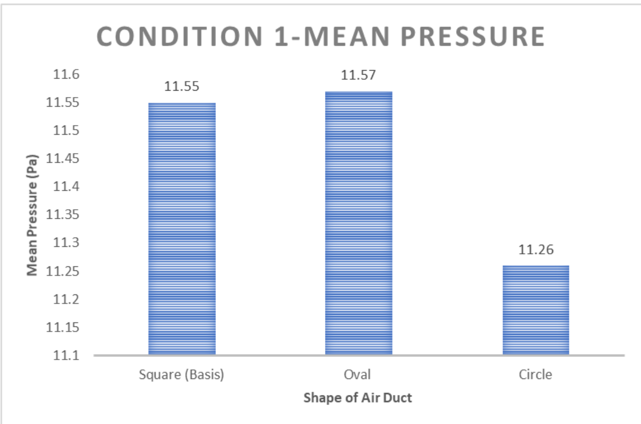


Fig. 7. Pressure at condition 1 (Probe 8)

Figure 8 illustrates the result of pressure at condition 2. Condition 2 has 0.025 m wave amplitude and 1.4201 s peak period. In this condition, the basis design has the lowest mean pressure of 11.26Pa compared to both proposed designs. Meanwhile, the oval and circle air duct obtained 13.81 Pa and 12.82 Pa, respectively. This graph shows that the proposed design has the highest pressure output during this medium wave condition compared to the basis design. The gap between the highest and lowest pressure is 2.55 Pa, considered significant due to the model size. The pressure distribution is asymmetrical in all square, oval, and circular air ducts. Nonetheless, the oval and circle air duct shows lower pressure drops.

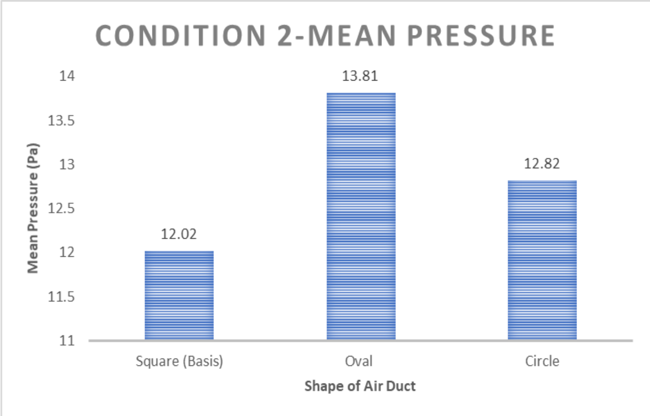


Fig. 8. Pressure at condition 2 (Probe 8)

Figure 9 indicates the result of mean pressure at the third condition, which is at the wave amplitude and peak period of 0.075 m and 2.1947 s, respectively. During this rough condition of waves, the result obtained is relatively high. The oval air duct has the highest pressure output of 15.40 Pa. In the meantime, the basis design and circle air duct shape produced a pressure of 12.22 Pa and 12.94 Pa, respectively. The pressure difference is 3.18Pa.

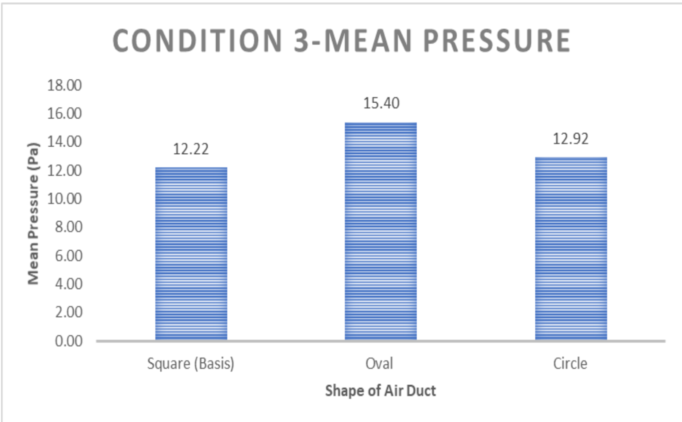


Fig. 9. Pressure at condition 3 (Probe 8)

3.2 Pressure Flow in Air Duct

The pressure flow at the air duct is analysed for basis and oval design. The oval shape records the highest mean pressure compared to the circular air duct for all three conditions. Therefore, the oval is chosen to be compared with the basis design since this study aims to find the most optimum air duct design. The result is interpreted from the probe's lowest to highest point position in the air duct, as indicated in Figure 3.

