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Experimental study to optimize the efficiency of the Oscillating Water Column wave energy converter by enhancing the air chamber design

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Abstract

One of the most active uses of renewable energy is wave energy conversion. One of the most popular techniques for converting wave energy is the Oscillating Water Column (OWC) device. This study looks at how the shape, design, and oscillating water column wave energy converter affect the airflow response. The chamber geometry is just as crucial as the turbine design, despite the fact that the majority of research concentrates on the turbine design to optimize the oscillating water column (OWC)'s performance. Optimizing the air velocity entering the turbine is the primary goal of this study since it will increase the device's output power and efficiency. Experimental investigations are performed in the wave tank laboratory to study the effects of air chamber designs, such as rectangular, cylindrical, and conical air chambers with different cross-sectional areas. The results demonstrate a considerable increase in air velocity flow from 3.1 m/s in the rectangular air chamber to 3.5 m/s in the cylindrical air chamber, and a maximum of 4.5 m/s in the conical air chamber.

Keywords: Air Chamber; Wave Tank; Air Velocity; Renewable Energy; Reynolds Averaged Navier-Stokes

1. Introduction

Many studies verify that fossil fuels are the main factor responsible for climate change and other environmental issues. The combustion of fossil fuels produces a major portion of the greenhouse gases (GHG) that blanket the Earth and trap the sun's heat [1,2,3]. Numerous studies have established that gasoline oil is the main factor contributing to both environmental and financial issues [4,5,6]. Due to growing worries about the environmental impact and cost of fossil fuels, the investigations for alternative renewable energy sources have become more urgent. One of the most active research areas for renewable energy is wave energy conversion [7]. Compared to other renewable energy sources like wind, solar, biomass, and geothermal, waves have the highest energy density. The principle of energy generation derives from the force of friction that the wind exerts on the surface of the sea. Wave energy extraction devices classified into 3 categories: oscillating water columns (OWC), oscillating bodies and overtopping systems [8]. Fig.1 shows the categories of wave energy converters [9].

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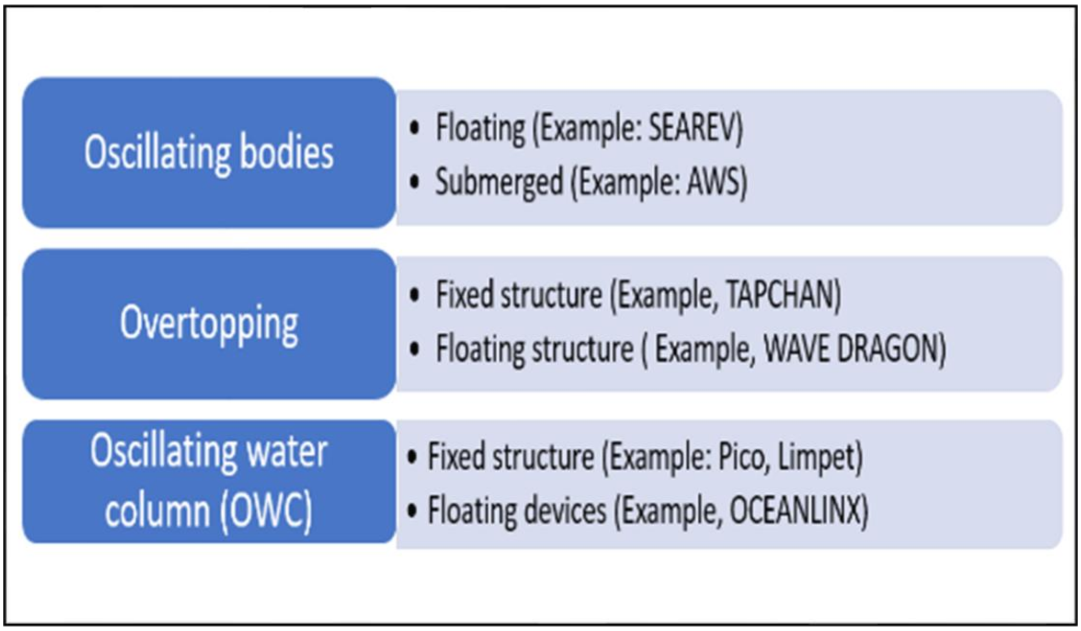

