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Experimental Study of Duct Cross-Sectional Area Reduction on Oscillating Water Column Performance Using Wave Period Variations

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Abstract: The development of renewable energy is a key approach to reducing fossil fuel dependence. This study examines the effect of modifying duct geometry into a convergent nozzle shape in an Oscillating Water Column (OWC) system. Experiments were conducted in a laboratory wave flume using sensors to measure wave height and pressure across nine wave period variations. Results show that reducing the cross-sectional area increases pressure by 57% and velocity by 44%, consistent with Bernoulli's principle. The maximum potential power in the laboratory-scale model was obtained at a wave height of 0.175 m and a wave period of 2.69 s. Using Froude scaling, this corresponds to a prototype wave height of approximately 1.75 m, generating 51.75 W.

Keywords: cross-sectional; duct; nozzle; OWC

1. Introduction

The escalation of Gross Domestic Product (GDP) and population growth in Indonesia continues to drive increasing energy demands¹. Fossil fuels, which have long served as the primary energy source, are becoming increasingly scarce, with daily consumption in Indonesia reaching approximately 1.6 million barrels². According to the Ministry of Energy and Mineral Resources, the country's fossil fuel reserves are projected to be depleted within the next fifteen years if current consumption rates persist³. Consequently, developing renewable energy sources is essential to mitigate negative impacts of fossil fuel dependency. Ocean waves offer a high energy density and abundant availability among various renewable sources, promising clean energy alternative⁴.

Ocean waves originate from the oscillatory motion of fluid particles in a sinusoidal pattern, resulting in mass air movement in the form of waves. Global wave energy potential is estimated to reach approximately 32,000 TWh

annually along offshore regions and about 2 TWh annually in coastal areas—values nearly equivalent to the world's annual energy consumption^{5,6}. This highlights the considerable potential of wave energy to replace fossil fuels and support a transition to cleaner, more sustainable energy systems. Among various types of Wave Energy Converters (WECs) developed over the past four decades, the Oscillating Water Column (OWC) has emerged as one of the most widely implemented technologies⁷. OWC systems convert ocean wave energy through a compress–decompress mechanism of fluid motion that generates pneumatic pressure using a Power Take-Off (PTO) mechanism. This process involves interaction between the ocean's free surface and the air within a chamber⁸. The OWC consists of a chamber that converts wave energy into pneumatic energy, which is subsequently transformed into mechanical energy by a turbine and then converted into electrical energy via a generator^{8,9}. OWC devices also exhibit a superior peak-to-average power ratio compared to other WECs, making them an efficient solution for wave

energy extraction¹⁰⁾.

This study addresses a research gap by investigating the effect of duct cross-sectional reduction using a convergent nozzle geometry. Theoretically, a nozzle is a conduit with a decreasing cross-sectional area that accelerates and directs fluid flow¹¹⁾. The Continuity Equation and Bernoulli's Principle govern the acceleration process, where increased fluid velocity is associated with greater extractable power¹²⁾. An experimental approach is employed using a laboratory-scale wave flume to analyze the influence of a convergent nozzle on airflow velocity, pressure distribution, and power potential. This study used regular waves with a fixed wave height of 0.175 m and nine wave period variations ranging from 2.06 s to 4.59 s. The wave height was intentionally maintained constant to isolate the effect of duct cross-sectional area reduction on OWC performance.

2. Literature Review

Several studies have explored the application of Oscillating Water Column (OWC) systems in wave energy conversion, focusing on key parameters such as wave height, wave period, and system geometry to optimize performance. A study by Adafiah¹³⁾ investigated the potential of OWC systems to generate electricity from wave energy, specifically analyzing the influence of water height on current and voltage generation. The results indicated that optimal electrical output did not occur at the highest wave height. Instead, the system performed most efficiently under resonant wave conditions aligned with the OWC system's design parameters, highlighting the importance of matching wave characteristics with system resonance. Further, Supriyanto¹⁴⁾ evaluated the hydrodynamic performance of two OWC configurations—L-shaped and U-shaped chambers—under varying wave heights and periods. The study found that chamber geometry redesign significantly affected the internal water oscillation behaviour, improving airflow velocity and pressure differentials within the chamber and duct sections. This finding emphasized the role of wave input variation in enhancing air movement and overall energy conversion efficiency. Marta¹⁵⁾ supported these findings through an experimental study using a 1:10 scale wave flume model based on the Froude Scaling Law. Their study investigated the effects of wave conditions, tidal variations, and water depth on OWC performance. The results demonstrated that changes in wave height and period increased airflow velocity and chamber pressure differences, leading to higher RPM values of the turbine and, thus, greater power output potential.

