

A multi-feature energy-concentrated OWC-array system for high-efficiency ocean wave energy harvesting: An experimental study

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ABSTRACT

Wave energy conversion is fundamentally constrained by the low energy density of ocean waves, the narrow operating bandwidth of conventional wave energy converters (WECs), and the excessive structural loads induced under extreme sea states. Here, a multi-feature energy-concentrated Oscillating Water Column (OWC) array system is proposed that integrates a parabolic wave energy concentrator, dual-chamber structure, and porous device to achieve both high power conversion efficiency and enhanced structural reliability. The parabolic concentrator amplifies the wave energy density at the focal point through multi-directional wave reflection and constructive wave interference, overcoming the bottleneck of low energy flow density in marine environments. The optimal integration combination of the optimized OWC array, the dual-chamber structure that exhibits a frequency-broadening effect under the tested wave conditions, and the porous device that mitigates wave-induced high-frequency forces without compromising energy capture performance enables the system to achieve an average Wave-to-Wire (WtW) efficiency of 50.0%. Specifically, compared with the baseline five-OWC array, the multi-feature energy-concentrated OWC array system achieves a maximum WtW efficiency improvement of 113.6%, while the porous device reduces the horizontal wave force by up to 24.1%. The proposed system provides a promising engineering pathway for efficient wave energy utilization in low-energy-density coastal regions, and it also provides a general strategy for advancing wave energy technologies beyond conventional geometric and hydrodynamic constraints.

1. Introduction

The urgent need to mitigate climate change and achieve carbon neutrality [1] has driven the global shift towards renewable energy sources [2,3]. Among various renewables, marine energy, particularly wave energy, stands out due to its large reserves, abundant storage and enormous development potential [4]. Estimates suggest that full exploitation of wave energy could satisfy approximately 40% of global electricity demand [5], equivalent to the output of 800 nuclear power plants [6] or half the electricity requirements of 44 coastal nations [7]. The variability of wave energy is a primary reason for its high cost and minimal exploitation [8,9]. Nevertheless, compared to solar and wind energy, wave energy exhibits superior supply continuity and predictability [10,11], designating it a critical complement to the global renewable energy portfolio. Consequently, the wave energy industry is gradually transitioning from small-scale and pilot demonstration

projects to high-level technologies, with improved reliability [12,13].

WECs exhibit various performance characteristics and have different operational modes [14–16]. OWC devices have emerged as the most mature WEC technology due to their simple structure and relatively high reliability [17]. However, three key challenges persist: (1) low energy conversion efficiency in the nearshore or Asian seas; (2) narrowband energy capture, as traditional single-chamber OWCs only operate efficiently under resonant conditions matching the incident wave frequencies [18]; and (3) poor survivability under extreme waves, as exemplified by the Mutriku wave power plant, which suffered severe structural damage during construction due to extreme wave loads [19,20]. To address the key issue of improving energy capture efficiency, a challenge that spans the entire wave energy exploitation process, most researchers have focused on optimizing the geometric configuration [21–23] or the energy transfer mechanisms [24–26] of OWC devices to reduce energy losses, but these approaches have yielded

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limited gains in low-energy marine environments.

Consequently, the Offshore Renewable Energy (ORE) group at Dalian University of Technology has devoted sustained efforts to exploring a novel strategy aimed at enhancing the first stage wave energy input to WEC systems. Inspired by the electromagnetic wave focusing mechanism employed in radio telescopes, and by extending this concept to the field of water waves [27], a parabolic ocean wave-concentrating structure has been proposed. This innovation represents a paradigm-changing approach, namely ocean wave energy concentrating. In contrast to Bragg-resonance-based wave concentration, which typically requires periodic seabed undulations or artificial bottom topography to trigger resonant wave amplification [28,29], the proposed wave energy-concentrating approach employs a surface-piercing parabolic device that concentrates incident waves from various directions toward a designed local location (referred to as the focal point) mainly through geometric reflection and constructive interference. In this manner, the local wave energy density can be amplified by several times [30].