Figure 1 The categories of wave energy converters [9]

The oscillating water column (OWC) device is one of the most common approaches for converting wave energy because of its simplicity. OWC offers various benefits while having few moving parts. The OWC's design can be modified. Along the coast, OWC can be applied to a variety of collector designs, and the air turbine's presence eliminates the need for gearboxes. OWC is reliable, simple to maintain, and effectively uses the available sea space. OWC can be differentiated into floating structures that are found offshore and fixed structures that are found near shore [10]. Table 1 shows the Differences between fixed and floating OWC [11,12]. Fig. 2 demonstrates Schematic layout of oscillating water column (OWC) system [13].

Table 1 The differences between fixed and floating OWC devices

	Fixed structures	**Floating structures**
Marine environment	Safe even in severe weather	Less safe specially in severe weather
Power production	Loss of wave power due to the shallow water effect	They can exploit the full power of the wave
Transport of energy	Insignificant energy losses	Large energy losses because of the use of submarine cables
Mooring lines	Not necessary	necessary
Life span of the device	Fewer moving parts and longer life	More moving parts and risk of damage during rough seas
Maintenance	Low maintenance cost	High maintenance cost

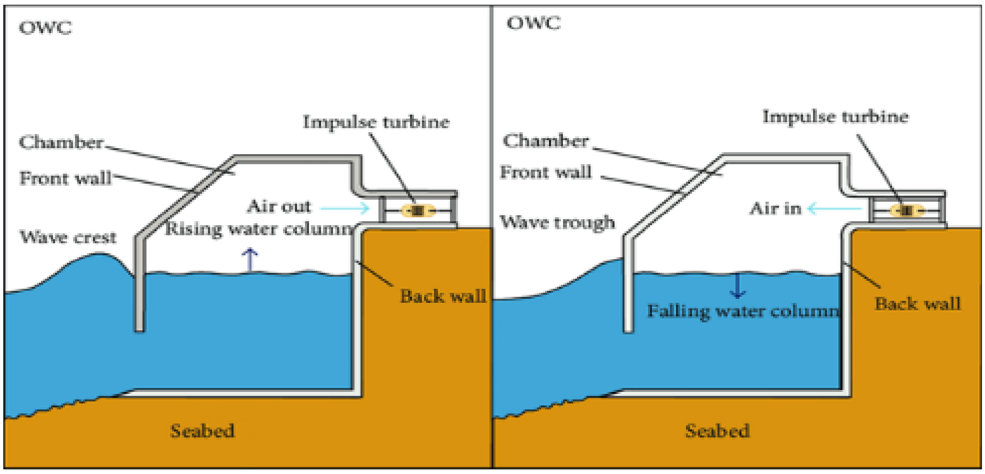

Figure 2 Schematic layout of oscillating water column (OWC) system [13]

OWC device is constructed of an empty chamber that is open to the sea under the surface. Due to wave action, the water column inside the chamber oscillates, alternately compressing and decompressing the air in the upper part of the chamber. The flow of air into and out of the chamber is the primary power source for the turbine. Self-rectifying air turbines are the most popular option that applies a unidirectional rotation to the turbines [14]. When it comes to maximizing the performance of an OWC device, the chamber geometry serves to be as important as the turbine design. The power needed to compute OWC efficiency is calculated by integrating the product of air pressure in the chamber and airflow rate over time [15,16,17]. This study was applied in the wave tank laboratory on a small-scale fiber model that represents the OWC. The air velocity entering the turbine plays a significant role to increase the overall power efficiency of the OWC. The purpose of this paper is to investigate the impact of various air chamber geometrical designs on air velocity entering the turbine.