Regarding nozzle design, Budiyanto¹⁶⁾ compared the performance efficiency between convergent nozzles and convergent-divergent (CD) nozzles used in duct design. The study revealed that the convergent nozzle exhibited 8–

12% higher efficiency than the CD nozzle configuration. The reduction in cross-sectional area effectively accelerated airflow, contributing to increased kinetic energy within the system. This finding was corroborated by Venkatesan¹⁷⁾, who tested convergent nozzle performance at low wind speeds. Their results showed a velocity increase from 5 m/s to 8.86 m/s due to the Venturi effect, significantly enhancing energy conversion efficiency. Chada¹⁸⁾ also demonstrated that fluid velocity consistently increased across the nozzle length with rising Mach numbers, maintaining a stable and predictable flow pattern.

Oscillating Water Column (OWC) technology has been extensively studied as one of the most mature and adaptable wave energy conversion systems. Comprehensive reviews have detailed the hydrodynamic principles governing OWC operation, including chamber resonance, air compressibility, and turbine coupling mechanisms^{19,20)}. Foundational theoretical analyses established the linear wave interaction theory and energy absorption mechanisms that determine OWC efficiency^{21–24)}. Subsequent experimental and numerical investigations validated hydrodynamic models under regular and irregular wave conditions, emphasizing the importance of resonance tuning between chamber geometry and incident wave period^{25–28)}. These studies collectively confirm that optimal performance is achieved when the natural frequency of the OWC chamber matches the dominant wave frequency.

Geometric optimization has been identified as a critical parameter affecting pneumatic power generation. Research on chamber configurations, breakwater-integrated OWCs, and offshore-mounted systems demonstrated that internal geometry significantly influences pressure oscillation amplitude and airflow velocity^{29–32)}. Advanced computational fluid dynamics (CFD) analyses further clarified airflow behavior, turbulence effects, and nonlinear wave–air interactions inside the chamber and duct system^{33–36)}. In particular, modifications to duct cross-sectional area and nozzle configurations have been shown to enhance airflow acceleration and pressure amplification in accordance with Bernoulli's principle and the continuity equation^{37–40)}. Optimization approaches, including constructed design and multi-objective techniques, highlight that convergent duct geometries can significantly improve energy capture when properly tuned to wave conditions^{41–44)}.

Beyond hydrodynamic performance, turbine characteristics and power take-off (PTO) control strategies strongly influence overall system efficiency. Studies on Wells turbines and impulse turbines indicate that airflow rate and pressure fluctuations directly affect torque generation and electrical output^{45–48)}. Investigations into scale effects, wave climate variability, and irregular sea states emphasize the necessity of matching chamber

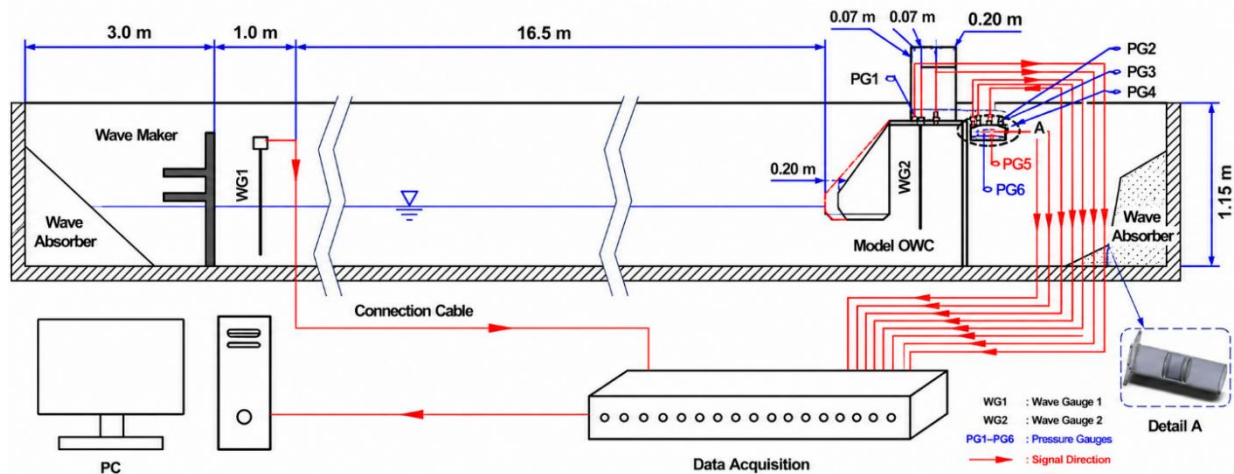


Fig. 1: Wave flume model and sensor installation scenarios

geometry and damping parameters to site-specific wave spectra⁴⁹⁻⁵²). More recent research has focused on hybrid offshore concepts, structural integration, and performance enhancement under varying wave periods⁵³⁻⁵⁶).