Recently, Ranjan et al. [31] experimentally compared rectangular and parabolic base OWC devices under varying wave conditions, and demonstrated that the parabolic base geometry can improve the hydrodynamic response and energy conversion performance of OWC devices. This study further confirms the potential of parabolic geometry in enhancing OWC performance. However, their work mainly focused on the influence of the OWC base geometry itself, whereas the present study employs an external parabolic wave energy concentrator to reshape the surrounding wave field. In previous studies, a cylindrical OWC device compatible with the multidirectional wave energy-concentrating characteristics of the parabolic reflector was introduced. The hydrodynamic efficiency of the OWC device installed at the focal point was found to be approximately 6.5 times higher than that under standard open-sea conditions [32]. In scaled model tests, the WtW efficiency was improved by 70% [33], a value that substantially surpasses previously recorded WtW efficiencies, which are typically around 14% in laboratory experiments [34].

Although the energy conversion efficiency of the OWC devices is substantially enhanced by this wave-focusing methodology, the inherent narrowband energy-capture characteristic still requires an urgent solution. Taking advantage of the capacity of multi-chamber configurations to broaden the effective bandwidth of OWCs, researchers have conducted experimental and numerical studies on dual-chamber [35,36], tri-chamber [37,38], quad-chamber [39], and even quintuple-chamber OWC systems [40]. A growing consensus within the research community indicates that multi-chamber technology represents a promising solution to this bottleneck. However, the majority of existing studies are still limited to two-dimensional analyses and lack effective integration with wave energy concentration technologies.

In the aforementioned strategies for improving the energy capture efficiency and power output of the OWC devices, elevated wave heights are commonly observed both inside the chamber and near the external chamber wall surfaces. Modifying the structural configuration [41,42] of OWC devices has been demonstrated to achieve load reduction effects, yet balancing such survivability-oriented modifications with the retention of device performance remains a critical challenge. Porous protective structures have been widely applied in coastal engineering applications due to their favorable wave load-mitigating characteristics. Extensive studies have shown that porous structures with optimized physical parameters [43,44] can reduce wave transmittance, and thereby enable effective wave energy dissipation. Accordingly, the wave-induced loads on the devices incorporating porous structures are significantly decreased [45–47]. Nevertheless, these studies have not addressed the application of porous devices in OWC systems operating under the wave-energy-concentrated conditions, where both the energy conversion performance and the wave loads acting on the device are considerably amplified.

For large-scale wave energy exploitation, the deployment of wave energy converter array [48–52] offers a promising pathway. However,

the inefficient performance induced by the shielding effect among individual WEC units within the array, together with the high capital and installation costs, presents a substantial challenge. Consequently, the optimization of array layouts [53], including the adjustment of inter-device spacing [54,55] and WEC configurations [51,56,57], has attracted considerable research interest. In addition, the integration of WEC systems with existing marine engineering structures, such as breakwaters [58,59], offshore wind turbines [60–62], harbor walls, represents a cost-effective and efficiency-boosting approach. Among these integrated solutions, the combination of WEC arrays with breakwaters has been demonstrated to achieve favorable synergistic effects [63,64].

Although previous studies have demonstrated the effectiveness of parabolic wave energy concentrator, OWC arrays, dual-chamber configurations, and porous force-mitigation devices separately, the integrated use of these strategies in an energy-concentrated OWC-array system has not yet been sufficiently investigated. In particular, it remains unclear whether the energy-harvesting enhancement achieved by a parabolic concentrator and OWC array can be maintained when additional structures are introduced to broaden the effective response range and reduce wave-induced forces. To clarify this issue, the present study develops a multi-feature energy-concentrated OWC array system by integrating an optimized five-OWC array, a dual-chamber OWC, and a porous device within a wave energy concentrated field. The main contributions of this study are fourfold. First, the parabolic concentrator serves to amplify the local wave energy density. Second, the optimized five-OWC array is used to harvest multiple energy-concentrated regions generated by the parabolic concentrator. Third, the dual-chamber structure is introduced into the primary OWC to improve the energy-capture response over the tested wave-period range. Finally, a porous device is integrated around the primary OWC to reduce horizontal wave force while preserving the power-enhancement advantage of the energy-concentrated OWC array. Compared with previous studies that focused on individual components, the present work experimentally evaluates the coupled effect of these strategies on both WtW efficiency and structural loading.

