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Experimental study on the performance of a slotted wells turbine in an oscillating water column device

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Abstract: Ocean wave energy has garnered significant attention as a sustainable power source, with the Oscillating Water Column (OWC) device emerging as a highly effective technology for wave-to-electricity conversion. Within this system, the Wells turbine serves as a critical component for energy extraction. While current literature predominantly relies on Computational Fluid Dynamics (CFD) simulations to analyze the performance of these turbines, this study employs a rigorous experimental approach to evaluate their dynamics. The experimental results demonstrate high reliability when compared with CFD simulation data. Furthermore, this research evaluates the performance of a slotted Wells turbine design. The comparative analysis reveals that the slotted Wells turbine achieves superior efficiency compared to the conventional Wells turbine design. These findings offer a comprehensive empirical foundation and provide critical insights for the future optimization of wave energy converters. Ultimately, this study serves as an essential precursor to subsequent developments aimed at enhancing the operational viability of OWC systems in practical, real-world applications.

Keywords: Wells turbine, oscillating water column device, hydrodynamics, aerodynamics, wave energy converter, experiment.

1. Introduction

Nowadays, wave energy is increasingly being developed. Among various technologies, the Oscillating Water Column (OWC) device has garnered significant research interest. The OWC device operates on a simple principle: when sea waves act upon the device, the water column within the chamber oscillates, creating an airflow that drives a turbine. The Power Take-Off (PTO) system is a critical component of the OWC device. This component reflects the device's efficiency in converting wave energy into electrical energy by

driving the turbine. Optimizing the performance of the Wells turbine is one of the key research directions aimed at increasing the energy conversion efficiency of OWC systems.

Research on optimizing Wells turbine performance through Computational Fluid Dynamics (CFD) analysis using response surface methodology has shown significant improvements in torque coefficient, operating range, and power output by delaying the dynamic stall phenomenon and reducing flow separation zones [1], [2]. Gratton et al. [3] applied a tabu search algorithm combined

with free-form deformation and CFD simulations to optimize blade profiles. Das et al. [4] employed an optimization approach for Wells turbines with end-plates by combining CFD techniques with automated algorithms to determine the balance between efficiency and torque. Kotb et al. [5] utilized a response surface optimization method based on CFD simulations to design variable tip clearances for Wells turbines. Valladares et al. [6] proposed a geometric optimization procedure for rotor blades using Bezier curves for a twin-turbine configuration OWC system, significantly improving performance under unsteady flow conditions. Additionally, Settar et al. [7] proposed the use of passive flow control devices in the form of elliptical leading-edge bulbs placed before the turbine blade leading edge to reduce flow separation, thereby improving peak torque by 38% and expanding the system's operating range by 22.2%. Furthermore, dynamic analyses of Wells turbines have also been conducted through experiments. An experimental study by Stefanizzi et al. [8] on a 3D-printed Wells turbine detected high-frequency torque oscillations during deceleration due to dynamic stall, highlighting the importance of understanding these unsteady phenomena to enhance structural durability in OWC turbine design. Experimental research by Licheri et al. [9], using detailed local three-dimensional flow field measurements, clarified aerodynamic characteristics and load distribution along the Wells turbine blades throughout the wave cycle, thereby explaining the overall efficiency limitations between the inflow and outflow phases in OWC systems. Experimental studies on novel Wells turbine models by Ding et al. [10] and Tu et al. [11] have demonstrated superior energy conversion efficiency. Currently, most studies focus on analyzing Wells turbine performance through CFD simulations, while experimental validation remains very limited.

In addition, Shehata et al. [12] systematically studied the effectiveness of multi-slot suction configurations on the stall performance of a Wells

turbine, finding that three slots located at 40%, 55%, and 90% of the chord length yielded the best performance, with the torque coefficient increasing by 26.7% before stall and 51% after stall. Shehata et al. [13] continued to focus on the slot angle parameter, indicating that a slot angle of 10° clockwise relative to a 0° slot improved the torque coefficient by 3% before stall and 15% after stall, while also reducing aerodynamic noise by 21.2%. Moreover, Harby et al. [14] conducted an experimental study on the suction slots of a Wells turbine, using a NACA0015 blade, comparing the performance of different slot configurations through experimental methods. The results showed that the three-slot configuration exhibited good characteristics in terms of pressure drop coefficient, turbine coefficient, and maximum turbine efficiency.

This research establishes an experimental system for an OWC device utilizing a slotted Wells turbine, focusing on investigating changes in the device's aerodynamic performance. By controlling parameters such as wave height, wave period, and turbine rotational speed, it allows for a comprehensive analysis of the device's energy conversion characteristics under experimental conditions. Furthermore, this study serves as a foundation for conducting broader assessments when evaluating the effectiveness of OWC devices in future research.

2. Methods and models

2.1. Surface wave mechanics

As defined by the Airy linear wave theory:

$$y(t) = a \sin(\omega t) = a \sin(2\pi f t) \quad (1)$$

Since $c = \lambda f$, it follows that:

$$y(t) = a \sin\left(\frac{2\pi}{\lambda} c t\right) \quad (2)$$

This expression captures the temporal evolution of a wind wave with amplitude a (m), wavelength λ (m), and propagation speed c (m/s), representing the macroscopic oscillation of water particles at a fixed location. To extend this

oscillatory motion to any point on the surface, we must introduce a new variable accounting for the spatial dimension along the direction of wave propagation.

$$y(x,t) = a \sin \left[\frac{2\pi}{\lambda} (ct - x) \right] \quad (3)$$

Next, considering the wave number k , which is defined as

$$k = \frac{2\pi}{\lambda} \quad (4)$$

Substituting Eq. (4) into Eq. (3) yields:

$$y(x,t) = \frac{H}{2} \sin(\omega t - kx) \quad (5)$$

where H (m) is the wave height. This expression relates the surface dynamics of a monochromatic linear wave to its characteristic parameters.