Despite substantial advancements in chamber and turbine optimization⁵⁷⁻⁶¹), limited experimental studies have specifically examined the influence of convergent nozzle duct modifications under controlled wave period variations⁶²⁻⁶⁷).

Therefore, further investigation into duct cross-sectional reduction and its interaction with wave characteristics remains essential to improving OWC performance⁶⁸⁻⁷¹). These studies collectively support the potential benefits of employing a convergent nozzle in OWC systems⁷²⁻⁷⁴), particularly in optimizing internal air dynamics and improving the overall efficiency of wave energy conversion⁷⁵⁻⁷⁶).

3. Methods

3.1. Experimental Setup

The experimental investigation was conducted using a two-dimensional wave flume with a width of 1 meter, a length of 36 meters, and a height of 1.5 meters. The maximum operational water depth was set at 0.8 meters, and the wave flume could generate wave periods ranging from 0.4 to 5 seconds. All tests were conducted at the Coastal Engineering Laboratory of the National Research and Innovation Agency (BRIN), certified under ISO 17025¹⁵). Wave generation was performed using a piston-type wave maker with a horizontally oscillating paddle manufactured by HR Wallingford. The configuration and spacing of the paddle followed the guidelines provided by Hydralab III¹⁶). The experiments employed two types of sensors: wave height gauge sensors (WG) and pressure gauge sensors (PG). The WG sensors used were resistive-type with an accuracy of ± 0.5 mm, while the PG sensors were flush face pressure transducers with a diameter of 17

mm and an accuracy of 0.5% of the full-scale range¹⁴). Two WG sensors were used in total. WG1 was placed near the wave maker to measure the generated wave height, while WG2 was installed inside the OWC chamber to measure internal wave elevation. A total of six pressure gauge (PG) sensors were deployed. PG1 was installed inside the chamber, 70 mm from the chamber edge. PG2, PG3, and PG4 were positioned along the duct with a spacing of 60 mm between adjacent sensors. PG2 measured the static pressure, while PG3 and PG4 were used to evaluate the pressure distribution within the duct. PG5 and PG6 were installed below the duct, also separated by 60 mm, to measure the total pressure during the compression and decompression phases, respectively. An illustration of the wave flume setup and sensor placements is presented in Figure 1.

This study used regular waves with three variations in wave height and nine variations in wave period. Experiments were conducted using two duct configurations: a standard cylindrical duct with a diameter of 160 mm and a modified duct with a reduced cross-sectional area, forming a convergent nozzle. The reduction was achieved using a reducer, resulting in a duct outlet diameter of 120 mm with a 4:3 contraction ratio. The wave generation parameters and configurations for each test group are presented in Table 1.

Table 1: Experimental testing matrix

Parameter	Variable		Variation Code
	H (m)	T (s)	
Wave Generation (Scenario Test)	0.175	2.06	A4
		2.37	B4
		2.69	C4
		3.00	D4
		3.32	E4
		3.64	F4
		3.95	G4
		4.27	H4
		4.59	I4
Model Wave	Reduction in cross-sectional Depth Water (d) = 0.75 m		

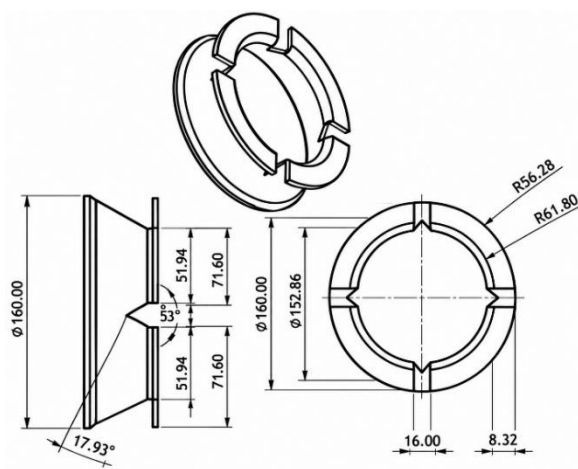
The procedure began with wave generation produced by a wave maker, based on the predefined variations in wave height and period set through the computer controller. During the wave generation process, the computer controller recorded WG and PG sensors. The generated waves moved from the wave maker along the wave flume until they entered the chamber, producing pressure that compressed the air above the water column and forced it into the duct. Pressure data acquisition was performed using the average of the peak sensor readings and the wave height difference once the wave generation reached a stable period upon entering the duct. The resulting pressure values were then converted into velocity using Bernoulli's principle. The parameters and variables were scaled in a 1:10 model using the Froude Scaling Law, with consideration for full-scale marine environments. This principle in fluid flow modeling is based on the Froude number (Fr), which represents the ratio between inertial forces and gravitational forces in fluid flow. The scale model applied was 1:10, meaning that model size corresponds to one-tenth of the actual field dimensions.