2. Methodology And Model Design

One of the factors that affects the OWC's performance is the air velocity that enters the turbine. The air chamber design has a significant impact on the outlet air velocity [7].

The following equations are the geometric relations for designing the OWC chamber [18,19]:

$$B = 0{,}42\lambda \ldots\ldots\ldots \qquad (1)$$

Where B is the chamber width and λ is the wave length.

$$Ha = 0{,}84B \ldots\ldots\ldots \qquad (2)$$

Where Ha is the height of the air chamber.

This paper represents a small-scale fiber model for an OWC device with a hollow duct in the middle of the air chamber top. The hollow duct is the replacement for the turbine. The hollow duct represents the outlet airflow, which is supposed to be the turbine inlet. Three air chamber cases will be illustrated in this paper to show the effect of air chamber design on the outlet air velocity. For Boundary conditions, all parameters applied are constant for the three cases. Wave Height (H) is 8.3 cm, Wave Length (L) is 71 cm, Liquid Depth (d) is 15 cm.

Calculations and mathematical operations are controlled by fluid flow governing equations. The Reynolds Averaged Navier-Stokes (RANS) equations, the continuity equation, and the conservation equations for momentum and energy are various instances of these equations. The following are the continuity equations and Reynolds Averaged Navier-Stokes (RANS) equations:

$$\frac{\partial u_i}{\partial x_i} = 0 \ldots\ldots\ldots \qquad (3)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \rho f_{x_i} + \frac{\partial}{\partial x_j}\left(v\frac{\partial u_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right) \ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where, ρ, p, and f_{x_i} are the fluid density, fluid pressure, kinematic viscosity coefficient, and body force, respectively. $x_i = (x, y, z)$ and $u_i = (u, v, w)$ represent the Cartesian coordinates and corresponding Reynolds-averaged velocity components. The component $\rho \overline{u_i' u_j'}$ are called Reynolds stresses.

The following are the momentum and energy conservation equations [20]:

$$\frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho u u) = -\nabla p + \nabla \cdot \tau + \rho g + F \ldots (5)$$

…

$$\frac{\partial(\rho C_p T_f)}{\partial t} + \nabla \cdot \left(\rho C_p T_f u\right) = \nabla\left(\Psi_e \nabla T_f\right) + S_T \ldots\ldots\ldots (6)$$

where u is the fluid velocity vector; τ is the viscous stress tensor; g is the gravitational acceleration; t is the time; F is the source of momentum due to surface tension;

T_f is the temperature; Cp is the fluid specific heat; Ψe is the fluid thermal conductivity; and S_T is the source term in the energy equation.

The viscous stress tensor is:

$$\tau = \mu_{eff}[\nabla u + (\nabla u)^T] + \frac{2}{3}\mu_{eff}(\nabla \cdot u)I \ldots\ldots\ldots (7)$$

where I is the identity tensor and μ_{eff} is the effective dynamic viscosity:

$$\mu_{eff} = \mu + \rho v_t \ldots\ldots\ldots\ldots (8)$$

where μ is the dynamic viscosity of the fluid and v_t is the turbulent kinematic viscosity.

3. Model Parameters

three different cases of the air chamber designs that will be studied in this paper to show their impact on the outlet air velocity. Fig. 3 shows the OWC 3D model and model geometry of the rectangular air chamber. Table 2 shows the rectangular air chamber model dimensions. Fig. 4 shows the OWC 3D model and model geometry of the cylindrical air chamber. Table 3 shows the cylindrical air chamber model dimensions.