As summarized in Table 1, the present study differs from previous work by experimentally combining four functions in a single system: wave-energy concentration, multi-point array energy extraction, dual-chamber response improvement, and porous load mitigation. This integrated design enables the proposed system to achieve substantial improvements in power output and energy conversion efficiency, while simultaneously guaranteeing the long-term survivability of the OWC devices.

The outline of this paper is as follows: Section 2 introduces the design of the proposed multi-feature energy-concentrated OWC array system. Section 3 describes the detailed experimental setup and the methodology. In Section 4, the system is examined with respect to its key characteristics, including the frequency-broadening mechanism and performance of the dual-chamber OWC device, the force-reduction mechanism and performance of the OWC integrated with the porous device. On this basis, the effectiveness and advantages of the multi-feature energy-concentrated OWC array system is elaborated and analyzed. Finally, the main conclusions are drawn in Section 5.

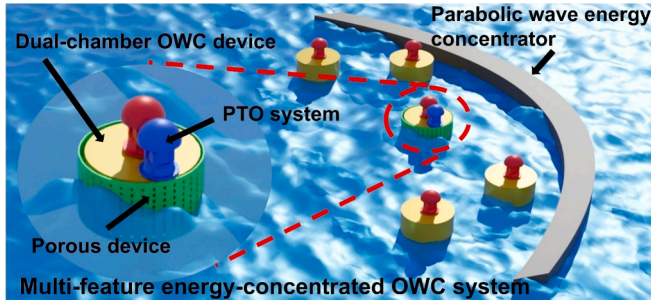
2. Design of the multi-feature energy-concentrated OWC array system

An innovative multi-feature energy-concentrated OWC array system is proposed as illustrated in Fig. 1. The system comprises four key components. A meticulously designed parabolic wave energy concentrator modifies the regional wave field by reflecting incident waves in multiple directions towards a single focal point; consequently, the wave energy density at this location is significantly enhanced through positive wave interference effects [32,33]. The optimized five-OWC array is strategically configured on the basis of the hydrodynamic interactions between the individual OWCs and the wave-energy-concentrating field.

Table 1

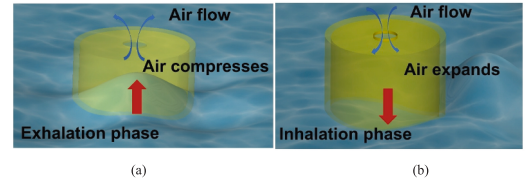
Comparison between representative previous studies and the present work.

Study	Configuration	Wave-energy concentration	OWC array	Dual/multi-chamber	Porous device
Mayon et al. (2021)	Single OWC	Yes	No	No	No
Main distinction from present work: Demonstrated focal-region energy capture, but did not consider array layout, dual chamber, or porous force mitigation.					
Mayon et al. (2023)	Single OWC	Yes	No	No	No
Main distinction from present work: Verified high WtW efficiency of single OWC, but no array-scale design or wave-force mitigation device.					
Mayon et al. (2024)	OWC array	Yes	Yes	No	No
Main distinction from present work: Investigated array behavior, but did not integrate dual-chamber structure or porous device.					
Ning et al. (2026)	OWC array	Yes	Yes	No	No
Main distinction from present work: Optimized array layout and discussed wave height effects, but did not include dual-chamber OWC or porous device					
Zhang et al. (2025)	Single OWC	Yes	No	Yes	No
Main distinction from present work: Demonstrated dual-chamber benefit, but not for a five-OWC array and without porous device					
Zhuang et al. (2026)	Single OWC	Yes	No	No	Yes
Main distinction from present work: Verified porous annulus for load reduction and power preservation, but only for a single OWC					
Present study	OWC array	Yes	Yes	Yes	Yes
Main distinction from present work: Integrates wave concentration, array-scale harvesting, dual-chamber response improvement, and porous wave-force reduction in one experimental system					

