Paper ID #52501

Hands-on Mechanics Learning through the Design and Testing of an Oscillating Water Column Wave Energy Converter in a Senior Capstone Project

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Abstract

This paper presents the design, fabrication, and educational implementation of an Oscillating Water Column (OWC)-based wave energy converter developed through a two-year senior capstone project at North Carolina A&T State University. The project integrates principles of fluid mechanics, dynamics, and structural design to create a hands-on learning experience for undergraduate students. The OWC system features a serpentine chamber and an axial impulse turbine, which were designed and fabricated by students to investigate airflow characteristics and turbine performance under controlled wave conditions. Through experimental testing in both laboratory-scale and large-scale wave tank environments, students collected and analyzed real-time flow velocity and turbine speed data to understand fluid-structure interactions, resonance effects, and energy conversion mechanisms. An initial small-scale prototype exhibited limited performance due to scale constraints, which was intentionally used as an instructional pivot toward a justified scale-up and successful large-scale testing. Beyond its technical outcomes, the project provided a platform for experiential learning—enhancing students' understanding of applied mechanics, instrumentation, and data acquisition while fostering teamwork and design thinking. Educational impact was evaluated using a structured capstone assessment framework aligned with ABET outcomes, incorporating milestone reviews, faculty committee feedback, peer evaluation, and artifact-based performance evidence. The paper details both the technical system development and the structured educational assessment model, offering a replicable framework for integrating wave energy systems into undergraduate mechanics curricula.

I. Introduction

The global demand for renewable and sustainable energy sources has led to growing interest in wave energy, an abundant yet underutilized resource. Unlike solar and wind, ocean waves exhibit high energy density and greater predictability over short time scales, making them ideal candidates for complementary integration into coastal energy systems. Among the diverse wave energy technologies, Oscillating Water Column (OWC) devices have emerged as one of the most mature and scalable solutions. OWC systems capture the heave motion of ocean waves by enclosing a volume of air above a water column inside a partially submerged chamber Ref [1]. As waves propagate, the rising and falling water level compresses and decompresses the air column, generating a bidirectional airflow that can be harnessed by a self-rectifying air turbine to produce mechanical or electrical power Ref [2-5].

At North Carolina A&T State University (NCAT), this wave energy concept was implemented in a two-year undergraduate capstone project designed to offer engineering students hands-on experience in renewable energy system development. The project aimed not only to educate but also to experimentally validate key principles of wave energy conversion. Supported by collaboration with the Coastal Studies Institute (CSI), students were able to extend their lab-scale prototype testing to a larger wave tank facility with programmable wave conditions, bridging the gap between theoretical modeling and experimental performance evaluation. This partnership significantly enhanced the fidelity and scalability of testing conditions and provided a platform for collecting high-quality sensor data under realistic wave forcing.

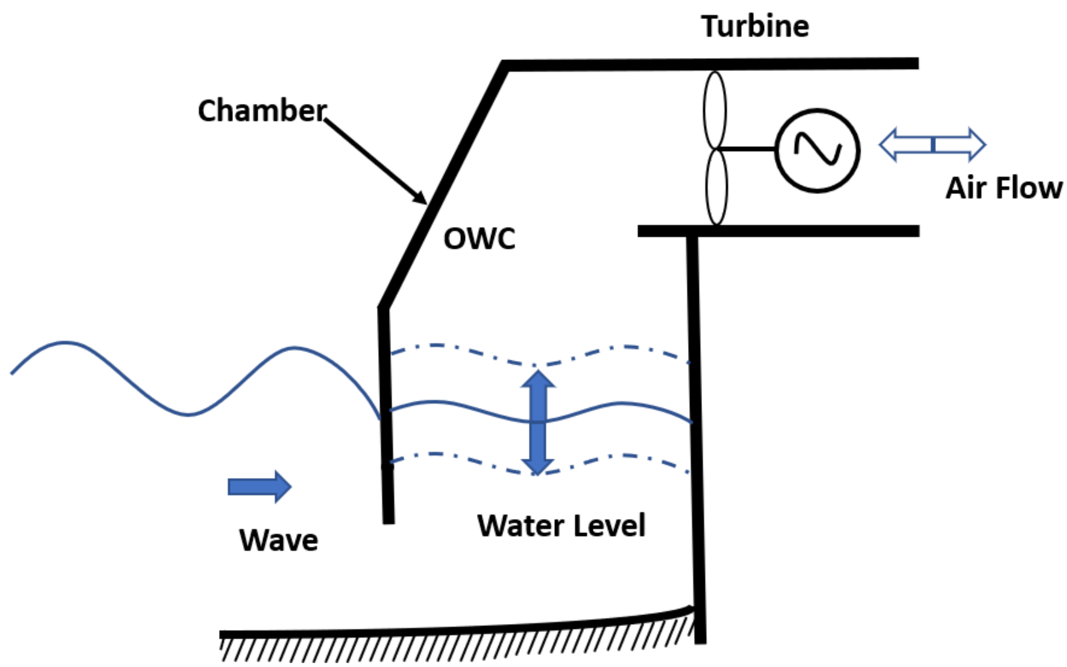

Fig. 1 Schematic Representation of OWC.

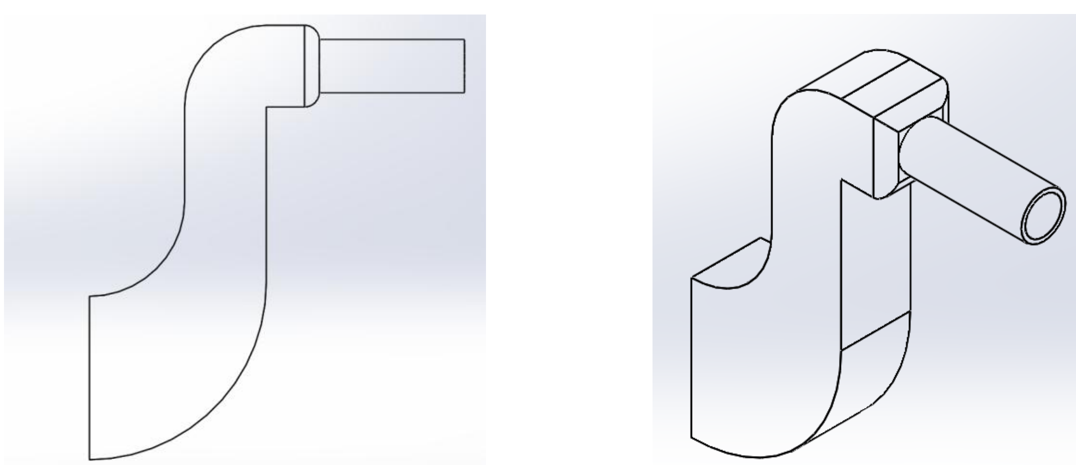

Fig. 2 NCAT OWC Exterior Design CAD Drawings, Front View (Left) and Isometric 3D View (Right).

A central innovation in the project was the design and fabrication of a serpentine-shaped OWC chamber, informed by prior computational fluid dynamics (CFD) studies conducted by our research group [6]. This chamber geometry was intended to enhance resonance behavior and airflow stability by extending the air path and reducing chaotic vertical structures [7-9]. The design aimed to more effectively compress air during wave surges, which is critical for maximizing pressure-driven turbine output [10]. The chamber was fabricated from transparent polycarbonate for educational visibility and iterative testing of airflow dynamics.

To convert airflow into usable mechanical energy, an axial-flow impulse turbine was chosen based on its superior characteristics in bidirectional flow environments. Unlike the commonly used Wells turbine, which suffers from flow separation and performance losses during airflow reversals, the impulse turbine maintains continuous unidirectional rotation, thereby eliminating efficiency-degrading dead zones. This choice aligns with recent studies suggesting that impulse turbines provide a broader operating envelope and are better suited to fluctuating pressure conditions inherent in real wave environments [11].