3.2. Geometric Design

This study investigates the effect of cross-sectional area reduction in the duct section, which typically serves as the turbine installation location in an Oscillating Water Column (OWC) system.

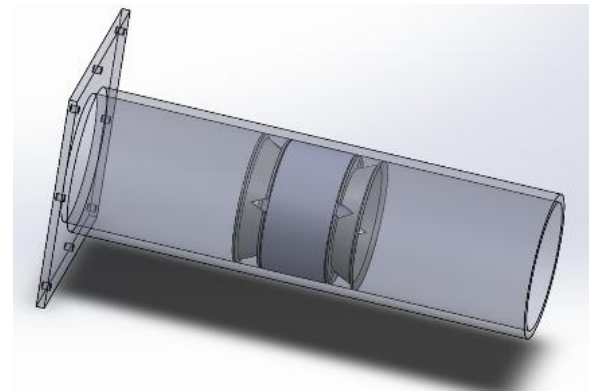


(a)

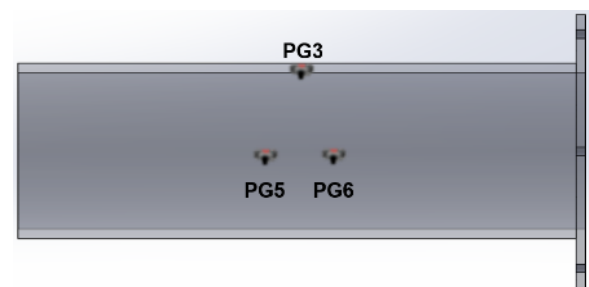


(b)

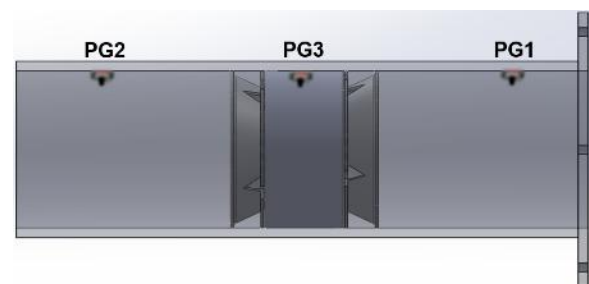
Fig. 2: (a) 3D print of reducer (b) Reducer geometry (in millimeters)



(a)



(b)



(c)

Fig. 3: (a) Instalation of reducer on duct (b) Sensor placing using reducer (c) Sensor placing without reducer

The reduction in cross-sectional area is modeled as a convergent nozzle geometry, which concentrates fluid flow and increases air velocity⁷⁷. A nozzle is a component with a tapered structure designed to accelerate fluid by reducing the flow's cross-sectional area⁷⁸. The convergent nozzle design was implemented by installing two reducers along the duct, with dimensions shown in Figure 2 and the installation scenario of reducers and sensors illustrated in Figure 3. The reducers were fabricated using 3D printing with PLA+ material, which offers easy manufacturing with smoother surfaces, minimizing disturbances to the fluid flow's aerodynamic behaviour⁷⁹⁻⁸¹. The sensor placement in the wave flume follows the configuration scenario used by Marta¹⁵.

3.3. Data Collection and Analysis

The Oscillating Water Column (OWC) system utilizes the vertical motion of ocean waves to generate air pressure, which can then be converted into power potential⁸². The

airflow inside an OWC chamber is inherently oscillatory and weakly compressible. However, the maximum measured airflow velocity in the present study remained below 20 m/s (Mach number < 0.06), indicating that compressibility effects are relatively small. Therefore, the airflow velocity was estimated using a quasi-steady Bernoulli-based approach, where the measured pressure difference was converted into an equivalent velocity during each compression and decompression phase. This formulation provides a first-order engineering estimate of airflow behaviour and is intended for comparative evaluation between duct configurations rather than for rigorous modelling of unsteady compressible flow⁸¹). For the duct configuration with a reduced cross-sectional area, the velocity equation is derived from Bernoulli's principle and adapted to the form of a venturi meter equation, as the geometry resembles that of a convergent nozzle⁸²). The formulation is based on the wave height measurements obtained from the wave gauge (WG) sensors.

$$P_1 + \rho gH + \frac{1}{2}\rho v_1^2 = P_2 + \rho gH + \frac{1}{2}\rho v_2^2, \quad (1)$$

within $A_1 v_1 = A_2 v_2$

$$v_1 = \sqrt{\frac{2gH}{\left(\frac{A_1}{A_2}\right)^2 - 1}} \quad v_2 = \sqrt{\frac{2gH}{1 - \left(\frac{A_2}{A_1}\right)^2}} \quad (2)$$