2.2. Capture chamber mechanics

The volume of water can be utilized to determine the air volume within the OWC chamber:

$$V(t) = V_c - V_w(t) \quad (6)$$

where V_c (m³) is capture chamber volume and V_w (m³) is water volume.

Subsequently, the integration of the water surface vertical variation across the chamber area is performed:

$$V(t) = V_c - \iint y(x,t) dA \quad (7)$$

Owing to the OWC chamber geometry

$$dA = w dx \quad (8)$$

where w is the width of the chamber. Therefore:

$$V(t) = V_c - \int_{-l/2}^{l/2} y(x,t) w dx \quad (9)$$

where l (m) is the length of the chamber.

Substituting Eq. (5) into Eq. (9) yields:

$$V(t) = V_c - \frac{wH}{2} \int_{-l/2}^{l/2} \sin(\omega t - kx) dx \quad (10)$$

Solving Eq. (10) gives:

$$V(t) = V_c - \frac{wH}{k} \sin \frac{kl}{2} \sin \omega t \quad (11)$$

This leads to the following expression for the instantaneous airflow $Q_a(t)$ (m³/s):

$$Q_a(t) = -\frac{dV}{dt} = \frac{wH\omega}{k} \sin \frac{kl}{2} \cos \omega t \quad (12)$$

$$= wHc \sin \frac{kl}{2} \cos \omega t$$

Based on this expression and considering that the airflow is conducted through a hollow cylindrical duct, the axial airflow velocity can be derived as follows:

$$v(t) = \frac{Q_a(t)}{A_c} = \frac{8awc}{\pi D^2} \sin \frac{\pi l}{cT} \cos \frac{2\pi}{T} t \quad (13)$$

where $A_c = \pi D^2/4$ (m²) is the duct cross-sectional area, D (m) is the diameter of the duct, and T (s) is the wave period.

2.3. Turbine mechanics

The turbine torque is expressed as [1]:

$$T_t = \frac{1}{2} C_T \rho A_t R_m \left[v^2 + (R_m \omega_t)^2 \right] \quad (14)$$

where ρ (kg/m³) is the air density, A_t (m²) is the total blade area, R_m (m) is the mean rotor radius, ω_t (rad/s) is the turbine angular speed, and C_T is the torque coefficient.

The relationship between the turbine angular speed ω_t and the pressure drop across the blades Δp is characterized by mutual feedback. The pressure drop is dependent on the angular speed, yet the torque T_t generated by the pressure drop simultaneously dictates the rotational dynamics. Hence, the efficiency of the turbine is given by [1]:

$$\eta = \frac{T_t \omega_t}{\Delta p Q} \quad (15)$$

where $Q = vA_c$ (m³/s) is the flow rate.

2.4. Turbine models

The slotted Wells turbine model used in this study is based on the model proposed by Shehata et al. [1]. This model is characterized by the following parameters: C is the blade chord length (m), L_{ss} is the suction slot location from the leading edge as a percentage of the chord, and D_{ss} is the suction slot diameter (m), as illustrated in Fig. 1.

The turbine blades are designed based on the NACA0015 airfoil profile. The dimensions are provided in Table 1, and the slotted Wells turbine model is constructed for various cases where L_{ss} varies as 40%, 45%, 50%, 65%, and 80%, as

shown in Fig. 2.

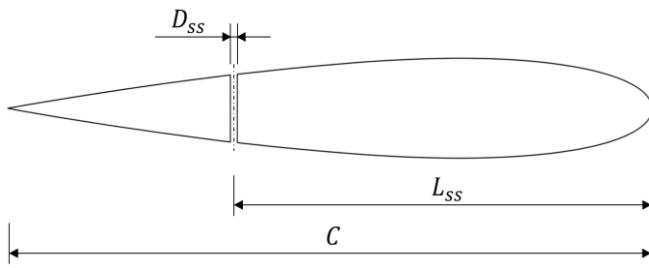


Fig. 1. 2D cross-section of a slotted airfoil

Table 1. Turbine dimensions

Parameter	Value	Unit
Airfoil profile	NACA0015	
The mean rotor radius R_m	41.7×10^{-3}	m
The blade chord length C	0.024	m
Number of blades n	7	
The suction slot diameter D_{ss}	3.2×10^{-4}	m

3. Experimental setup

3.1. Experimental model

A narrow wave tank was employed for experiments to facilitate wave propagation along a single primary axis. An internal width of 0.5 m was chosen to suppress complex effects in three dimensions and to ensure that waves behave as plane waves in accordance with mathematical model assumptions. Fig. 3 shows the geometry of the tank, including the plunger, the water level, and the propagation area. To ensure structural rigidity and to avoid mechanical vibrations, the apparatus uses a 4×4 cm steel box frame, while 10 mm thick tempered glass side walls allow for visual observation and data verification. The system features a total length of 3.3 m and a water depth of 0.5 m, which allows waves to develop fully before they interact with the test section. An oscillating water column chamber constructed from transparent mica is attached at the downstream end 0.3 m above the floor with an internal width of 0.45 m. Because the tank is limited in length, data regarding the elevation of the free surface is recorded continuously to capture the full evolution of the wave field. Data analysis focuses on a time window between 20 and 40 seconds after initial transients have passed and the wave field has

achieved stability. This technique provides stable wave amplitudes and periods for accurate comparison with the numerical model.