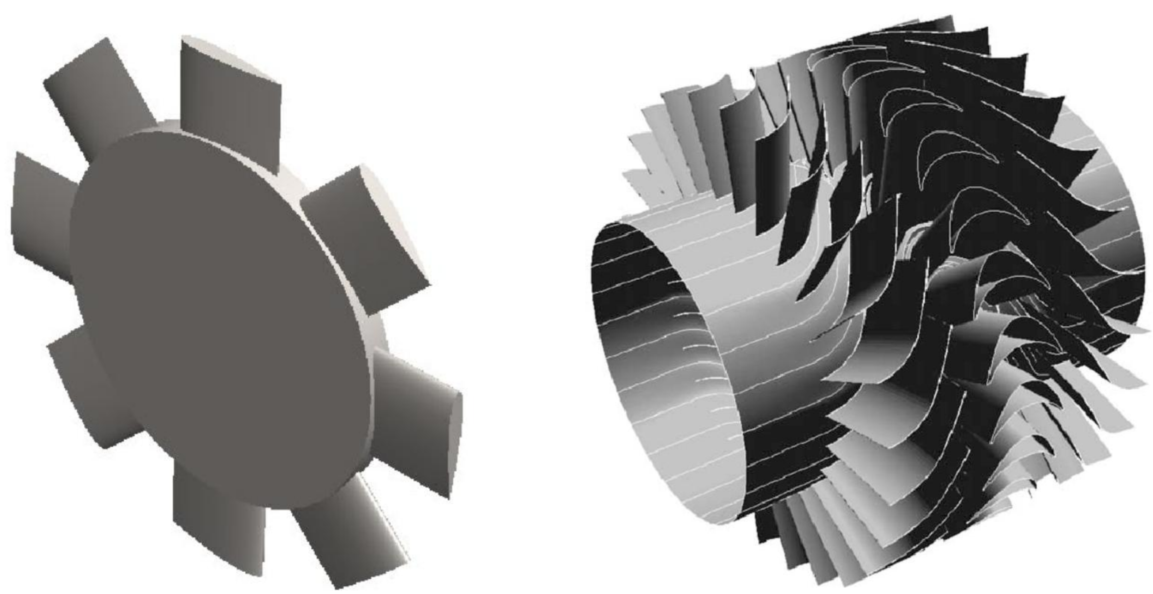

Fig. 3 CAD model of the Wells turbine (Left) and Bi-direction Impulse Turbine (Right).

A key technical advancement in the second year of the project was the integration of a high-precision torque and RPM sensor onto the turbine shaft. This required custom coupling design and careful mechanical alignment, enabling real-time acquisition of performance data under dynamic flow conditions. Complementing this, an anemometer was installed at the air outlet to measure instantaneous airflow velocities in both turbine and non-turbine configurations. These combined measurements allowed students to quantify not only turbine speed but also the overall effectiveness of the OWC system as an energy conversion platform [12-14].

Testing was conducted at two different scales. Preliminary validation was performed in NCAT's small in-house wave tank to verify sensor function, turbine startup response, and airflow behavior. More rigorous experiments were then carried out at the Coastal Studies Institute (CSI) using a programmable large-scale wave tank. Under optimal wave conditions—a period of 1.5 seconds and a wave height of 0.125 m, the turbine achieved rotational speeds exceeding 9,000 RPM, a performance level not attained in earlier capstone iterations. Peak airflow velocities were also recorded at the chamber outlet, confirming the chamber's ability to generate high-quality pneumatic flow suitable for energy harvesting.

This work demonstrates how a student-led capstone project can serve as an effective experimental platform for investigating small-scale wave energy system behavior. The results validate the performance of serpentine chambers in stabilizing airflow and support the continued use of impulse turbines in variable wave conditions. Future iterations of the system will explore turbine-generator coupling, refined flow modeling via CFD, and the development of a field-deployable prototype.

To facilitate high-fidelity wave energy testing, the project leveraged a modular, open-channel wave tank system developed by OMEY Labs Ltd and hosted at the Coastal Studies Institute (CSI). This facility, designed for both research and educational purposes, offers a scalable and cost-effective alternative to large-scale offshore deployments. The wave tank is composed of multiple 2-meter-long welded steel tank modules, with end caps and a dry-back hinged paddle wave maker, allowing for versatile wave condition generation. Transparent side panels made of toughened glass provide full-length visibility for flow diagnostics and educational demonstration.

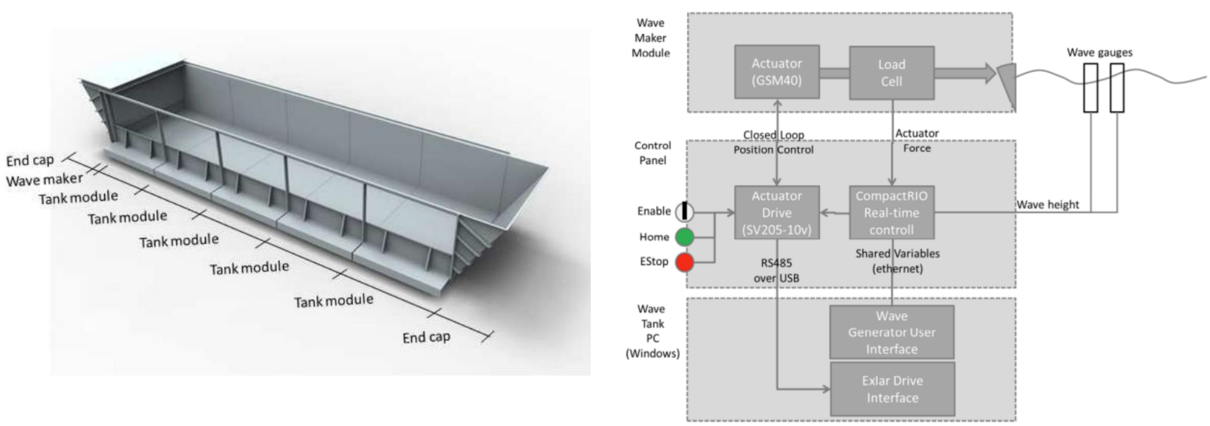

Fig. 4 Wave Tank Package Overview (Left) & Functional Architecture Block Diagram (Right).

The wave maker system is actuated via an Exlar GSM40 linear actuator integrated with a load cell for force feedback and controlled in real time using a National Instruments CompactRIO platform. The control system operates on LabVIEW-based closed-loop PID control, interfacing with a dedicated Windows PC through RS485-over-USB communication. A user-friendly interface allows researchers and students to configure wave spectra (regular or irregular), monitor actuator stroke and velocity, and collect wave gauge data in real time. Safety and reliability are ensured through a multi-tier control scheme, including hardware emergency stops and software ramp-down routines.

This experimental setup enabled precise and repeatable wave generation with periods ranging from 0.5 to 2.0 seconds and wave heights up to 0.2 meters. The tank was critical for validating the performance of the OWC prototype under controlled conditions. Both wave elevation and turbine response (in RPM and torque) were monitored during multiple test sequences, contributing to a robust data set that reflects realistic dynamic forcing conditions. The collaboration with CSI allowed the student team to transcend traditional lab limitations, reinforcing the value of multi-institutional partnerships in applied renewable energy research.

Beyond its technical goals, this two-year senior capstone project was intentionally designed as a hands-on mechanics learning experience for undergraduate students. The primary educational objectives were to: (1) enable students to apply core fluid mechanics and dynamics concepts to a real-world, unsteady energy system; (2) develop competency in experimental design, instrumentation integration, and data acquisition for coupled fluid–structure systems; and (3) foster engineering judgment through iterative design, testing, and redesign across multiple semesters. Importantly, the project was structured to intentionally allow students to encounter early-stage experimental failures, particularly due to scale limitations, and to use these outcomes as learning opportunities rather than stopping points. By embedding these objectives within a renewable energy context, the project aimed to bridge theoretical mechanics coursework with authentic engineering practice. Across two academic years, 13 senior mechanical engineering students contributed to the development, redesign, and testing of the system. Students were directly responsible for CAD modeling, chamber fabrication, turbine assembly, sensor integration, wave tank testing, and data analysis.

II. Governing Equations and Methodology

This section introduces the theoretical framework and simplified analytical models used to interpret the experimental performance of the Oscillating Water Column (OWC) system developed in this capstone project. While the system was primarily evaluated through hands-on testing, we applied basic conservation laws to estimate wave power input, airflow energy, turbine shaft power, and conversion efficiencies. These formulations helped contextualize measured results such as airflow velocity and turbine RPM, Ref [15].

A. Wave Power Estimation

The theoretical power available in an incoming wave train per unit width of wave front can be approximated using the deep-water wave energy equation:

$$P_w = \frac{1}{8}\rho g H^2 c_g \quad Where\ c_g = \frac{gT}{4\pi} \tag{1}$$

In this equation, ρ represents the water density, taken as approximately 1000 kg/m^3; g is the gravitational acceleration, 9.81 m/s^2; H is the wave height in meters, and T is the wave period in seconds. The group velocity c_g, which accounts for the energy transport speed of the wave packet, is calculated under the deep-water assumption. Wave heights and periods were controlled and monitored using the programmable wave maker system at the Coastal Studies Institute (CSI).

B. Airflow Velocity and Pneumatic Power

As waves induce vertical oscillations of the water surface within the chamber, the resulting air displacement creates a bidirectional flow through the turbine duct. The air velocity, u_a, was experimentally measured using a handheld anemometer positioned near the chamber outlet in the no-turbine configuration. Assuming quasi-steady, incompressible flow and negligible pressure losses prior to the turbine, the pneumatic power delivered by the airflow can be estimated as:

$$P_{air} = \frac{1}{2}\rho_a A u_a^3 \quad (2)$$

Here, ρ_a denotes the air density, taken as 1.2 kg/m³, A is the cross-sectional area of the turbine inlet duct, and u_a is the measured air velocity. This relation provides a useful estimate of the kinetic energy available to drive the turbine.