Meanwhile, for the duct configuration without cross-sectional reduction, the velocity model is simplified using Bernoulli's Equation in the form typically applied to a pitot tube⁸³), as expressed in the following equation, where P1 represents the pressure difference, and P2 denotes the static pressure.

$$P_1 + \rho gH + \frac{1}{2}\rho v_1^2 = P_2 + \rho gH + \frac{1}{2}\rho v_2^2, \quad (3)$$

within $v_2 = 0$

$$v_{1,2} = \sqrt{\frac{2(P_2 - P_1)}{\rho}} \quad (4)$$

The potential power generated in the duct section of the OWC system is influenced by the airflow rate entering the duct⁸⁴), which the following equation can express.

$$P_{OWC} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \quad (5)$$

4. Results

4.1. Effect of Duct Cross-Sectional Area Reduction on Pressure Compression and Decompression

Figure 4 demonstrates the effect of using a reducer the

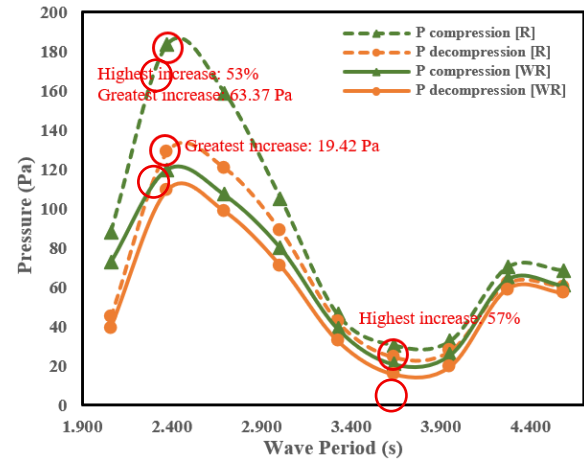


Fig. 4: Pressure compression and decompression

standard cylindrical duct configuration configured as a convergent nozzle, which effectively increases both the compression pressure (green line) and decompression pressure (orange line). During the compression phase, the highest percentage increase occurred in variation 2.37S wave period, reaching 53%, with the highest pressure increase also observed in 2.37S wave period at 63.37 Pa compared to the non-reduced duct configuration the convergent nozzle configuration. In the decompression phase, the highest percentage increase was recorded in variation 3.64S WAVE PERIOD at 57%, while the highest absolute pressure increase was again found in 2.37S WAVE PERIOD at 19.42 Pa. The graph shows that compression pressure values are consistently higher than decompression pressures. This is because, during the wave inflow, the water surface rises rapidly, significantly reducing the air volume above it and causing firm compression. Conversely, when the wave recedes and the water level drops, the decompression process is relatively slower and more gradual, resulting in lower pressure reduction than the compression phase^{85,86}). When ocean waves interact with the OWC structure, the force distribution during compression tends to be more concentrated, whereas during decompression, it is more dispersed⁸⁷). Based on the results of three repeated tests for each wave variation code, the obtained standard deviation ranged from 6% to 9%, indicating that the test results were obtained under stable testing conditions with a measuring instrument of sufficient accuracy. Moreover, it is evident that using a convergent nozzle to reduce the cross-sectional area effectively enhances pressures across various wave period variations.

4.2. Effect of Duct Cross-Sectional Area Reduction on Velocity Compression and Decompression

Figure 5 presents the effect of applying a reducer the standard cylindrical duct configuration in the form of a convergent nozzle, which enhances both the compression

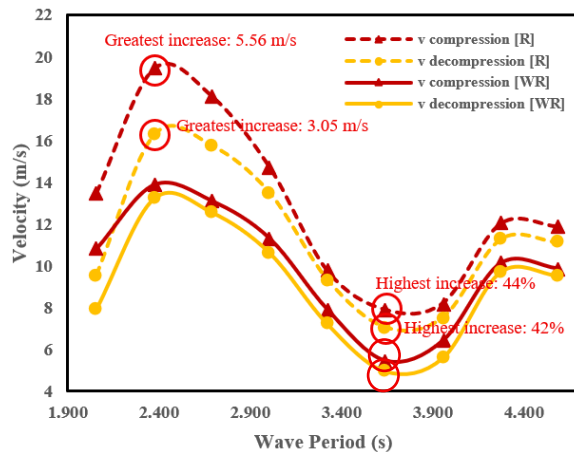


Fig. 5: Velocity compression and decompression

(red line) and decompression (blue line) velocity. The highest percentage increase was recorded in variation 3.64S wave period at 44% during the compression phase. In contrast, the highest absolute increase in compression velocity was observed in variation 2.37S wave period at 5.56 m/s compared to the configuration without cross-sectional area reduction the convergent nozzle configuration. In the decompression phase, the highest percentage increase was also found in variation 3.64S wave period at 42%, with the most significant velocity increase occurring in variation 2.37S wave period at 3.05 m/s. Similar to the phenomena in Figure 3, the reduction in cross-sectional area contributes to the increase in flow velocity, which aligns with the principle of the Continuity Law. This law states that the mass flow rate must remain constant throughout a streamline; therefore, when the cross-sectional area is reduced, the fluid velocity must increase accordingly to conserve the mass flow rate^{88,89}. Three repetitions were conducted for each wave variation code, yielding a standard deviation between 5% and 12%. This range reflects stable experimental conditions and the use of a measuring instrument with adequate accuracy.