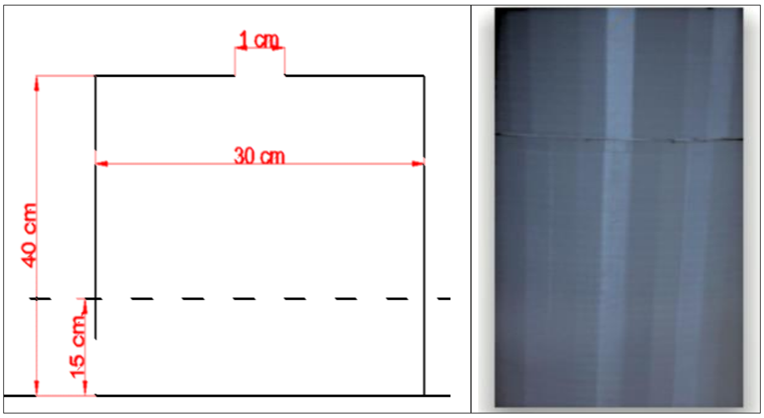

Figure 3 3D model and model dimensions of rectangular air chamber

Table 2 Rectangular air chamber model dimensions

Model dimensions	
Hole diameter	1 cm
Free surface elevation	25 cm
Still water depth	15cm
Chamber length	30 cm
Cross sectional area	707 cm^2

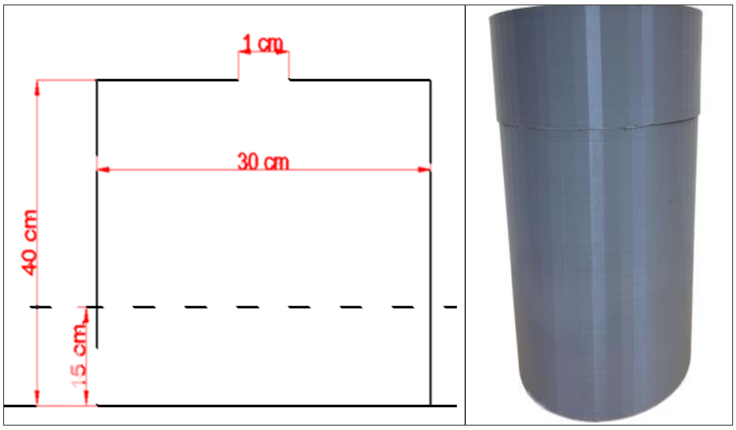

Figure 4 3D model and model geometry of the cylindrical air chamber

Table 3 Model dimensions

Model dimensions	
Hole diameter	1 cm
Free surface elevation	25 cm
Still water depth	15cm
Chamber length	30 cm
Cross sectional area	707 cm^2

Fig. 5 shows the cylindrical air chamber model during the experiment in the wave tank and shows the anemometer that used in the experiment to measure the air flow velocity. Figure 6 shows the OWC 3D model and model geometry of the conical air chamber. Table 4 shows the conical air chamber model dimensions.