C. Shaft Power Calculation

To quantify the mechanical output of the turbine, a torque and RPM sensor was installed in line with the turbine shaft. Shaft power was computed using the relationship:

$$P_{shaft} = \tau \cdot \omega = \tau \cdot (\frac{2\pi \cdot RPM}{60}) \quad (3)$$

In this expression, τ is the torque measured in newton-meters, and ω is the angular velocity in radians per second, derived from the measured revolutions per minute (RPM). These values were collected in real time, allowing direct calculation of the instantaneous shaft power under various wave conditions.

D. Energy Conversion Efficiencies

To assess the system's performance, two primary efficiency metrics were employed. The air-to-shaft efficiency, η_{as}, evaluates how effectively the airflow's kinetic energy is converted into useful mechanical power by the turbine. It is defined as:

$$\eta_{as} = \frac{P_{shaft}}{P_{air}} \quad (4)$$

Additionally, the overall wave-to-shaft efficiency, η_{total}, offers a theoretical assessment of how much of the incoming wave energy is ultimately transferred to the turbine shaft. It is given by:

$$\eta_{total} = \frac{P_{shaft}}{P_W \cdot W} \quad (5)$$

In this formulation, W represents the effective width of the incident wave front interacting with the chamber, approximated by the chamber width in our test setup.

E. Notes on Measurement and Application

Wave conditions, including height and period, were preset using the CSI's programmable control interface. Air velocity measurements were collected during no-load (no-turbine) tests to evaluate the chamber's intrinsic airflow-generating capability, while torque and RPM were recorded during turbine-on conditions to measure actual mechanical output. These simplified equations were not used for prediction but rather to interpret experimental trends, validate chamber and turbine design choices, and guide discussion of performance-limiting factors [16].

III. OWC Chamber Design and Instrumentation Integration

To facilitate effective airflow generation and enhance pressure differentials within a compact footprint, the Oscillating Water Column (OWC) system in this project was designed around a vertically mounted, serpentine chamber. The design process was influenced by prior computational studies conducted by our research group, particularly the investigation into duct geometry and chamber shape reported in Ref [6].

These studies found that modifying the chamber's internal flow path can significantly affect pneumatic output, as geometric resonance between wave excitation and internal air volume dynamics plays a major role in the system's overall efficiency [17-20]. Based on this, a vertically oriented serpentine chamber was chosen for its dual benefit: elongating the effective path length without increasing the physical footprint, and maximizing the volume of compressible air above the water column [21, 22].

Figure 5 shows the mounted prototype in the wave tank at the Coastal Studies Institute (CSI), where the OWC chamber is partially submerged. The curved aluminum housing at the top contains both the impulse turbine and instrumentation used for airflow energy conversion and measurement. The chamber was designed to support visible oscillation of the internal water surface, which acts as a piston compressing and decompressing the air above. This vertical displacement leads to bidirectional air movement through the top duct, enabling energy transfer via the turbine.

A. Original Chamber Design

The initial chamber was constructed primarily from transparent polycarbonate sheets, enabling full visibility of the internal air–water interface during operation. Its design was guided by the objective of maximizing both educational clarity and experimental repeatability. The overall structure measured approximately 47 inches in vertical height, with a curved path that extended horizontally by about 40 inches from inlet to outlet, as illustrated in Figure 5. The chamber cross-section was rectangular, measuring 16.7 inches in height and 7.9 inches in width. These dimensions were chosen to accommodate a water volume sufficient to respond dynamically to waves in the CSI tank, while remaining compatible with standard support structures for safe mounting.

Fig. 5 The Mounted Prototype in the Wave Tank at the Coastal Studies Institute (CSI).

The serpentine geometry was adapted from the multi-plane curved design explored in prior CFD work [23-26], where it was shown that adding duct curvature and offset between inlet and outlet improved airflow rectification and allowed pressure to build more efficiently. In our physical model, the curvature was achieved by bonding laser-cut panels and incorporating a semi-circular end cap to transition between vertical and horizontal segments. This configuration allowed for resonance tuning through geometry alone, without the need for mechanical valves or active flow control systems.

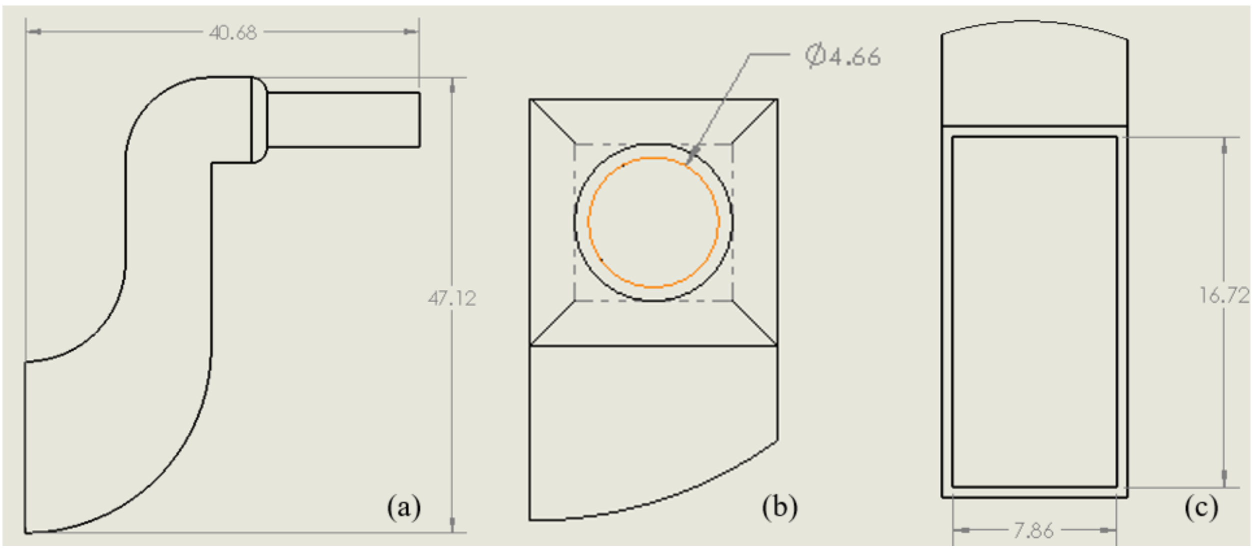

Fig. 6 Dimensions of the NCAT OWC Chamber Prototype: (a) Side view showing the overall chamber height (~47.1 in) and length (~40.7 in); (b) Outlet view showing the circular air duct with a diameter of 4.66 in; (c) Inlet view showing the rectangular water intake with dimensions of 16.72 in (height) × 7.86 in (width).

The chamber's outlet was fitted with a cylindrical transition piece (diameter 4.66 inch) leading into a removable turbine housing. This modularity allowed the system to operate in both turbine-on and turbine-off modes for comparative testing of airflow and mechanical output. The chamber was supported above the CSI wave tank using adjustable C-clamps and reinforced rails, ensuring both stability and positional flexibility during experiments.

B. Challenges from First-Year Testing

The initial phase of testing during the first year of the project revealed several limitations related to scale, instrumentation, and environmental conditions. The first version of the OWC prototype, shown in Figure 7(a–c), was constructed using laser-cut polycarbonate panels and 3D-printed components for the air nozzle, turbine hub, and guide vane supports. While this setup provided a modular and lightweight platform for early experimentation, the NCAT wave tank—narrow and limited in wave energy—posed inherent constraints on the usefulness of data collected from this model.

To address these challenges, second-phase experiments were conducted at the Coastal Studies Institute (CSI), where a large programmable wave tank enabled the use of a full-scale chamber under more realistic ocean-like conditions in Ref [27, 28]. However, new obstacles emerged during testing at CSI. While the large-scale prototype offered improved dynamic excitation, the inclusion of a bidirectional impulse turbine significantly obstructed visual and instrument-based access to the rotor region. The turbine housing, necessary for airflow channeling and structural support, limited visibility and made it difficult to verify operational characteristics such as blade motion, torque onset, and stall behavior. This problem was compounded by the fact that the impulse turbine's design, inspired by Ref [11], is inherently optimized for steady aerodynamic performance but not for easy visual observation or sensor mounting.

To circumvent these issues, the team focused the first round of CSI testing on the chamber operating without the turbine installed, thereby isolating and quantifying the airflow capacity of the chamber itself. These no-load tests offered clearer insight into the pressure response of the chamber under varying wave heights and periods. An anemometer was mounted at the air outlet to record instantaneous airflow velocity. The complete results from this testing phase are summarized in Table 1.