**Fig. 1.** Schematic of the wave energy concentrating device coupled with the multi-feature OWC WEC.

The primary OWC was positioned at the theoretical focal point, where the strongest energy concentration occurs, while the secondary and tertiary OWCs were symmetrically arranged on both sides of the central axis to utilize the secondary and tertiary energy-concentrated regions formed by the hydrodynamic interactions between multidirectional reflected waves and OWCs. Within the array, a cylindrical dual-chamber OWC device is tailored to match the multidirectional wave-energy-concentrating characteristics of the modified wave field. Additionally, a porous device is concentrically integrated around the OWC device to alleviate wave-induced forces, thereby improving the long-term survivability of the device.

Fig. 2(a) shows the working principle of the hydrodynamic energy conversion process for the OWC device. As a pneumatic wave energy converter, the OWC operates in both inhalation and exhalation phases during the wave energy extraction. Specifically, Fig. 2(a) illustrates the exhalation phase, during which the wave crest enters the air chamber

**Fig. 2.** The principle of the hydrodynamic energy conversion process for the OWC device: (a) exhalation phase, (b) inhalation phase.

and compresses the internal air volume, forcing the air to flow outward through the orifice mounted on the chamber top. In contrast, as shown in Fig. 2(b), the inhalation phase occurs when the wave trough arrives and expands the air volume inside the chamber, creating a negative pressure that draws external air into the chamber through the orifice. This periodic oscillating process enables the conversion of wave energy into pneumatic energy.

Fig. 3 shows the conversion process from pneumatic energy to electrical energy, and together with the practical power supply application scenarios. Initially, pneumatic energy is converted to electrical energy through the Power Take-Off (PTO) system. The cross-sectional diagram clearly visualizes the internal airflow dynamics. The PTO system, which is hermetically connected to the orifice of the OWC device, mainly comprises an air turbine and a permanent magnet synchronous generator (PMSG). As the water column oscillates inside the chamber, the bidirectional air flow drives the pneumatic turbine to rotate. The rotational motion of the turbine is transmitted through a fixed shaft to drive the PMSG, thereby generating electricity. This mechanism realizes the energy conversion from the pneumatic power to the electrical power. The alternating current (AC) produced by the PMSG is rectified into direct current (DC) by a rectifier module, and then regulated by a DC electronic load module. The generated electrical energy can be used for practical scenarios such as power supply for remote island communities and other off-grid or grid-connected power-demand scenarios.

3. Methods

3.1. Experimental methods

The experiment was conducted at a Froude scale of $S = 1:15$ at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology. The Froude similarity was adopted to reproduce the gravity-dominated free-surface hydrodynamics and wave-structure interaction of the proposed OWC array system. However, for OWC devices, model-prototype similarity is complicated by the coupled hydrodynamic-aerodynamic response of the oscillating water column. The compressibility of the air volume trapped above the internal free surface of the OWC chamber, together with PTO load conditions and turbine-generator dynamics, cannot be fully scaled using Froude similarity alone. Therefore, the present physical model is mainly used to compare the relative performance of the three tested cases under consistent laboratory-scale conditions. As shown in Fig. 4, the wave basin used in the tests is 55 m in length, 34 m in width and 1.3 m in depth. An articulated paddle wave maker is installed at one end of the basin, while an absorbing beach is placed at the opposite end to suppress reflected waves. The geometric profile of the parabolic wave energy concentrator employed in this study follows the parabolic equation:

$$y^2 = -4L_f x + \left(\frac{l}{2}\right)^2, \quad (1)$$

where L_f denotes the theoretical focal length, and l represents the chord length. Specifically, the concentrators were fabricated by welding 17 steel plate units and secured to the wave basin floor using bolted triangular brackets. Curvature-positioning steel bars were welded to the top and bottom of each steel plate unit to guarantee the accuracy of the