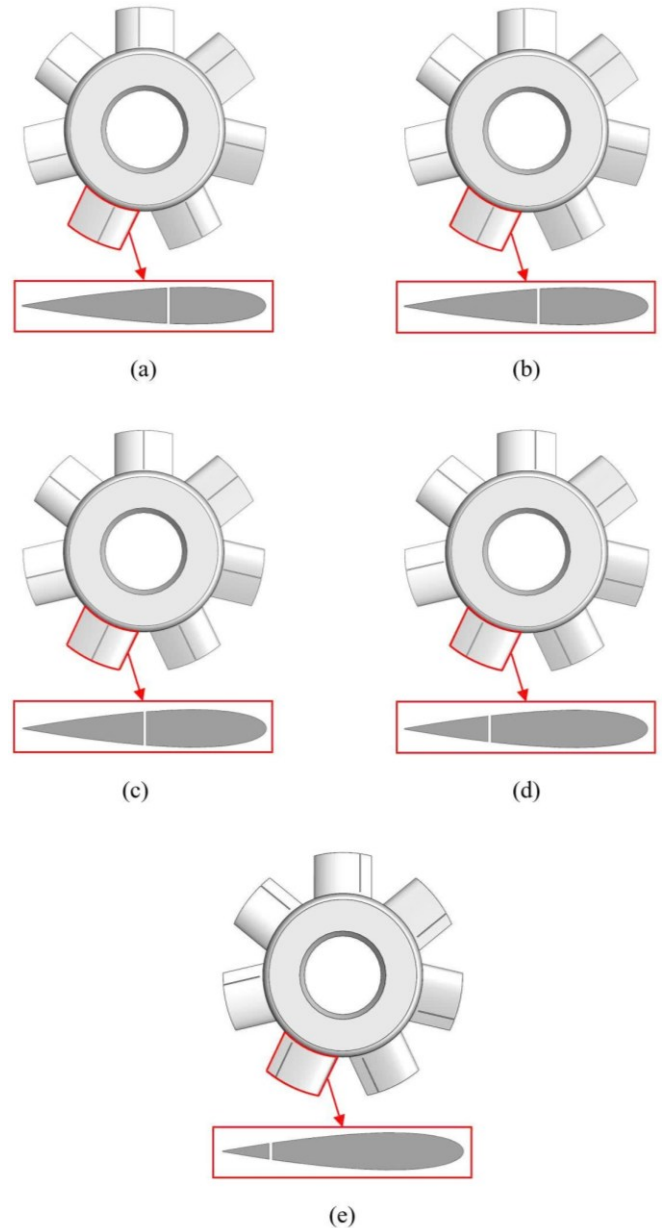


Fig. 2. Slotted Wells turbine models with varying L_{ss} values: (a) 40%, (b) 45%, (c) 50%, (d) 65%, (e) 80%.

In Fig. 3, the chamber is rectangular with a square cross-section of 0.45×0.45 m, positioned 0.3 m above the bottom of the tank. The air duct is a hollow cylindrical pipe with a diameter of 0.1 m, containing a turbine inside. Using 3D printing technology to fabricate turbine prototypes from PETG plastic, which has a density of 1016 kg/m³.

3.2. Measured quantities

The measurement system utilizes an industrial-grade ultrasonic sensor with a 10 Hz sampling rate (Fig. 3), providing the temporal resolution necessary for real-time waveform reconstruction. To isolate vertical wave displacement from horizontal oscillations or lateral motion, the reflective float is restricted by vertical guide rails. A lightweight plastic sphere, chosen for its superior wave-following performance, acts as the float; it offers a stable reflective surface that minimizes signal noise typically induced by wave profile slopes. This floating-element approach significantly improves measurement robustness in

ultrasonic level monitoring by maintaining a consistent tracking reference and mitigating the interference of surface ripples.

In this experiment, wind velocity is measured using an Extech AN200 anemometer with a measurement range of 0.4-30 m/s and an accuracy of $\pm 3\%$. The pressure drop is measured using an Extech HD755 differential pressure manometer with a range of 0-0.5 psi and an accuracy of $\pm 0.3\%$ full scale. Turbine angular speed is measured using a PCE-DT 65 tachometer with an optical measurement range of 2-99999 RPM and an accuracy of $\pm 0.05\%$ RPM (Table 2).