Figure 5 the cylindrical air chamber model and the anemometer

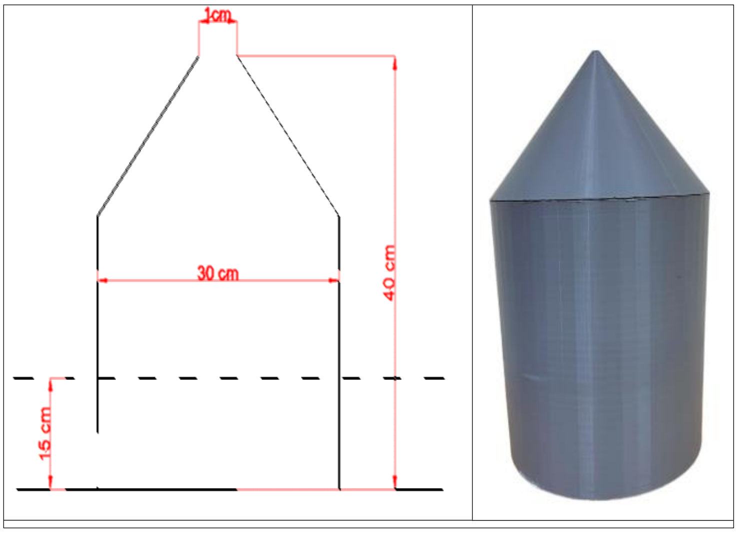

Figure 6 3D model and model geometry of the conical air chamber

Table 4 The conical air chamber model dimensions

Model dimensions	
Hole diameter	1 cm
Free surface elevation	25 cm
Still water depth	15cm
Chamber length	30 cm
Cross sectional area 1	707 cm^2
Cross sectional area 2	0.78 cm^2

4. Results and Discussion

Recent advancements in air chamber design have focused on improving the air flow velocity to ensure higher air flow velocity to the turbine. Increasing the air velocity will lead to an increase in the total output power of the OWC. The following three cases will illustrate the air flow velocity results according to three air chamber designs. Fig. 7 shows the air flow velocity of rectangular air chamber with outlet air velocity 3.1 m/s. Fig. 8 shows the air flow velocity of cylindrical air chamber with outlet air velocity 3.5 m/s. Fig. 9 shows the air flow velocity of conical air chamber with outlet air velocity 4.5 m/s.