4.3. Effect of Duct Cross-Sectional Area Reduction on Potential Power

OWC system generates at a constant wave height of 0.175 m across various wave period configurations. Figure 6 demonstrates the influence of using a convergent nozzle the convergent nozzle configuration compared to a duct without cross-sectional area reduction the standard cylindrical duct configuration.

The highest percentage increase in potential power was observed in variation 3.64S wave period at 70%. In contrast, the most significant absolute power increase occurred in variation 2.37S wave period at 18.35 Watts compared to the configuration without area reduction. The using of a convergent nozzle does not consistently lead to power enhancement across all wave period variations. A decrease in power output was observed in variation D4 by 6% and in variation G4 by 2%. This reduction is attributed

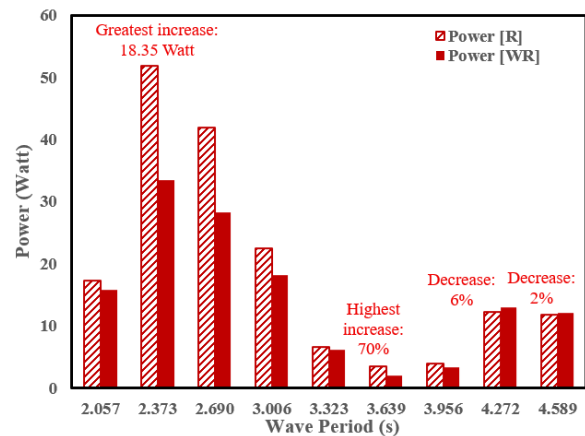


Fig. 6: Potential power

to the relatively insignificant velocity increase when the cross-sectional area is reduced, considering that fluid power is proportional to the cube of the velocity⁹⁰. For each wave variation code, three test repetitions were performed, resulting in a standard deviation of 8-12% indicates that the measurements in stable conditions using a sufficiently accurate measuring device. Since the reduced area is smaller (with a 4:3 ratio), the observed velocity gains were insufficient to compensate for the reduction in area, as indicated by Equation 5.

5. Discussion

5.1. Correlation Between Free Surface Elevation (FSE) and Pressure

Figure 7 shows that water surface elevation (blue line) is directly proportional to the pressure value (green line); as the water surface rises—indicated by an increase in elevation—the air chamber volume decreases, leading to air compression and a subsequent increase in air pressure. Conversely, when the free surface elevation decreases, the pressure drops due to the expansion of the air volume. This behaviour aligns with Boyle's Law, where the compressibility of air in the OWC chamber follows the principle that a decrease in volume

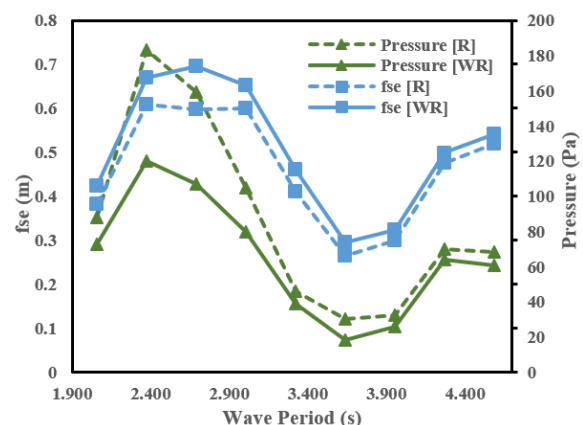


Fig. 7: Correlation between FSE and pressure

due to water displacement results in an increase in pressure⁹⁰). The effect of cross-sectional area reduction the convergent nozzle configuration on water surface elevation shows a decrease in elevation values, as the convergent nozzle restricts the flow area, generating resistance to water movement within the chamber. This restriction limits the airflow entering the duct, causing more wave energy to be converted into air pressure rather than kinetic energy used to raise the water column. As a result, the elevation of the water surface is lower⁹¹). On the other hand, the pressure graph indicates that the reduced cross-sectional area hinders the airflow, and using a convergent nozzle accelerates pressure buildup due to the narrower air volume, thereby increasing pressure more effectively⁹²).