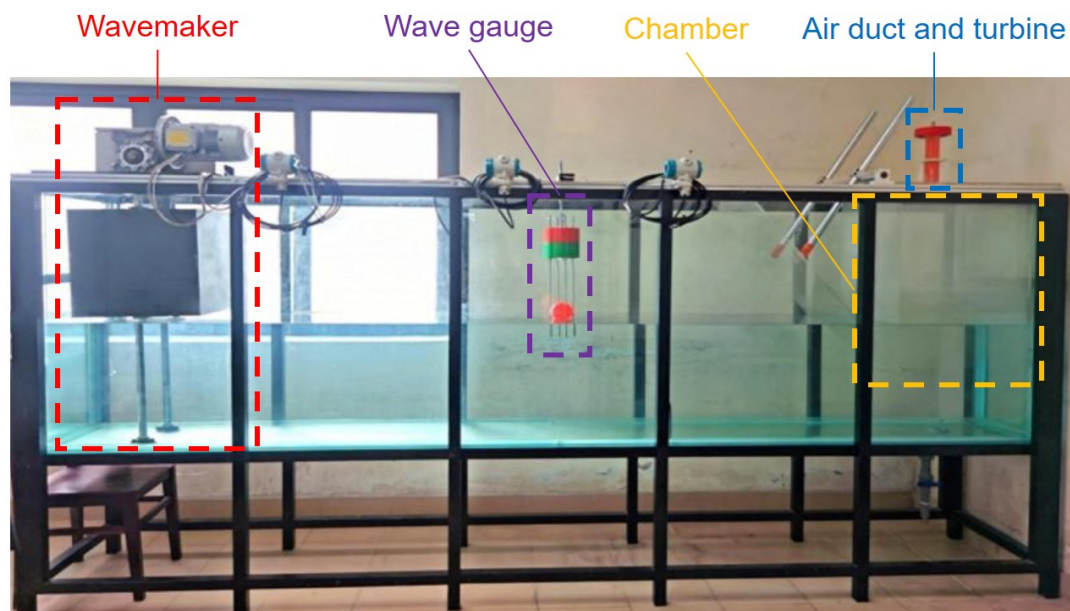


Fig. 3. OWC experimental model

Table 2. Measuring equipment

Measuring instruments	Name	Company	Measurement range	Accuracy	Standard
Wind velocity v	Extech AN200	Teledyne FLIR	0.4-30 m/s	$\pm 3\%$	NIST
Pressure drop Δp	Extech HD755	Teledyne FLIR	0-0.5 psi	$\pm 0.3\%$	NIST
Angular speed ω_t	PCE-DT 65	PCE Deutschland GmbH	2-99999 RPM	$\pm 0.05\%$	NIST

NIST: National Institute of Standards and Technology (USA)

When the air duct system stabilizes at a defined airflow velocity, the turbine rotor reaches a constant angular speed, where the angular acceleration vanishes. According to Newton's second law for rotation, the net torque is zero, implying the aerodynamic torque is perfectly

balanced by the internal mechanical friction torque ($T_t = T_{ms}$). Thus, by measuring the steady-state RPM using a PCE-DT 65 tachometer across various conditions, the actual aerodynamic torque can be explicitly derived from the shaft friction characteristic equation, previously calibrated via a

spin-down test:

$$T_t = T_{ms} = I\alpha \quad (16)$$

where I is the moment of inertia (kgm^2), and α is the angular acceleration (rad/s^2). An external air source is used to accelerate the turbine beyond its operating threshold. Once the source is cut off, the rotor is left to coast down, driven solely by internal mechanical friction. RPM data ω_t is recorded over time to determine the angular deceleration α as follows:

$$\alpha = \frac{d\omega_t}{dt} \quad (17)$$

3.3. Numerical simulation setup

The numerical model used in this study is developed based on the simulation framework and parameter settings reported in [15]. The simulation model, developed using ANSYS Fluent, is used to compare with the experimental model to check the accuracy of the experimental process. The geometric dimensions of the simulation model are given in Fig. 4.

Appropriate boundary conditions are applied to represent the physical behavior of the numerical

wave tank. The box-shaped wavemaker is modeled as a rigid body undergoing a prescribed vertical oscillatory motion and is implemented as a moving wall boundary condition through a user-defined function. The harmonic motion of the plunger is defined as $y(t) = S \sin(\omega t)$, where S (m) represents the stroke amplitude of the plunger, and ω (rad/s) denotes the angular frequency calculated as $\omega = 2\pi/T$, with T (s) being the target experimental wave period. For the numerical validation case, the specific input parameters were set to $T = 4$ s and $S = 0.15$ m to accurately reproduce the physical wave profile. This imposed motion drives the surrounding fluid and generates regular waves within the tank. The bottom and side walls of the tank are treated as stationary no-slip walls, while the upper boundary represents the air phase. The free-surface elevation is monitored using a wave level probe placed downstream of the wavemaker, which records the temporal variation of the water surface for subsequent analysis and validation.

4. Results and discussion

4.1. Validation experiment

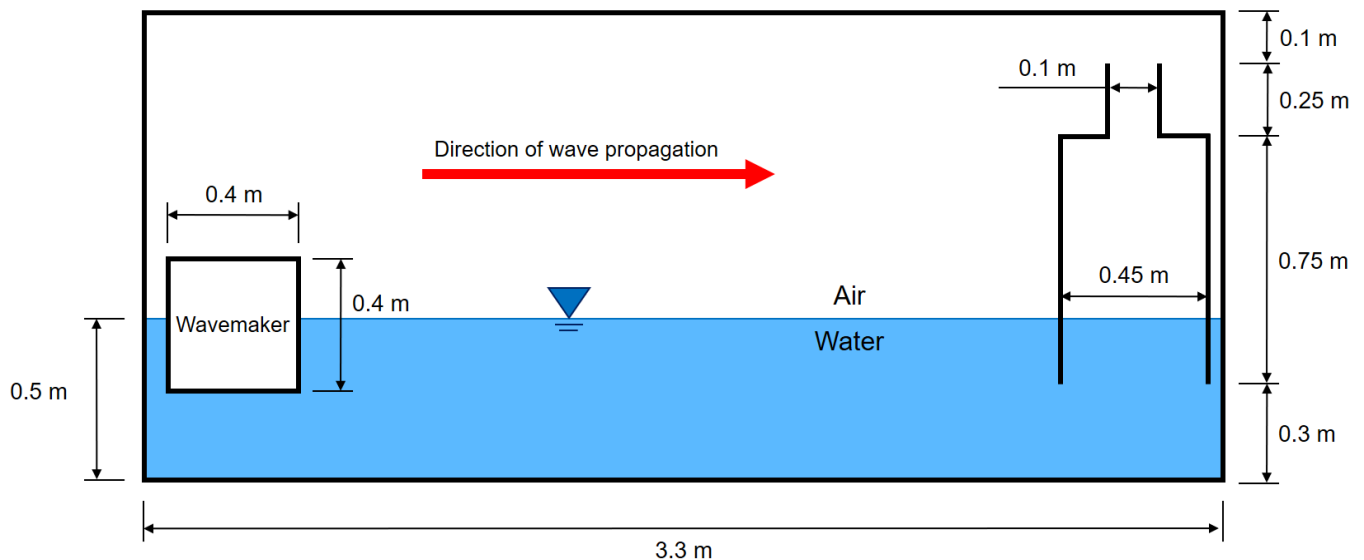


Fig. 4. Dimensions of the numerical wave tank with the box-shaped plunger wavemaker and OWC chamber