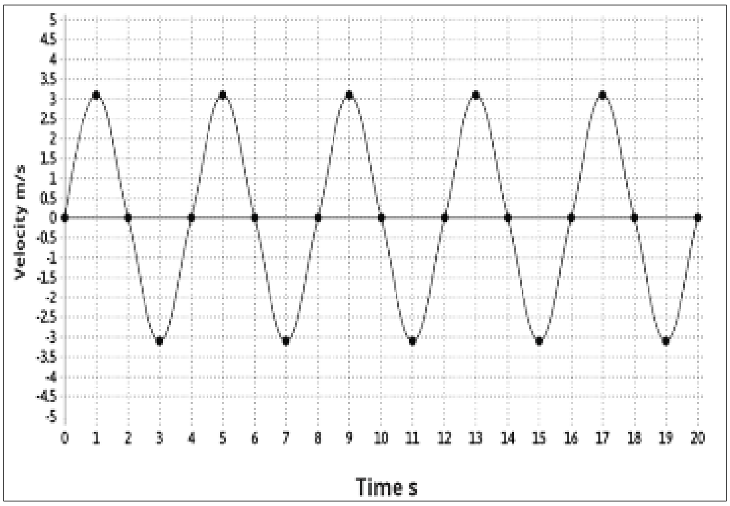

Figure 7 Air flow velocity of rectangular air chamber

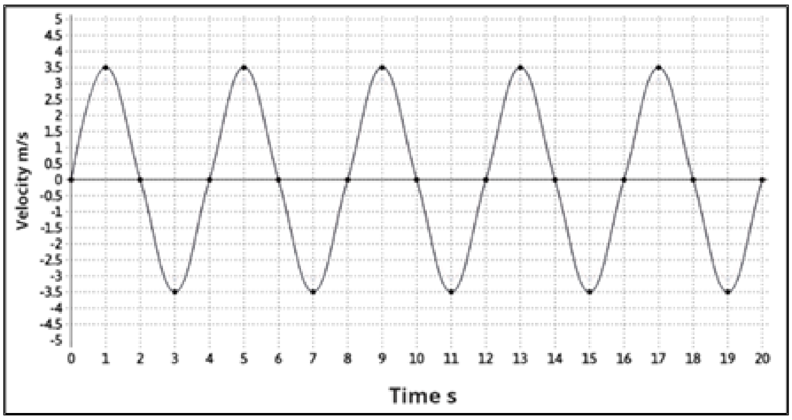

Figure 8 The air flow velocity of cylindrical air chamber

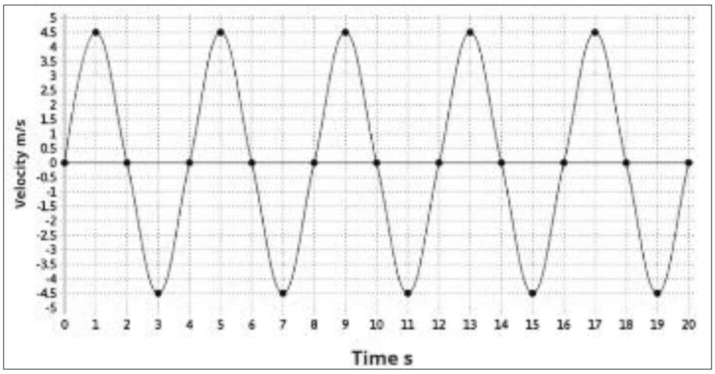

Figure 9 The air flow velocity of conical air chamber

The results show that the air chamber design has a significant influence on outlet air flow velocity, which directly affects turbine efficiency. The cylindrical air chamber is more efficient than the rectangular one, as it avoids losses caused by sharp right-angle edges. The conical air chamber has a better effect than the cylindrical one, as it has the maximum outlet air velocity due to continuity equation characteristics. Fig. 10 shows the outlet air velocity of the three cases.

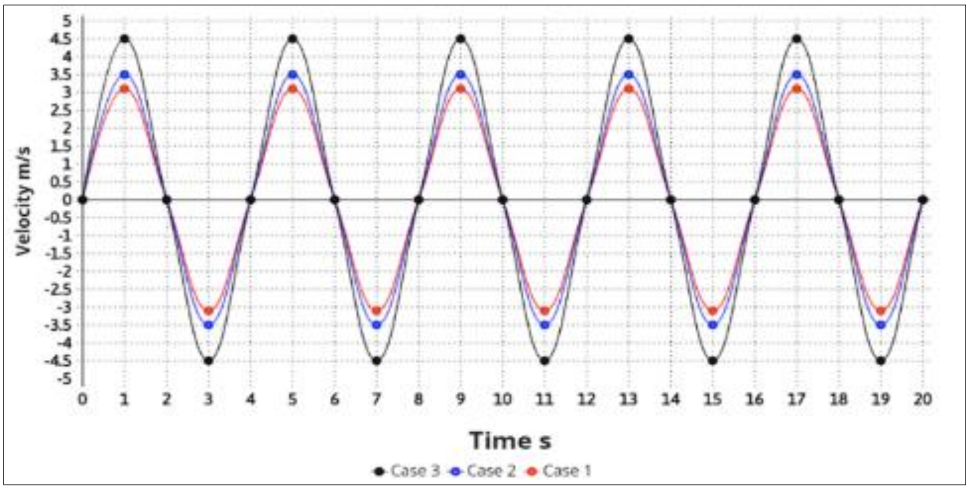

Figure 10 The outlet air velocity of the three cases

5. Conclusion

Recent developments in air chamber design have focused on increasing air flow velocity to the turbine. The total output power of the OWC will increase as the air velocity increases. The three cases shown in this study illustrate the air flow velocity results for three different air chamber designs. The results show that air velocity flow increased significantly from 3.1 m/s in the rectangular air chamber to 3.5 m/s in the cylindrical air chamber and 4.5 m/s in the conical air chamber. The outlet air velocity of the conical air chamber equals 145% of the outlet air velocity of the standard rectangular air chamber. The research results show that the air chamber design has a substantial impact on the exit air flow velocity, which has a direct impact on turbine efficiency. The cylindrical air chamber appears to be more efficient than the rectangular one. The cylindrical air chamber avoids the losses that occur in the rectangular air chamber due to corner effects. The results also reveal that the conical air chamber is better than the cylindrical air chamber. Because of the continuity equation effects caused by the different cross-sectional areas, the conical air chamber has the highest outflow air velocity.

Compliance with ethical standards

Disclosure of conflict of interest

There is no conflict of interest to be disclosed.

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