Figure 10 illustrates the pressure flow inside the air duct at condition 1. During condition 1, the basis and oval design have slightly different pressure patterns. However, the oval air duct produces the highest pressure output at all four-probe, even in low wave conditions.

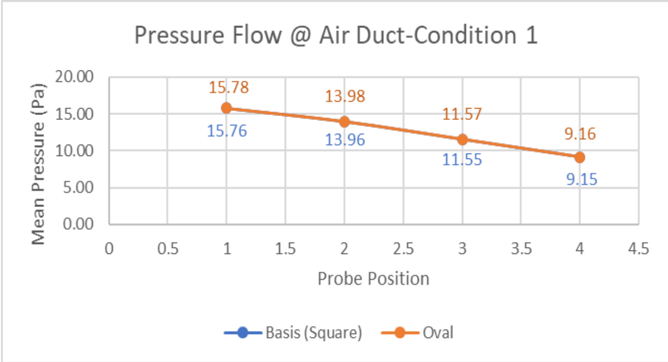


Fig. 10. Pressure flow at condition 1

The pressure-flow trend is slightly similar during medium and rough wave conditions, as shown in Figure 11 and Figure 12. The pressure flow inside the basis design's air duct is smaller than the flow pressure of the oval air duct. The pressure difference produces between the basis and oval design is quite significant. Therefore, it is observable that the oval design outperforms the basis design. In other words, the oval design is more efficient than the basis design. However, this can only be proved by calculating the amount of energy production.

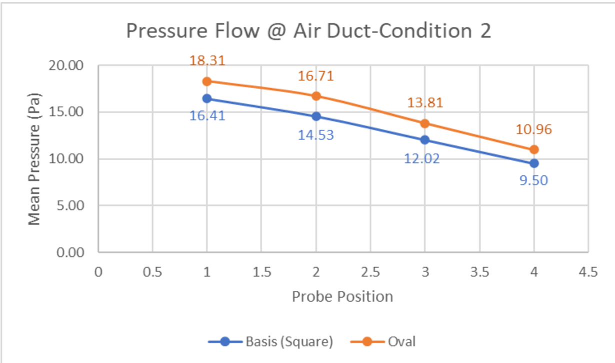


Fig. 11. Pressure flow at condition 2

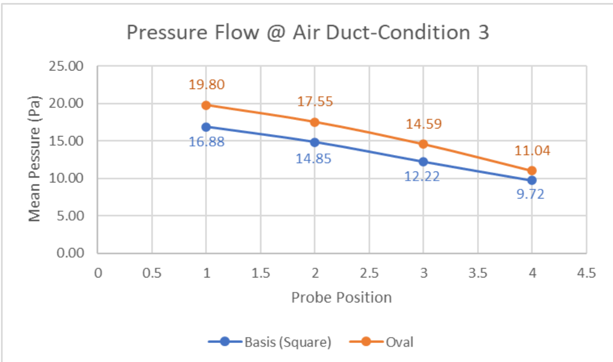


Fig. 12. Pressure flow at condition 3

3.3 Energy Estimation

The energy estimation includes the velocities for all designs from three conditions. The mean velocity is calculated based on the pressure peak time. Figures 13, 14, and 15 illustrate the mean velocity according to the conditions.