5.2. Correlation Between Pressure and Velocity

Figure 8 shows pressure vs. velocity which are calculated using Equation 2 for the test condition with cross-sectional reduction the convergent nozzle configuration and Equation 4 for the test condition without cross-sectional reduction the standard cylindrical duct configuration. The pattern across each variation is similar for both pressure and velocity. As the pressure increases, the velocity also increases. When pressure builds up within the chamber, the air expelled from the chamber undergoes a pressure-to-kinetic energy conversion, resulting in higher airflow velocity⁹³). Similarly, in test conditions involving cross-sectional reduction, the velocity increases due to the narrowed outlet area, which accelerates fluid flow—transforming pressure into velocity following the Continuity Law⁹⁴). When the wave rises, the water compresses the air within the chamber and forces the concentrated airflow through the convergent nozzle-shaped duct, leading to higher pressure and velocity. From both aspects shown in the graph, it can be concluded that there is a positive correlation between pressure and fluid velocity, with cross-sectional area reduction significantly enhancing both pressure and velocity.

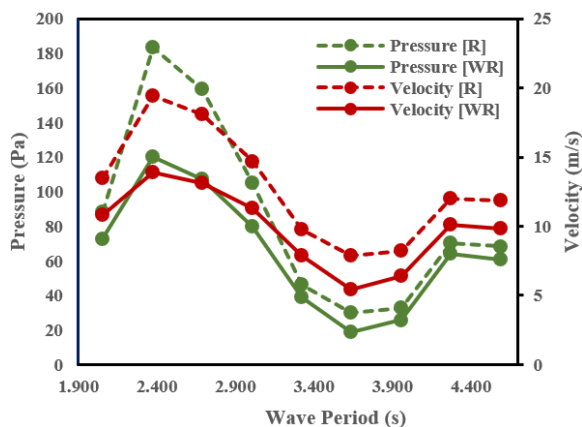


Fig. 8: Correlation between pressure and velocity

5.3. Correlation Between Velocity and Potential Power

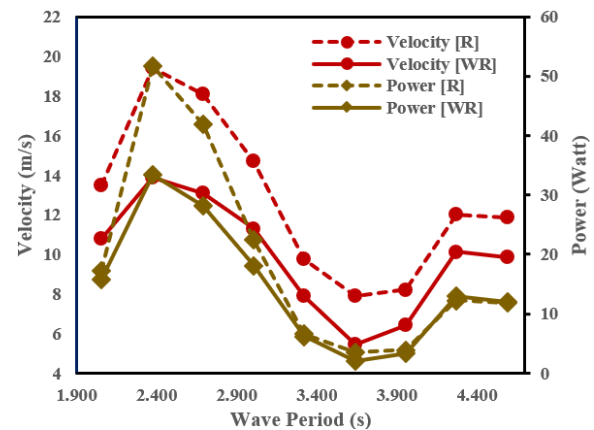


Fig. 9: Correlation between velocity and potential power

Figure 9 illustrates the correlation between airflow velocity and the potential power generated in the duct section of the OWC system. The potential power is calculated using Equation 5. The graph shows that velocity directly influences the power output generated by the OWC system. Although velocity increases across all test variations with cross-sectional reduction the convergent nozzle configuration, the resulting power output does not increase significantly. There are two test variations where the potential power is lower than the duct without cross-sectional reduction the standard cylindrical duct configuration. Despite the velocity increase due to the cross-sectional reduction, the gain is insufficient to compensate for the smaller cross-sectional area. As a result, the potential power produced under reduced cross-sectional area conditions is lower than that of the unreduced duct. From the comparison based on the substitution into Equation 5, where the duct radius is 60 mm with reduction and 80 mm without, it is found that—to achieve equivalent power output—the velocity in the reduced cross-sectional duct must be approximately 21.67% higher than that in the unreduced duct under the same wave height and period conditions.

Using the pressure transducer accuracy and the dimensional tolerance of the reducer geometry, the propagated uncertainty in the calculated power was estimated to be approximately $\pm 2.2\%$. For the maximum power condition (51.75 W), the corresponding uncertainty was ± 1.14 W. This uncertainty is significantly smaller than the observed performance differences between the two duct configurations, indicating that the reported trends are experimentally meaningful.

The test results suggest that the convergent nozzle design is more effective for short-period waves, as higher wave periods tend to increase pressure losses due to friction and energy dissipation, which hinder airflow⁹⁵). If the target output is to maximize power output, the most effective

configuration occurs at a wave height of 0.175 m and a wave period of 2.37 s. However, suppose the goal is to achieve the highest percentage increase in power output using a convergent nozzle. In that case, the optimal configuration occurs at the same wave height with a period of 3.64 s. Overall, the OWC system configuration with a convergent nozzle is most effective for low to moderate wave periods ($T < 4$ s), as it significantly enhances airflow velocity. These experimental results are supported by the field-scale application of an OWC in Cetraro, Italy⁹⁶, which operates in small wave conditions ranging from 0 to 1 meter yet is capable of generating electricity effectively. Furthermore, the results also corroborate the CFD testing conducted by Budiyo¹⁶, which demonstrated that a reduction in cross-sectional area can effectively increase air velocity and kinetic energy in the system. However, the convergent nozzle design may decrease potential power output at more extended wave periods due to increased pressure loss that impedes airflow efficiency.