The experiment was conducted with a wave period of $T = 4$ s, yielding the wave heights shown in Fig. 5. Simultaneously, the wind velocity at the

air duct inlet was measured at $v = 0.91$ m/s in the absence of a turbine. These parameter values represent the average results obtained from five

measurements taken once the wave conditions reached a steady state.

As shown in Fig. 5, the experimental and numerical wave signals show strong correlation in both period and wave height. The slight

discrepancies observed at the peaks and troughs are mainly associated with measurement noise and finite tank effects. To improve data quality, a Kalman filter [16] was applied, effectively mitigating these disturbances.

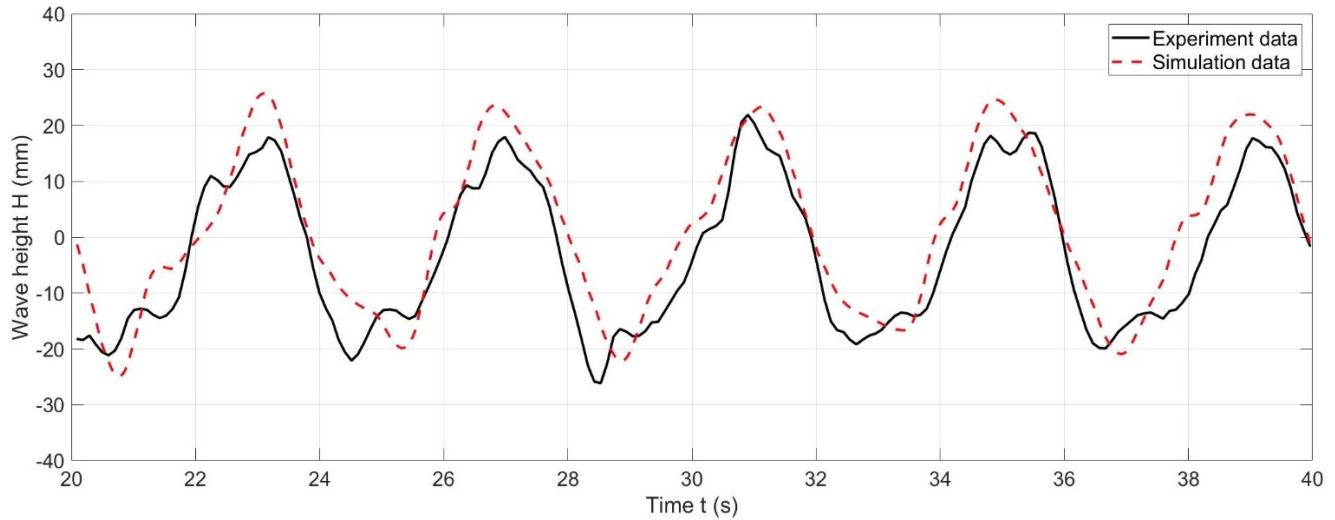


Fig. 5. Comparison of simulated and measured wave heights at $T = 4$ s.

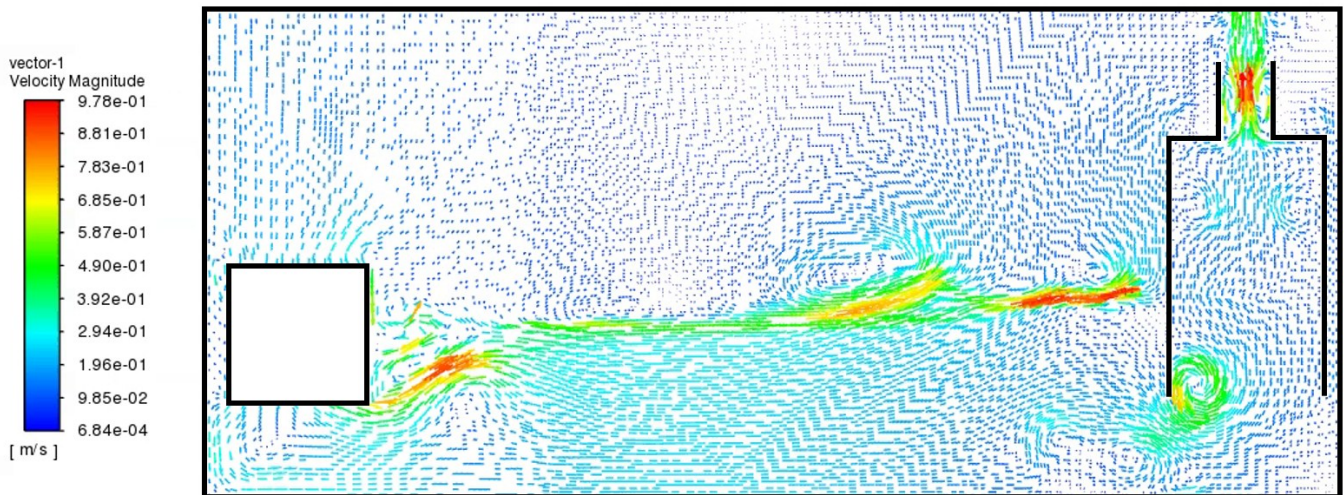


Fig. 6. Velocity field at $T = 4$ s.