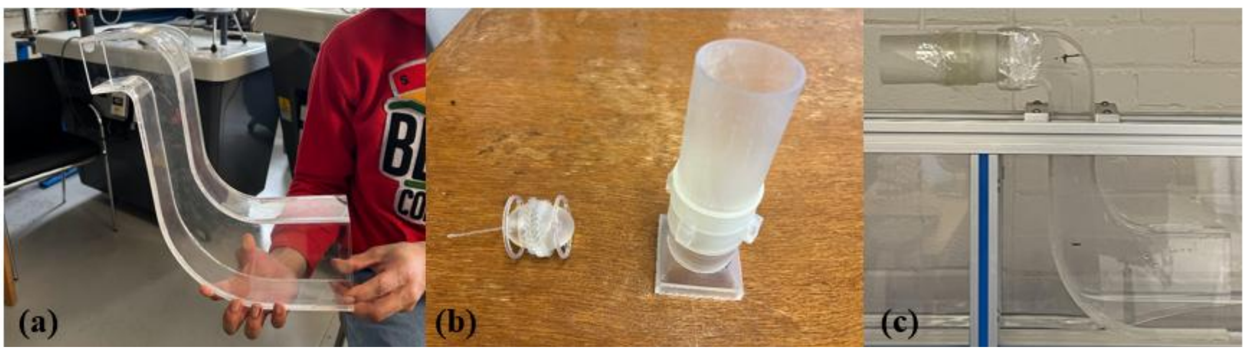

Fig. 7 Fabricated Components of the Small-scale OWC Prototype Used for Initial Testing at NCAT: (a) Transparent serpentine OWC chamber constructed from laser-cut polycarbonate sheets; (b) 3D-printed impulse turbine rotor and nozzle assembly; (c) Assembled small-scale prototype mounted on the NCAT in-house wave tank.

As shown, the highest velocity recorded was 9.6 m/s, occurring at a wave period of 1.5 seconds and a wave height of 0.125 meters, indicating a strong resonance condition between the wave forcing and the air volume in the chamber. This trend was consistent across multiple test runs and confirmed the chamber's potential as an effective air compression device even without turbine load. These measurements provided essential boundary conditions for the next round of turbine-integrated testing.

Moreover, these results aligned closely with predictions from previous studies of impulse turbine performance, which indicate optimal operation when the input air velocity ranges between 6–10 m/s under alternating flow conditions. The chamber, therefore, demonstrated capacity to serve as a viable input device for further turbine and generator coupling, with sufficient dynamic range for system optimization and performance mapping.

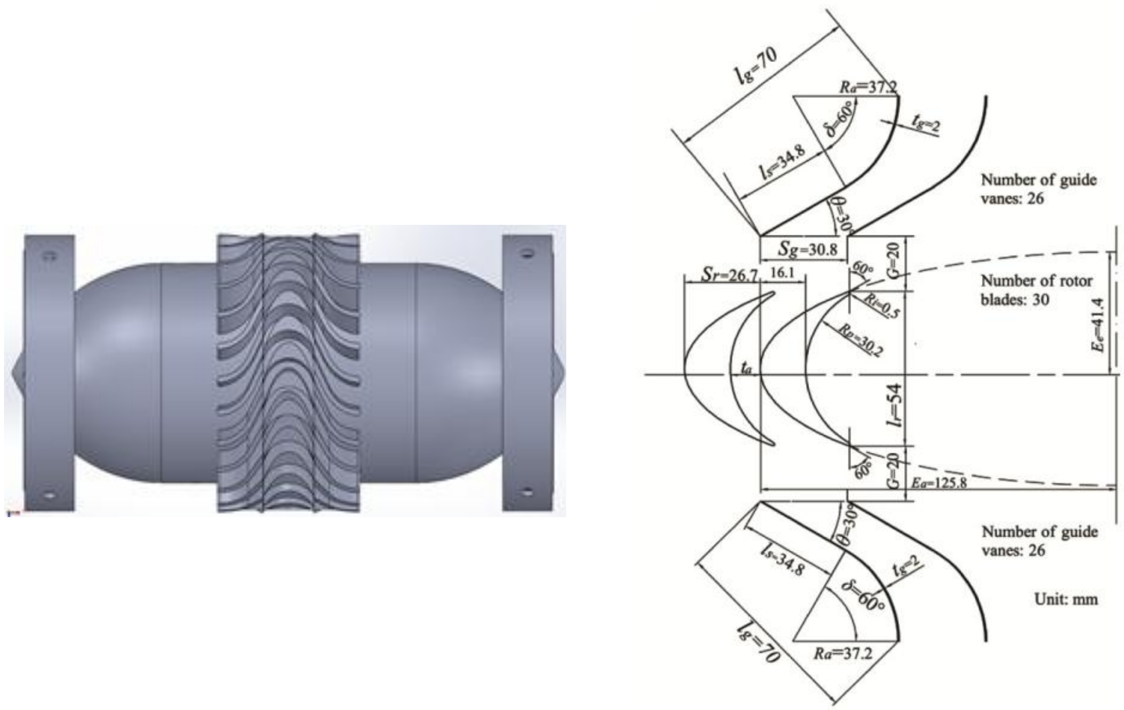

Fig. 8 Impulse Turbine Design Used in the NCAT OWC Prototype and Reference Design from Literature. (Left) 3D CAD model of the impulse turbine designed at NCAT, based on published specifications; (Right) Reference schematic of an axial-flow impulse turbine from Liu et al. (2017), showing rotor and guide vane geometry.

Table 1. Prototype without Turbine.

Wave Period (Sec)	Wave Height (m)	Velocity (m/s, min-max)
1	0.05	0.1
	0.08	0.8
	0.1	0.6-1.1
	0.125	2.2
1.2	0.05	0.4-0.5
	0.08	1.0-2.4
	0.1	2.4-3.8
	0.125	3.8-4.2
1.4	0.05	1.4-3.6
	0.08	3.6-5.9
	0.1	3.8-6
	0.125	4.8-6.4
1.5	0.05	3.8-5.4
	0.08	4.2-7
	0.1	5.4-7.8
	0.125	5.7-9.6
1.6	0.05	3.4-4.3
	0.08	3.1-6.2

	0.1	4.6-7.4
	0.125	6.4-8.6
1.8	0.05	0.6-1.1
	0.08	2.5-4
	0.1	4.1-5.5
	0.125	3.8-5.6

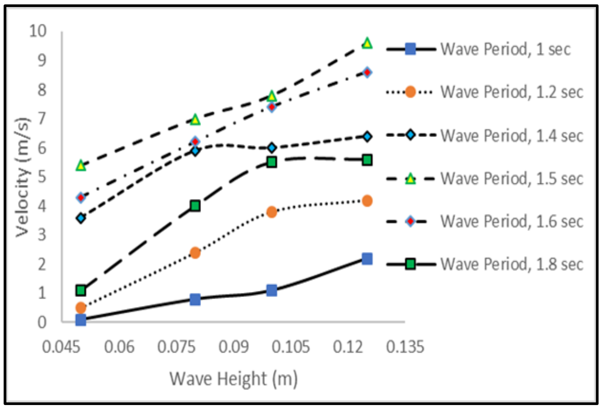

Fig. 9 Experimental Results Showing Velocity vs Wave Height for Various Wave Periods.

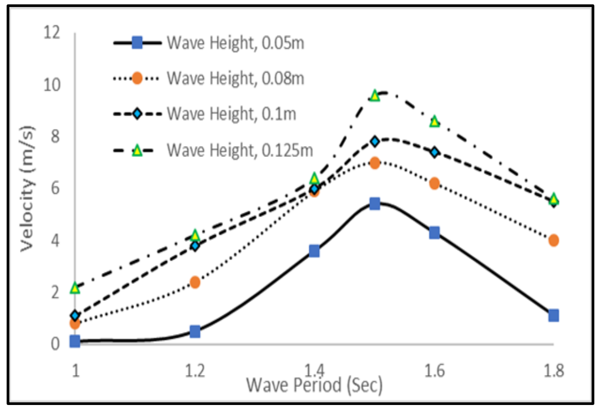

Fig. 10 Experimental Results Showing Velocity vs Wave Period for Various Wave Heights.

The data collected also helped the team identify mechanical and structural shortcomings in the early prototype. For example, the use of 3D-printed turbines led to subtle asymmetries and strength limitations that made them unsuitable for higher RPM operation. Additionally, limited internal access to the turbine housing constrained the placement of torque sensors and introduced noise into RPM measurements. These challenges provided critical insight that directly informed the second-year redesign, which prioritized modular turbine mounting, improved flow routing, and sensor integration—topics addressed in the next section.

C. Redesigned Structure for Instrumentation Integration

Building on the lessons learned during first-year testing, the second phase of this project prioritized the development of a robust and transparent structure capable of supporting real-time turbine performance monitoring. A key shortcoming identified earlier was the inability to reliably measure turbine RPM and torque due to poor accessibility, low visibility, and unstable mechanical interfaces. To address these issues, the chamber-turbine system was completely redesigned with modular instrumentation integration in mind.