5.4. Froude Scaling Law for Actual Conditions

This study applied the Froude Scaling Law to estimate the corresponding values under full-scale marine environments. The scaling was performed using a 1:10 ratio between the model and the prototype (Scale factor = $\lambda = 10$). For variation code 2.37S WAVE PERIOD, which exhibited the highest velocity increase, the estimation under actual conditions can be calculated accordingly.

Based on the calculations using the Froude Scaling Law, an OWC installation with the same modeling setup can effectively enhance airflow velocity through the duct, which can then be converted into potential power generation, without accounting for turbulence and energy losses. Under an actual wave height of 1.75 meters and a wave period of 7.5 seconds, with a reducer geometry of 1.6 meters at the inlet and 1.2 meters at the outlet, the airflow velocity is estimated to reach approximately 61.414 m/s. It should be noted that the Froude Scaling Law preserves gravity-dominated hydrodynamic behavior but does not fully reproduce viscous and aerodynamic effects. At full scale, airflow inside the chamber and convergent nozzle may experience additional losses associated with turbulence generation, wall friction, flow separation, pneumatic damping, and exit kinetic energy losses.

Table 2: Actual condition using froude scaling law

	Scale Factor	Model Condition	Actual Condition
Wave height	λ	0.175 meter	1.75 meter
Wave periode	$\sqrt{\lambda}$	2.37 second	7.5 second
Nozzle geometry (inlet diameter)	λ	0.16 meter	1.6 meter
Nozzle geometry (outlet diameter)	λ	0.12 meter	1.2 meter
Velocity	$\sqrt{\lambda}$	19.42 m/s	61.414 m/s

These effects scale nonlinearly with Reynolds number and flow velocity and may reduce the actual airflow velocity and power available to the turbine. Therefore, the prototype-scale values presented in Table 2 should be regarded as theoretical estimates rather than exact performance predictions.

A limitation of the present study is the use of a quasi-steady Bernoulli formulation to estimate airflow velocity. Although the airflow inside an OWC is inherently unsteady and compressible, the relatively low Mach numbers observed in the experiments (<0.06) justify the use of an incompressible approximation for comparative analysis. Future work should employ transient CFD simulations or direct velocity measurements to capture the full unsteady compressible behaviour of the airflow.

6. Conclusion

Based on the results and discussion regarding the reduction of duct cross-sectional area using a convergent nozzle in the Oscillating Water Column (OWC) system, it was found that an increase in fluid flow velocity and pressure occurs as the flow passes through the convergent nozzle during both compression and decompression phases across various wave period variations. The reduction in duct cross-sectional area enables pressure enhancement of up to 57% and velocity increase of up to 44% compared to the duct without cross-sectional decrease due to the convergent nozzle's ability to accelerate and concentrate fluid flow, following Bernoulli's Equation and the Continuity Law.

Furthermore, the experimental results indicate that using a convergent nozzle effectively increases the potential power generated in the duct section of the OWC system, particularly under low to moderate wave periods ($T < 4$ s), as it significantly enhances airflow velocity. However, at higher wave periods, the convergent nozzle design reduces power output due to increased pressure losses caused by friction and energy dissipation within the nozzle, which hinder airflow and reduce the efficiency of wave energy conversion. This study's most effective parameter combination for wave energy capture occurred at a wave height of 0.175 m and period of 2.69 s, resulting in a maximum potential power output of 51.75 Watts.

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Nomenclature

Symbol	Description
A	Cross-Sectional Area (m ²)

A_1	Inlet Cross-Sectional Area (m ²)
A_2	Outlet Cross-Sectional Area (m ²)
g	Gravitational Acceleration (m/s)
H	Wave Height (m)
OWC	Oscillating Water Column
P_1	Inlet Flow Pressure (N/m ²)
P_2	Outlet Flow Pressure (N/m ²)
PG	Pressure Gauge
P_{OWC}	Potential Power of the OWC System (Watt)
ρ	Air Density (kg/m ³)
R	Reduced Cross-Sectional Area Variation
v_1	Inlet Flow Velocity (m/s)
v_2	Outlet Flow Velocity (m/s)
WG	Wave Height Gauge
WR	Non-Reduced Cross-Sectional Area Variation

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