Fig. 6 illustrates the velocity field of the OWC system obtained from CFD simulations. The simulated velocity at the air duct outlet is $v = 0.96$ m/s, representing a deviation of only 5.5% compared to experimental measurement. This high level of agreement successfully validates the numerical model against the experimental benchmark, providing a reliable basis for extracting the complex velocity field (Fig. 7).

4.2. Performance of the slotted Wells turbine

Following the validation of the experimental

reliability, measurements of wind velocity, turbine angular speed, and pressure drop were conducted for various turbine models at $T = 3.5$ s, $T = 4$ s, and $T = 5$ s.

4.2.1. Turbine angular speed and pressure drop

Fig. 7 and Fig. 8 illustrate the measurement results for turbine angular speed and pressure drop, respectively, across the various turbine models evaluated at time intervals of $T = 3.5$ s, $T = 4$ s, and $T = 5$ s. Upon analysis, it is evident that the values recorded at $T = 3.5$ s are significantly

higher compared to the data obtained at the other two time points.

This observed decline at larger wave periods T is attributed to the kinematic behavior of the oscillating water column. At longer wave periods, the lower oscillation frequency results in a slower vertical displacement rate of the water surface inside the chamber, thereby reducing the generated airflow rate and the resulting wind velocity within the air duct. This subsequently

causes both the turbine angular speed and the pressure drop to decrease accordingly. Moreover, a comparative assessment of the different designs reveals that the slotted Wells turbine model with $L_{ss} = 45\%$ exhibits the highest angular speed and pressure drop under typical operational wave periods $T = 3.5$ s and $T = 4$ s. At $T = 5$ s, the highest angular speed and pressure drop are recorded for $L_{ss} = 50\%$ and $L_{ss} = 80\%$, respectively, due to the modified low-flow aerodynamic response.

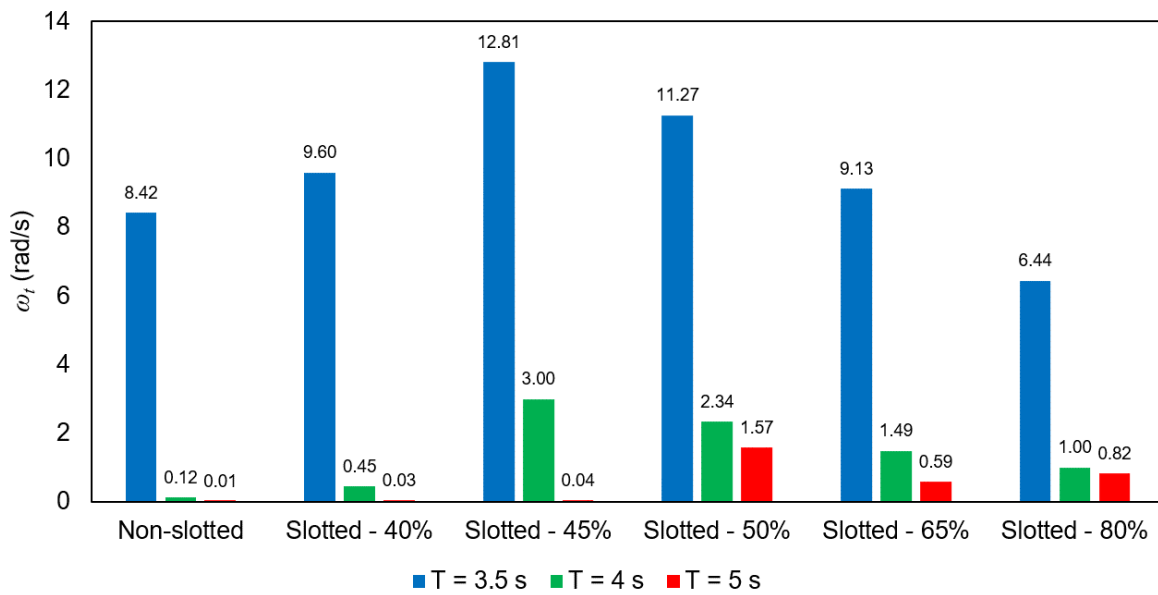


Fig. 7. Turbine angular speed for turbine models.