The updated design, shown in Figures 11 and 12, includes a fully exposed instrumentation chain that connects a 3D-printed bi-directional impulse turbine to a dynamic torque and RPM sensor. The turbine is mounted on a central shaft and aligned using a custom fixture to minimize radial runout and mechanical losses. The torque sensor was selected based on its real-time digital output capability, compatibility with DAQ hardware, and rated range suited for expected torque levels. This configuration allowed precise measurement of shaft angular velocity and load resistance, both of which are critical for calculating power output and system efficiency.

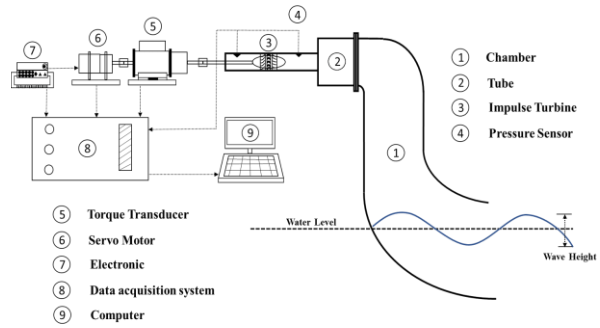

Figure 11. Torque and RPM Sensor Instrumentation Block Diagram Showing DAQ Connections for Turbine Testing.

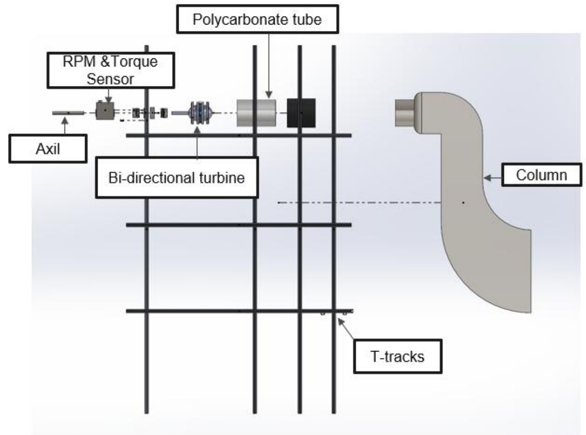

Figure 12. SolidWorks Model of the Redesigned OWC–Turbine Assembly with Instrumentation: Including the Bi-directional Impulse Turbine, Polycarbonate Duct, and Torque Sensor, all Mounted Using Modular T-track Supports.

A significant material change was made to improve visibility and facilitate visual inspection during operation. While the original air duct was made of opaque aluminum, the revised version replaced this section with a transparent polycarbonate tube. Polycarbonate was chosen after a comparative evaluation (as shown in the design matrix from the team's presentation) for its balance of optical clarity, impact resistance, and chemical stability. This transparency allowed observers to visually confirm turbine rotation during airflow pulses and ensured easier alignment of optical or mechanical sensors.

To physically secure the entire system within the large-scale wave tank at the Coastal Studies Institute (CSI), the mounting framework was fully redesigned using T-tracks and modular aluminum extrusions. This approach replaced prior ad hoc clamping with a lightweight but rigid structure that could accommodate various vertical heights and component spacing. The turbine module, air duct, and chamber outlet were all mounted on adjustable vertical tracks, simplifying reassembly and improving alignment accuracy across testing sessions.

The complete instrumentation integration layout is shown in Figure 12, where the airflow enters from the curved OWC chamber (right), passes through a transparent polycarbonate duct housing the turbine, and exits through the torque sensor module. This axial arrangement also ensures minimal turbulence before and after the turbine blades. All DAQ cabling was routed externally and securely mounted to avoid vibration interference. The sensor data was monitored in real time via LabVIEW and used to compute instantaneous power and RPM under varying wave conditions.

This redesign represents a substantial improvement in both structural robustness and experimental reproducibility. The transparent duct, modular sensor platform, and flexible mounting system together create a versatile testbed for future turbine optimization studies and real-time system identification experiments.

D. Integration Summary of Fabrication Changes

The successful implementation of the redesigned OWC test system required a series of coordinated fabrication changes that addressed both mechanical and experimental limitations identified in the first-year prototype. These changes focused on four key areas: instrumentation compatibility, structural stability, visibility and access, and experimental flexibility.

First, in contrast to the limited sensor access in the original design, the second-generation system (Figure 13) featured a fully integrated torque and RPM measurement setup. The bi-directional impulse turbine was mounted in line with a digital torque sensor, and a smooth polycarbonate duct was installed to maintain airflow consistency. The turbine-duct-sensor assembly was aligned horizontally and supported using a reinforced T-track rail system, allowing fine adjustments in position and minimizing mechanical misalignment. Additionally, the axial shaft was upgraded from 3D-printed supports to machined metal inserts, improving rotor balance and ensuring torque measurements were not affected by flex or vibration.

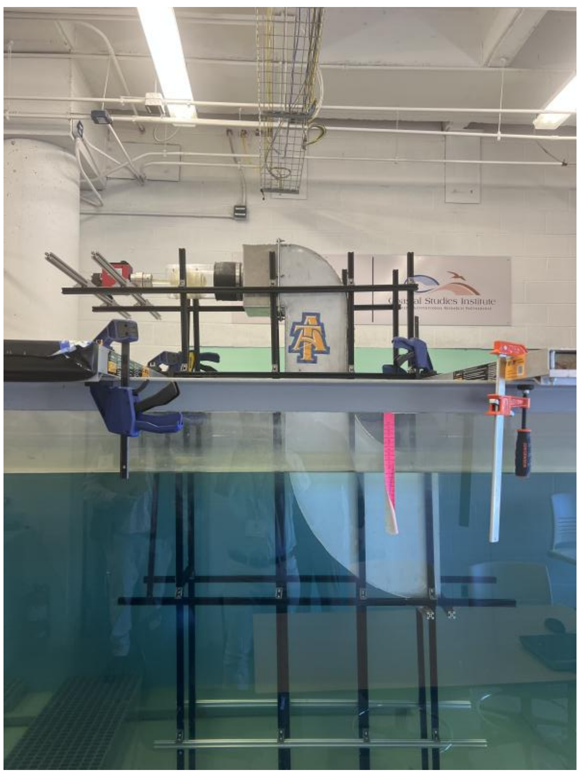

Figure 13. Front View of the Second-generation OWC-turbine System Mounted in the CSI Wave Tank, Showing Transparent Duct, Torque Sensor, and Modular T-track Support Frame.

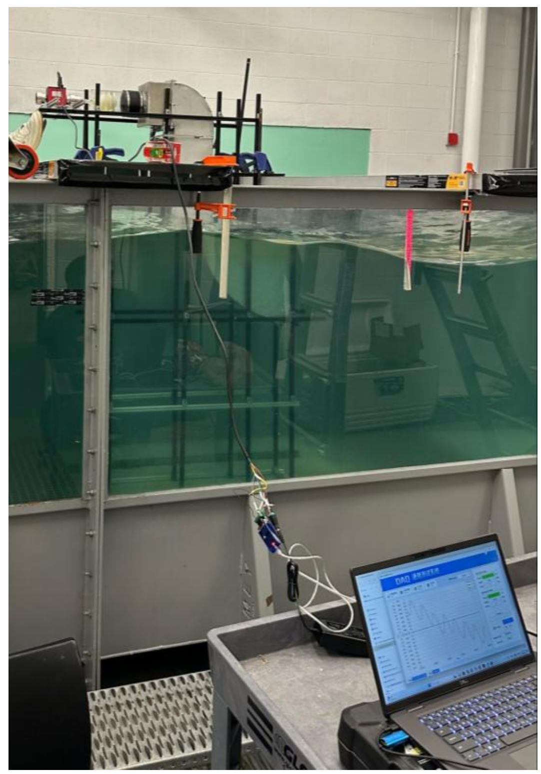

Figure 14. Operational Configuration of the System During Real-time testing, with Sensor Output Captured via LabVIEW on a Laptop-based DAQ System.

Second, the choice of materials was revised to enhance optical and experimental clarity. This change enabled visual inspection of the turbine during operation and simplified the alignment of both sensors and external markers. It also reduced weight, which was beneficial for mounting and transport, especially during repeated installations in the Coastal Studies Institute (CSI) wave tank.

Third, the structural support of the system was fundamentally reimagined. The prototype was re-mounted using a modular aluminum T-slot framing system, eliminating the reliance on improvised C-clamps or wooden blocks used in the earlier version. This rigid yet flexible support framework allowed the entire chamber-turbine assembly to be precisely positioned over the wave tank and adjusted based on test conditions. The modular nature of the setup also makes it adaptable for future upgrades, such as generator integration or airflow control valves.

Finally, real-time data acquisition was achieved through full integration with a LabVIEW-based DAQ system, as shown in Figure 14. Velocity and torque signals were recorded and visualized during each run, allowing immediate feedback for wave condition tuning and experimental replication [29, 30]. The laptop-based control system provided stable and portable operation, which was essential for field deployment.