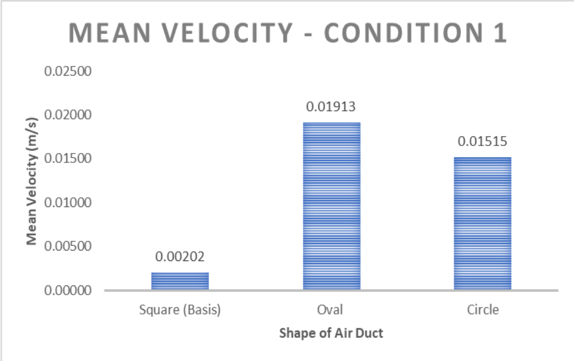


Fig. 13. Mean velocity at condition 1

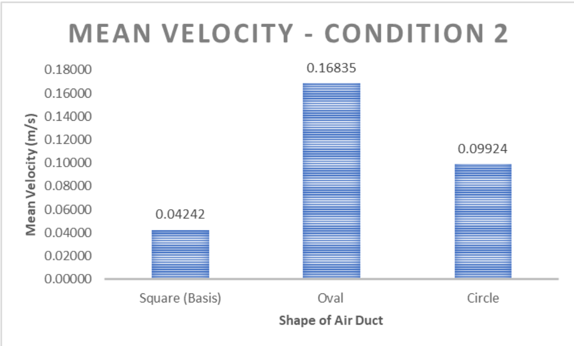


Fig. 14. Mean velocity at condition 2

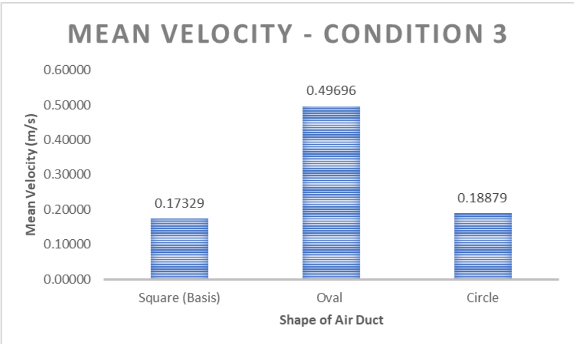


Fig. 15. Mean velocity at condition 3

Table 4 shows the energy estimation for all three designs at the air duct's output at Probe 8. The air density is 1.225 kg/m^3, and this calculation neglects the mass of the air.

Table 4
Energy estimation

Design	Condition	Pressure (Pa)	Velocity (m/s)	Potential energy (J/kg)	Kinetic energy (J/kg)	Mechanical energy (J/kg)
Basis	1	173.28834	0.00783	9.81	0.00003	9.81003
(Square)	2	180.28694	0.16427	9.81	0.01349	9.82349
	3	183.34683	0.67113	9.81	0.22521	10.03521
	1	173.62433	0.07407	9.81	0.00274	9.81274
Oval	2	207.14119	0.65202	9.81	0.21257	10.02257
	3	218.84777	1.92474	9.81	1.85231	11.66231
	1	168.95642	0.58151	9.81	0.16908	9.97908
Circle	2	192.30725	0.38434	9.81	0.07386	9.88386
	3	194.08760	0.73119	9.81	0.26732	10.07732

Mechanical energy is measured in all three conditions. Based on the results, it can be inferred that the oval design exhibits superior performance, followed by the circle and square shapes of the air duct. The tabulated result shows that the objectives of this research study are managed to accomplish.

4. Conclusion

In conclusion, a 3D analysis of the air duct design for the OWC device has been carried out. Two designs of air ducts have been proposed to improve further the existing basis air duct design. The final study on the air duct design has been carried out, and the results show improvement compared to the basis air duct design. The air duct's proposed design obtains impressive pressure results at Probe 8, which is the most compatible with the turbine to be located.

In this study, the oval design shows significant improvement in mechanical energy compared to the basis design. The oval design produced 9.81, 10.02, and 11.66 J/kg of mechanical energy compared to 9.81, 9.82, and 10.04 J/kg as prompted by the basis air duct design in all three conditions. The mean pressure and pressure flow obtained by the oval air duct is also relatively high, increasing the rotation of the turbine and harnessing the wave energy. Thus, an oval air duct design is recommended at a small wave height of 0.25 - 2.25 meters.

The result shows that the air pressure produced by the non-edge duct shape is much higher than the sharp edge of the air duct shape. Thus, the oval air duct design is proven to be more efficient and able to increase the performance of the OWC device at low wave height, specifically at Kapas Island, Terengganu.

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