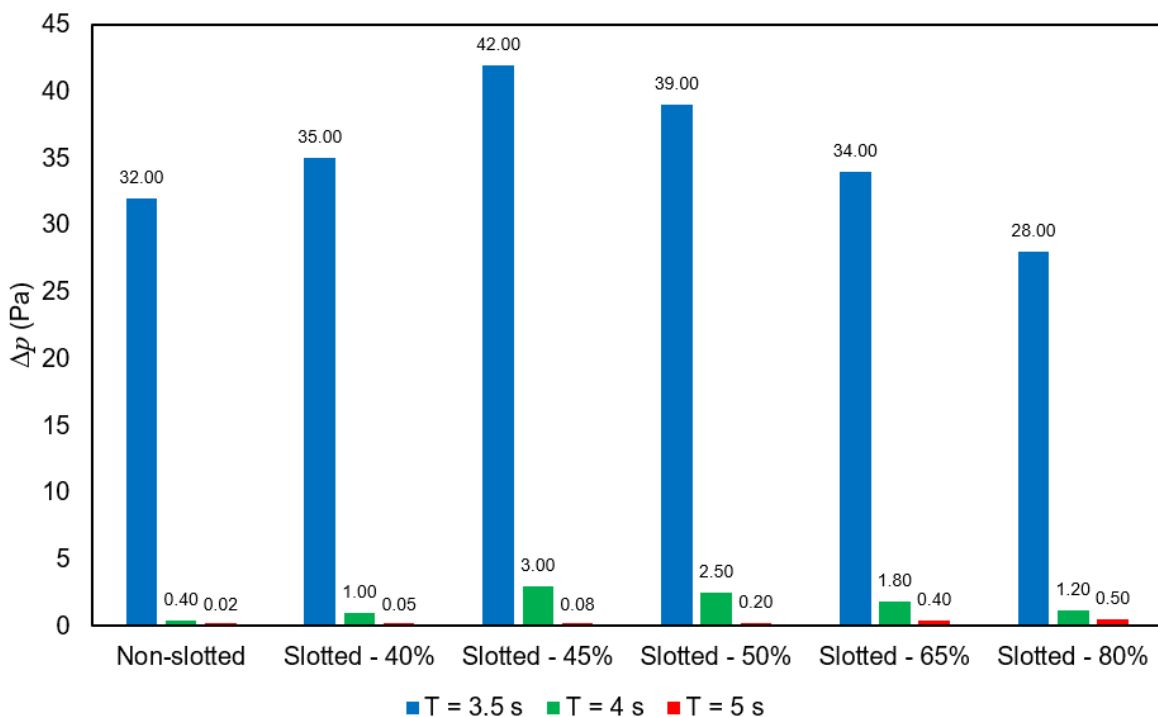


Fig. 8. Pressure drop for turbine models

4.2.2. Turbine torque and efficiency

Fig. 9 shows the acceleration α obtained from the spin-down test. Substitute the measured turbine angular speed values for each case into the approximation equation in Fig. 9 to calculate the corresponding α values. Since the slotted dimensions are very small, the moment of inertia I can be considered the same for all turbine models, with $I = 3.245 \times 10^{-5} \text{ kgm}^2$. Use Eq. (16) to calculate the turbine torque for the turbine models as shown in Fig. 10. Fig. 10 illustrates the variation of turbine torque, revealing that the torque value at $T = 3.5 \text{ s}$ is notably higher than those observed at $T = 4 \text{ s}$ and $T = 5 \text{ s}$. This discrepancy is directly attributed to the reduction in aerodynamic kinetic energy at longer wave periods, where the decrease in wind

velocity leads to a corresponding decline in the lift forces acting on the turbine blades. Specifically, at $T = 4 \text{ s}$ and 5 s , the generated aerodynamic lift is extremely weak and completely dominated by the inherent mechanical friction of the small-scale model, resulting in nearly identical minimal torque values. Furthermore, a comparative analysis demonstrates that the slotted Wells turbine model with $L_{ss} = 45\%$ exhibits a superior torque performance compared to the non-slotted turbine model, achieving an enhancement of 32.1%. These findings clearly indicate that the incorporation of the $L_{ss} = 45\%$ slot configuration significantly improves the operational performance of the Wells turbine when contrasted with the conventional non-slotted design.

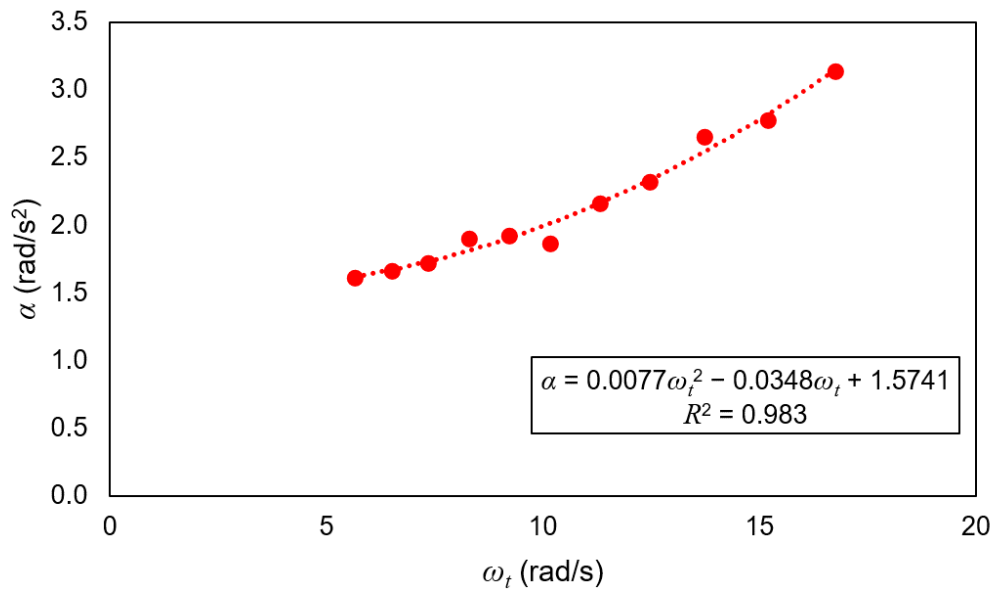


Fig. 9. Angular acceleration α from spin-down test.