Taken together, these changes transformed the OWC prototype from a conceptual demonstration tool into a fully instrumented, testable experimental system. The new platform provides both mechanical reliability and high-resolution measurement capability, forming a solid foundation for further turbine evaluation and system optimization under varying wave conditions.

IV. Experimental Results and RPM-Based Performance Analysis

This chapter presents the experimental results obtained from the wave tank testing conducted at the Coastal Studies Institute (CSI). The goal of the testing was to evaluate the performance of the redesigned Oscillating Water Column (OWC) system under controlled wave conditions. Although a torque and RPM sensor was installed in the second-generation system, no external mechanical or electrical load was applied during testing. As a result, measured torque values remained near zero, and mechanical power output could not be meaningfully evaluated under no-load conditions. However, the system was instrumented to capture real-time rotational speed (RPM), which serves as an effective proxy for assessing turbine airflow response and energy conversion behavior. From the raw test data, several key characteristics were identified: (1) Torque readings remained at zero throughout all tests, indicating that no load was applied to the turbine; (2) Power output was also zero, as it is a direct function of torque; (3) RPM data was consistently recorded, providing valid, time-resolved measurements of turbine rotational speed; (4) Each data sheet was preceded by test condition metadata, including wave period and wave height, enabling organized performance analysis. In the following sections, the experimental configuration, test matrix, and resulting RPM trends are examined in detail.

A. Overview of Testing Conditions

All experimental testing was conducted in the CSI wave tank, using monochromatic wave profiles with systematically varied parameters. The wave tank is equipped with programmable wave paddles and real-time control software capable of generating precise and repeatable waveforms. Each trial was configured with a defined wave period (ranging from 1.0 to 1.8 seconds) and wave height (ranging from 0.05 to 0.125 meters), as recorded in the metadata of each test file.

During the experiments, the turbine was allowed to spin freely without any applied mechanical resistance, enabling the chamber to operate under minimal flow restriction. This configuration was specifically chosen to isolate the effects of air displacement due to wave-induced oscillations and to capture turbine responsiveness in terms of rotational velocity (RPM).

Each test lasted approximately 60 seconds, during which over 100 RPM data points were captured at a high temporal resolution. The turbine's RPM was measured using a Hall-effect sensor coupled to a data acquisition system, which enabled continuous logging without interrupting wave generation or flow behavior.

By maintaining consistent wave generation conditions and collecting robust time-series RPM data, the experiment established a strong foundation for analyzing how chamber oscillations translate into turbine motion, even in the absence of direct power output.

B. RPM Trends Across Wave Conditions

The primary performance indicator collected during turbine-on testing was the rotational speed (RPM) of the turbine under different wave conditions. Figure 15 illustrates the maximum RPM measured under varying wave periods for four different wave heights. All values presented were extracted after the system had reached steady oscillation, typically several seconds after wave generation began. Although each plot shows peak RPM, the standard deviation across each run was less than 20%, meaning the maximum values are a valid and consistent representation of overall performance.

As shown in Figure 14, the turbine's RPM increases significantly with wave height. For instance, at a wave height of 0.06 m, maximum RPM remained below 4000, while at 0.12 m it peaked at approximately 9519 RPM under a 1.6 s wave period. This indicates that higher wave heights induce stronger air compression within the OWC chamber, which translates into higher rotational speeds.

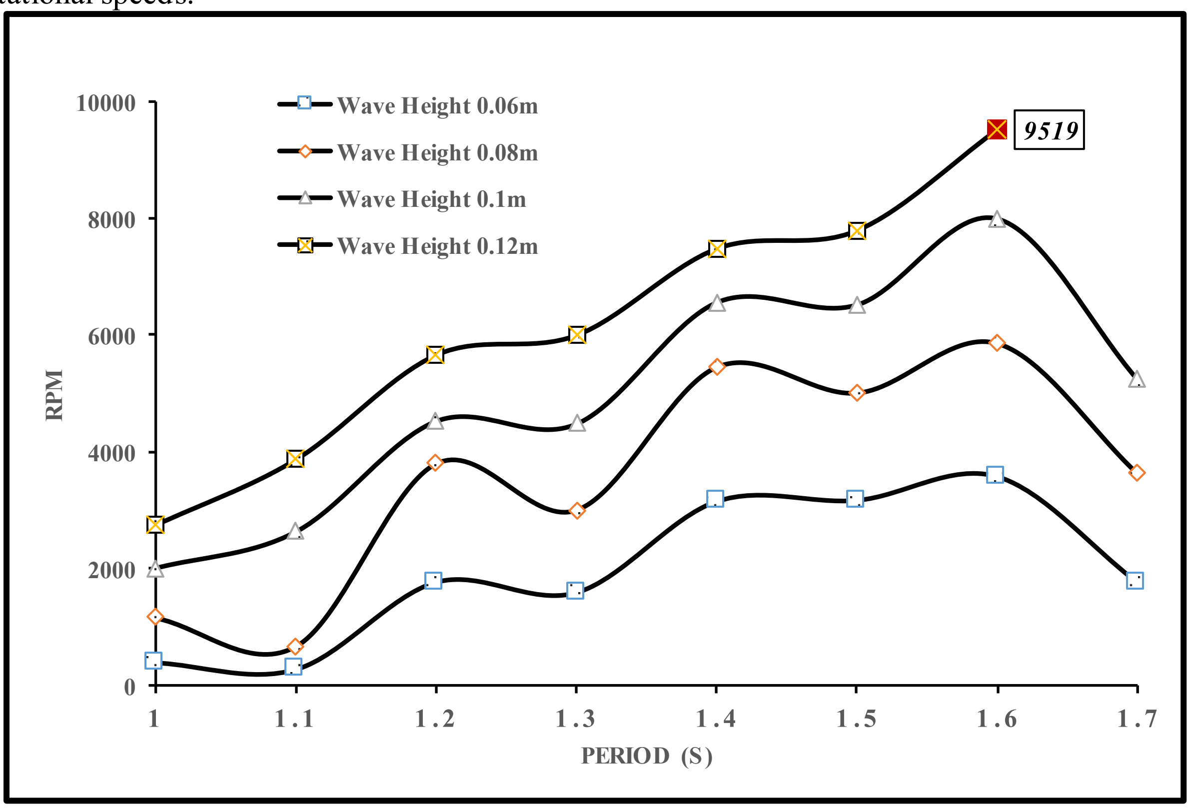

Figure 15. Maximum Turbine RPM Under Various Wave Periods and Wave Heights. Peak RPM Reached 9519 at 0.12 m Height and 1.6 s Period.

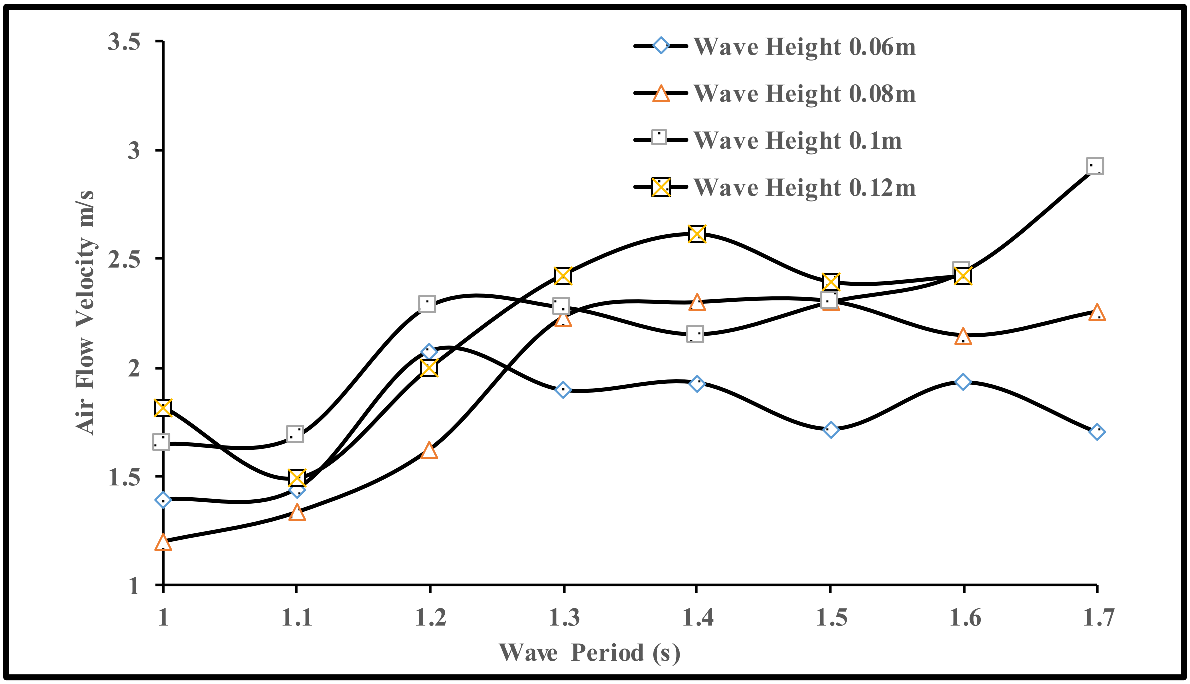

Figure 16. Measured Air Velocity at the Turbine Outlet Under Different Wave Conditions. Values Represent Post-extraction Airflow.

However, the effect of wave period on RPM is more nuanced. The RPM does not simply increase with longer periods. Instead, for most wave heights, the RPM peaks around a wave period of 1.6 seconds. Beyond this point (i.e., at 1.7 s), the RPM either plateaus or drops—suggesting a possible resonance point near 1.6 seconds for the chamber-turbine system. Due to experimental limitations at the CSI facility, tests at 0.12 m wave height and 1.7 s wave period could not be completed, as the actuator control system reached its operational bounds.

In parallel, airflow velocity at the turbine outlet was measured using an anemometer placed just downstream of the turbine housing. These values are shown in Figure 16, again categorized by wave height and plotted against wave period. A key observation is that the air velocity behind the turbine was considerably lower than in turbine-free conditions, as documented in earlier chamber-only testing. This drop is expected due to energy extraction by the turbine.

Interestingly, airflow velocity did not vary as significantly as RPM across the full wave condition matrix. Regardless of wave period or height, the post-turbine air velocity ranged from approximately 1.6 to 2.5 m/s. This suggests that while the chamber continues to generate pressure variations, the turbine is effectively absorbing much of the available kinetic energy and converting it to rotation, thus dampening airflow fluctuations.

These findings confirm that the turbine functions as an effective energy extraction mechanism. The RPM response follows chamber-induced airflow patterns closely and reveals a sweet spot in operating conditions near 0.12 m wave height and 1.6 s period. Moreover, the relatively consistent post-turbine airflow velocity implies that most of the usable airflow energy is being transferred to mechanical motion promising result for future power take-off integration.

C. Implications for Turbine Matching

The RPM-based analysis provides important insights into the effectiveness of the redesigned Oscillating Water Column (OWC) system and the operational suitability of the selected impulse turbine under no-load conditions. Although torque and power data remained at zero due to the absence of mechanical resistance, the recorded RPM values offer a reliable indication of the pneumatic energy transferred through the turbine.

As introduced in Section 2, the available pneumatic power from chamber airflow is characterized by Equation (2), while the potential mechanical output of the turbine is described by Equation (3). While no torque was imposed during testing, the turbine consistently achieved high rotational speeds, with the highest recorded RPM reaching 9519 at a wave period of 1.6 seconds and a wave height of 0.12 meters. This suggests that the OWC chamber, operating near its resonant frequency, was capable of delivering substantial airflow energy.

Reference data from Ref [11] show that axial impulse turbines used in bidirectional OWC systems typically perform efficiently within the 3000–9000 RPM range. Based on this comparison, the turbine in our system was operating at the upper threshold of this range under optimal wave forcing, indicating effective momentum transfer and low internal losses within the air duct.

The velocity data collected from the turbine outlet further supports this conclusion. When the turbine was removed, airflow velocities reached up to 9.6 m/s, whereas post-turbine outlet speeds were reduced to around 2.5 m/s. This drop confirms that a significant portion of the airflow's kinetic energy was being absorbed and converted to mechanical rotation by the turbine blades.

Moreover, with the turbine installed, outlet velocity variations remained relatively flat across the range of wave heights and periods. This suggests that the turbine acts as a stabilizing component in the system, effectively regulating airflow and mitigating pressure fluctuations. Such behavior is advantageous for future generator integration, as it implies a more consistent mechanical input and potentially smoother power output.

In summary, the RPM results demonstrate that the turbine matched well with the chamber's dynamic airflow. Even without torque feedback, the system achieved performance levels that align with published turbine efficiency ranges, establishing a strong foundation for future power take-off optimization and closed-loop energy conversion studies.

V. Structured Educational Assessment and Capstone Evaluation Framework

Over two academic years, a total of 13 senior mechanical engineering students participated in the OWC capstone project (7 students in Year 1 and 6 students in Year 2). Team roles evolved dynamically across conceptual design, fabrication, instrumentation integration, and experimental testing phases. While faculty provided overall project structure and milestone scheduling, leadership roles and task assignments were determined collaboratively within each cohort.

Student learning was evaluated within the formal MEEN 481/482 capstone assessment structure, which aligns with ABET outcomes. The grading framework included:

Table 2. Alignment Between Capstone Design Process and ABET Outcomes.

Capstone Design Element	Faculty Oversight Focus	ABET Outcome
Multiple concept generation	Decision matrix verification	2
Requirement definition	Constraint clarity review	2
Iterative redesign	Analytical justification	1
Experimental validation	Data interpretation review	6
Oral defense & Expo	Technical communication evaluation	3

Faculty oversight therefore focused on process integrity rather than solution ownership. Students retained responsibility for CAD modeling, turbine fabrication, instrumentation integration, and experimental execution, while instructors ensured adherence to ABET-aligned design methodology. This structured oversight model ensured that the capstone functioned not merely as a build exercise, but as a formal implementation of the engineering design cycle as defined in ABET accreditation criteria.

A critical learning moment occurred during the initial small-scale prototype phase. The first-generation OWC model, designed for testing in a limited in-house wave tank, produced inconsistent airflow and failed to reliably drive turbine rotation. This outcome was primarily attributed to insufficient wave energy, strong sidewall effects, and measurement constraints inherent to the small-scale test environment. Rather than treating this result as a project failure, students were guided to analyze the physical and experimental limitations of the system, identify non-scalable assumptions, and distinguish between design flaws and testing constraints.

Based on this analysis, an instructional decision was made to proceed with the design and fabrication of a larger-scale prototype suitable for testing in a programmable wave tank environment. Students were required to justify the scale-up using physical reasoning, including wave energy scaling, resonance behavior, airflow compression potential, and expected improvements in pneumatic power generation. This transition demanded substantial redesign efforts, including structural reinforcement, revised chamber geometry, improved instrumentation accessibility, and integration of real-time RPM and airflow measurements.

Learning outcomes were assessed through performance-based indicators and design artifacts produced across both project phases. Evidence was drawn from documented design reviews, final experimental demonstrations, and recorded RPM and airflow datasets. Students demonstrated the ability to (1) diagnose experimental failure modes, (2) revise system architecture based on first principles reasoning rather than trial-and-error, and (3) successfully implement a complex, testable system under realistic dynamic conditions. The successful operation of the large-scale OWC prototype—achieving stable airflow and high turbine rotational speeds—served as engineering validation of the redesigned system and provided concrete evidence of students' ability to apply iterative reasoning across design cycles.

In addition to graded artifacts, students presented their work during publicly held Group Oral Presentation Reviews (GOPR), attended by senior mechanical engineering students and all senior design faculty. Although GOPR sessions primarily served as formative critique platforms, faculty committee discussions following presentations influenced final evaluation decisions. Students were required to defend design choices, scaling rationale, instrumentation integration, and experimental interpretation in an open-question format.

The project culminated in a university-wide Senior Design Expo, where the OWC prototype and research poster were evaluated using a structured rubric assessing technical merit, research strategy, clarity, and presentation quality. These milestone-based evaluations served as triangulated evidence of learning across conceptual reasoning, experimental mechanics, and professional communication domains.

A critical indicator of learning emerged during the transition from the first-year small-scale prototype to the second-year large-scale implementation. Students correctly identified that zero torque readings under no-load conditions did not indicate system failure but rather reflected the absence of applied resistance. This distinction between rotational response (RPM) and mechanical power output demonstrated conceptual understanding of energy conservation and turbine dynamics. Such reasoning was explicitly evaluated during milestone reviews and final reporting.

Although this project spanned two academic years, its structure can be modularized for institutions operating within one- or two-semester capstone formats. The first-year phase (concept validation and small-scale prototype) can function as a standalone semester project focused on experimental feasibility and failure analysis. The second-year phase (scale-up, instrumentation integration, and performance validation) can be implemented as an advanced continuation or separate design stream. The key transferable element is not duration, but the structured integration of failure-informed redesign and milestone-based evaluation.

VI. Conclusion and Future Work

A. Conclusion

This study presents the design, fabrication, and experimental testing of a small-scale Oscillating Water Column (OWC) wave energy converter developed over two consecutive senior capstone project cycles at North Carolina A&T State University (NCAT). The device employs a multi-chamber, serpentine flow configuration with an axial impulse turbine for pneumatic-to-mechanical energy conversion. The system was iteratively refined based on prior prototype limitations, resulting in enhanced instrumentation integration, a modular structure compatible with CSI's wave tank environment, and improved flow visualization using transparent ducting materials.