The measured wind velocities in the air duct at $T = 3.5 \text{ s}$, 4 s , and 5 s are 3.15 m/s , 0.91 m/s , and 0.33 m/s , respectively. Use Eq. (15) to calculate the efficiency for the turbines. Fig. 11 illustrates the energy conversion efficiency η of the various turbine configurations across the three tested wave periods. The results demonstrate a consistent trend of efficiency enhancement across all models as the wave period T increases from 3.5 s to 5 s , confirming the improved energy extraction capability under conditions of greater wave oscillation amplitudes. Among the configurations,

the $L_{ss} = 45\%$ design demonstrates the most optimal and stable efficiency within the standard operating periods ($T = 3.5 \text{ s}$ and 4 s), benefiting from the suction slot placement precisely at the flow separation region, which effectively stabilizes the boundary layer. For the $L_{ss} = 65\%$ and 80% configurations at $T = 5 \text{ s}$, although the calculated efficiency values appear highest, these results are heavily influenced by operation at very low airflow rates, where the near-zero pressure drop (Δp), combined with low rotational speeds, approaches the sensitivity limit of the measurement

instrumentation, leading to mathematical error amplification in the efficiency calculation. Nevertheless, the positive performance variance in rotational speed for these configurations (particularly cases $L_{ss} = 65\%$ and 80%) at $T = 5$ s still underscores the superior self-starting and low-speed rotation capabilities facilitated by the

asymmetric pressure distribution mechanism, even under limited aerodynamic power. Consequently, the $L_{ss} = 45\%$ configuration is confirmed as the optimal design, ensuring the best equilibrium between torque maintenance and overall operational stability throughout the full range of experimental conditions.

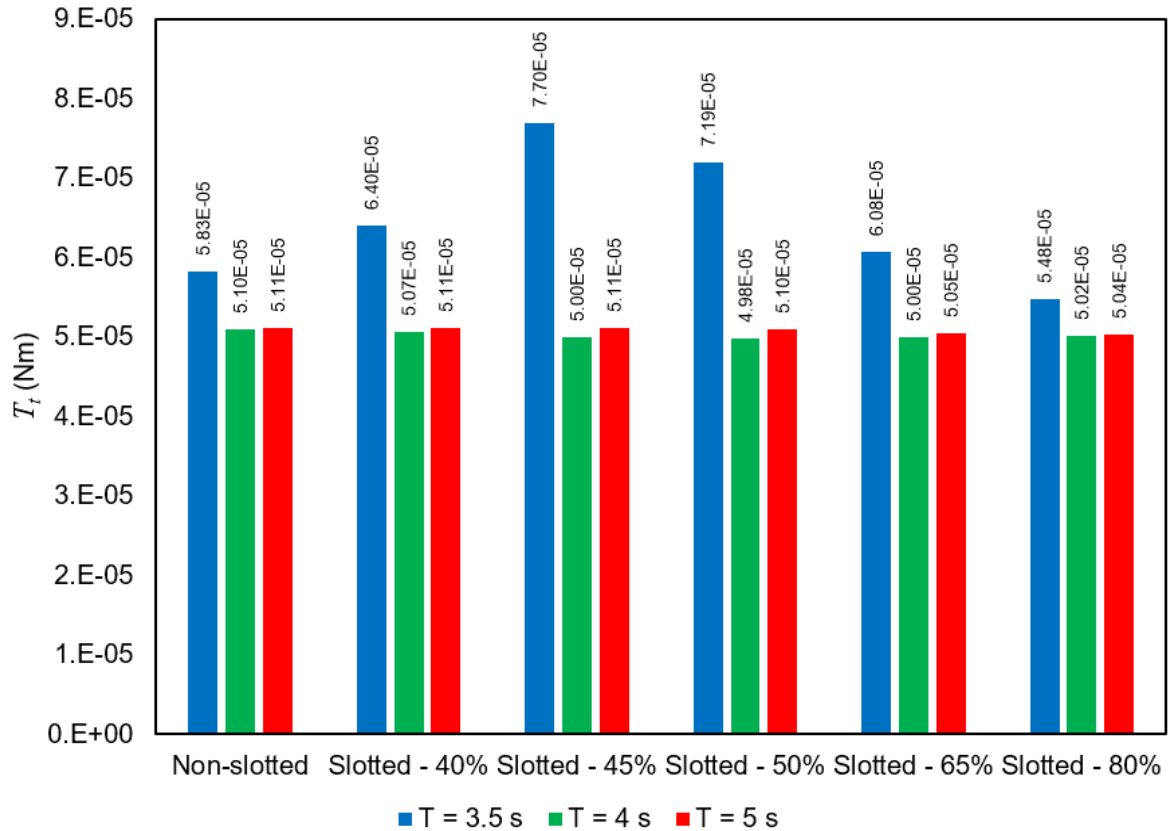


Fig. 10. Turbine torque for turbine models.



Fig. 11. Efficiency for turbine models.

5. Conclusions

This study has successfully evaluated the reliability of the OWC experimental results, demonstrating a high degree of correlation with numerical data, evidenced by a very small margin of error when compared to the CFD simulations. Furthermore, the slotted Wells turbine models demonstrate enhanced aerodynamic performance compared to the conventional Wells turbine design, particularly in terms of torque output and operation under primary wave regimes $T = 3.5$ s and $T = 4$ s. In particular, the turbine configuration with an L_{ss} ratio of 45% provides the most significant operational advantages within these periods. However, under long-period wave conditions $T = 5$ s, efficiency variations across configurations become sensitive to minimal pressure differentials and mechanical friction, indicating that the aerodynamic superiority of slotted blades is strongly dependent on the operating wave period. Despite these findings, this study is subject to certain limitations, as it did not account for complex, irregular wave conditions or the influence of various external forces and hydrodynamic interactions. Consequently, future research is necessary to address these complexities and to further optimize the turbine design for broader, more realistic oceanic applications.

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Declaration of Generative AI

During the preparation of this work, the

authors do not use Generative AI and AI-assisted technologies tools in order to generate the content of the manuscript.

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