From an educational standpoint, this capstone model demonstrates the effectiveness of structured, failure-informed design within a milestone-based assessment framework. Rather than evaluating students solely on final prototype success, learning was measured through iterative documentation, public defense presentations, faculty committee review, and artifact-based evaluation aligned with ABET outcomes. The dynamic two-year structure enabled students to engage in longitudinal system refinement, reinforcing conceptual mechanics principles through authentic experimental constraints.

Experimental testing was conducted under controlled wave conditions using CSI's wave tank facility. Although no mechanical load was applied to the turbine (i.e., torque remained zero), real-time RPM data were successfully captured and used as a proxy for assessing airflow-induced turbine response. The system achieved rotational speeds as high as 9519 RPM at a wave period of 1.6 seconds and wave height of 0.12 meters, suggesting resonance behavior and confirming effective air pressure and release within the chamber.

The observed RPM range aligns well with the expected operating envelope of impulse turbines in similar OWC systems, as cited in previous literature. Comparative airflow measurements before and after turbine installation demonstrated a significant reduction in outlet velocity, indicating successful energy transfer from airflow to turbine rotation. Moreover, the relatively stable output under varying wave inputs shows the turbine's potential to act as a flow stabilizer—an important feature for future generator integration.

Overall, the results verify the viability of the chamber-turbine configuration and provide a validated baseline for future power extraction system design.

B. Future Work

Future research should focus on integrating a controllable mechanical load to enable direct torque and power measurements, thereby allowing for a complete performance evaluation of the turbine. Enhancing the instrumentation setup to include pressure sensors, flow velocity mapping, and temperature measurements would deepen the understanding of internal chamber dynamics. Additionally, turbine optimization—such as redesigning blade profiles or implementing variable-geometry features—could improve efficiency across a wider range of wave conditions. Numerical modeling based on the current test results may also guide future design iterations and support scaling analysis for larger prototypes. Testing under irregular or multidirectional wave patterns would further validate the system's real-world applicability. Finally, as an educational project, this work sets a strong precedent for multidisciplinary undergraduate training in renewable energy system development and experimental design. Future iterations of this capstone project will incorporate structured pre/post conceptual surveys and rubric-based learning analytics to quantitatively measure gains in experimental reasoning and system-level design competency.

References

[1] M. Rosati, J.C.C. Henriques, J.V. Ringwood "Oscillating-water-column wave energy converters: A critical review of numerical modelling and control" Energy Conversion and Management: X Volume 16, December 2022, 100322.

[2] Y. Masuda, Wave-activated generator, Int. Coll. on the Expositions of the Oceans (Trans.), Bordeaux, France.

[3] Ross D. Power from the Waves. USA: Oxford University Press; 1995.

[4] Falc˜ao AFO, Gato LMC. Air turbines. In: Sayigh A, editor. Comprehensive Renewable Energy, vol. 8. Oxford: Ocean E, Elsevier; 2012. p. 111–49. https://doi.org/10.1016/B978-0-08-087872-0.00805-2.

[5] Falc˜ao AFO, Henriques JCC, Gato LMC. Self-rectifying air turbines for wave energy conversion: A comparative analysis. Renew Sustain Energy Rev 2018; 91:1231–41. https://doi.org/10.1016/j.rser.2018.04.019.

[6] Frimpong Opoku, MN Uddin, M Atkinson., "A review of computational methods for studying oscillating water columns – the Navier-Stokes based equation approach" Renewable and Sustainable Energy Reviews Volume 174, March 2023, 113124.
[7] Bouali B, Larbi S. Contribution to the geometry optimization of an oscillating water column wave energy converter. Energy Procedia Volume 36, 2013, Pages 565-573.
[8] Gomes MN, Nascimento CD, Bonafini BL, Santos ED, Isoldi LA, Rocha LAO. Twodimensional geometric optimization of an oscillating water column converter in laboratory scale. Rev Eng T´ermica 2012; 11:30-6.
[9] Lopez I, Iglesias G, Lopez M, Castro F, Rodriguez MA. Turbine-chamber couplingin an OWC wave energy converter. In: Proceedings of the 33rd conference on coastal engineering; 2012.
[10] Zhang Y, Zou Q, Greaves D. Air-water two-phase flow modelling of hydrodynamic performance of an oscillating water column device. Renew Energy 2012; 41:159–70.
[11] Zhen Liu, Ying Cui, Ming Li, Hongda Shi. Steady state performance of an axial impulse turbine for oscillating water column wave energy converters. Energy Volume 141, 15 December 2017, Pages 1-10.
[12] Dhanak MR, Xiros NI. Ocean wave energy conversion concepts. Springer Handb Ocean Eng 2016;45. A:1137-9.
[13] Falcao AFO, Henriques JCC. Oscillating-water-column wave energy converters and air turbines: a review. Renew Energy 2016; 85:1391-424.
[14] Falcao AFO, Gato LMC, Nunes EPAS. A novel radial self-rectifying air turbine for use in wave energy converters. Renew Energy 2013; 50:289-98.
[15] Halder P, Samad A. Optimal Wells turbine speed at different wave conditions. Int J Mar Energy 2016; 16:133-49.
[16] Setoguchi T, Takao M, Santhakumar S, Kaneko K. Study of an impulse turbine for wave power conversion: effects of Reynolds number and hub-to-tip ratio on performance. J Offshore Mech Arctic Eng 2004;126(2):137e40.
[17] J.C.C. Henriques, A.A.D. Carrelhas, L.M.C. Gato, A.F.O. Falcao, J.C.C. Portillo, J. Varandas, Peak-shaving control – A new control paradigm for OWC wave energy converters, in: Proceedings of the European Wave and Tidal Energy Conference, Cork, Ireland, 2017.
[18] Monk K, Winands V, Lopes M. Chamber pressure skewness corrections using a passive relief valve system at the pico oscillating water column wave energy plant. Renewable Energy 2018; 128:230–40. https://doi.org/10.1016/j. renene.2018.04.037.
[19] A.F. de O. Falcao, L.C. Vieira, P.A.P. Justino, J.M.C.S. Andre, By-Pass Air-Valve Control of an OWC Wave Power Plant, J Offshore Mech Arctic Eng 125 (3) (2003) 205–210. doi:10.1115/1.1576815.
[20] Henriques JCC, Portillo JCC, Sheng W, Gato LMC, Falc˜ao AFO. Dynamics and control of air turbines in oscillating-water-column wave energy converters: Analyses and case study. Renew Sustain Energy Rev 2019; 112:571–89. https://doi.org/10.1016/j.rser.2019.05.010.
[21] M. Rosati, T. Kelly, G.D. Violini, J.V. Ringwood, Data-based hydrodynamic modelling of a fixed OWC wave energy converter, in: Proceedings of the 14th European Wave and Tidal Energy Conference, Plymouth, UK, 2021, pp. 1–10. URL: https://www.researchgate.net/publication/354544067_Data_based_hydrodynamic_modelling_of_a_fixed_OWC_wave_energy_converter.
[22] Rosati M, Kelly T, Ringwood JV. Nonlinear data-based hydrodynamic modeling of a fixed oscillating water column wave energy device. IEEE Access 2021; 9:149756–65. https://doi.org/10.1109/ACCESS.2021.3125600.

[23] Uddin MN, Atkinson M, Opoku F. Numerical investigation of a modified dennissauld turbine. In: Proceedings of AIAA aviation forum; 2022.
[24] Opoku F, Atkinson M, Uddin MN. Numerical investigation of an offshore oscillating water column. Am J Mech Eng 2020; 8:88–105.
[25] Opoku F, Atkinson M, Uddin MN. In: Computational fluid dynamics investigation of a novel oscillating water column. Proceedings of AIAA SciTech Forum; 2022.
[26] N, Atkinson M, Opoku F. A computational fluid dynamics investigation of a numerically simulated wave tank. Am J Mech Eng 2020; 8:40–9.
[27] Starzmann R. Aero-acoustic analysis of Wells turbines for ocean wave energy conversion. PhD thesis. Universitat Siegen; 2012.
[28] Starzmann R, Carolus T. Model-based selection of full-scale Wells turbines for ocean wave energy conversion and prediction of their aerodynamic and acoustic performances. Proc Inst Mech Eng Part A J Power Energy 2014;228(2):2-16.
[29] T. Kelly, T. Dooley, J.V. Ringwood, Experimental determination of the hydrodynamic parameters of an OWC, in: Proceedings of the 12th European Wave and Tidal Energy Conference, Cork, Ireland, 2017, pp. 1–10. URL: https://mural.maynoothuniversity.ie/12459/.
[30] Kelly T. Experimental and numerical modelling of a multiple oscillating water column structure. National University of Ireland Maynooth; 2018. Ph.D. thesis, URL: https://www.proquest.com/docview/2187528122?pqorigsite=gscholar&fromopenview=true.