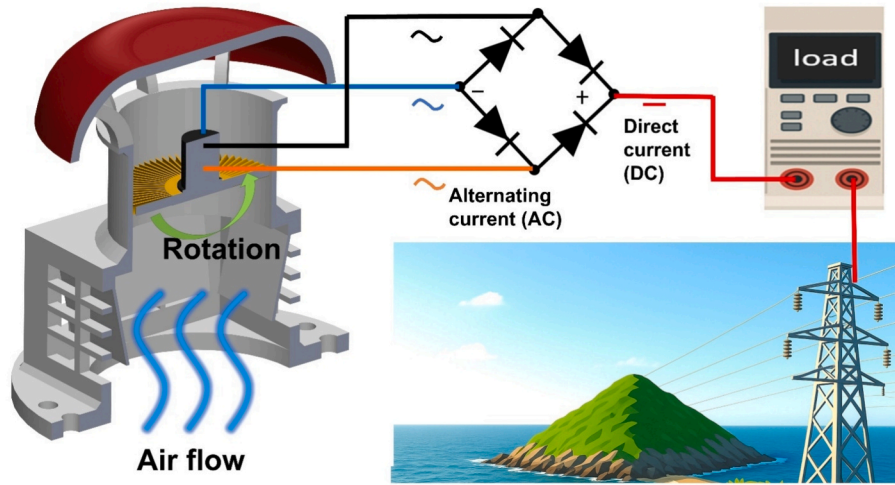


Fig. 3. The conversion process of the electrical energy and the practical power supply application scenarios.



Fig. 4. Photo of the wave basin.

parabolic curvature.

To prevent excessive displacement and failure of the experimental setup under extreme wave conditions, the OWC device and the parabolic wave energy concentrator were fabricated from industrial-grade steel. The OWC units employed in the experiment were manufactured with uniform dimensions using steel rolling, which ensured the circularity of the OWC chambers. The OWC devices were rigidly attached to the wave basin floor through support columns. Sealant was applied at the joints between the OWC chamber sidewall and the acrylic roof, as well as between the roof and the flange of the PTO system, to maintain hermetic sealing. In addition, the porous device used in the experiment was manufactured from industrial steel plate by steel rolling, with consistent dimensions. The openings in the porous device were formed by the laser cutting. Similar to the OWC units, the porous device was secured to the bottom of the wave basin using bolted support columns.

Three experimental cases were considered in this study, as

Table 2

The description of three cases in the experiment.

Cases	OWC degree	OWC configuration	Rated power
Case 1	Primary	Single-chamber	300 W
	Secondary		75 W
	Tertiary		50 W
Case 2	Primary	Dual-chamber	300 W
	Secondary		75 W
	Tertiary		50 W
Case 3	Primary	Dual-chamber and porous device	300 W
	Secondary		75 W
	Tertiary		50 W

summarized in Table 2. These cases were subsequently tested under the incident wave conditions listed in Table 3. The incident wave height was fixed at $H = 0.15$ m in the present study to isolate the effects of wave period, dual-chamber configuration, and porous device on the integrated OWC array system. The influence of the wave height on the energy-focused OWC-array system has been systematically investigated in the previous work [65]. The previous results showed that increasing wave height significantly enhances power output, whereas the WtW efficiency may decrease because the additional incident wave energy cannot be fully converted and may be partly dissipated through viscous losses, nonlinear free-surface motion, and stronger chamber-wall interactions. Therefore, the present study adopts $H = 0.15$ m to evaluate the incremental effects of the dual-chamber and porous device under a controlled and relatively energetic condition. The selected tested wave range of $T = 1.4$ – 2.6 s was designed to cover the main response region of the OWC-array system at model scale and to include both relatively high-frequency and low-frequency conditions. In addition, under the adopted Froude scale of 1:15, this model-scale period range corresponds approximately to typical prototype wave periods relevant to the coastal waters in China with the peak wave period within the range of 5 s to 10 s. Fig. 5(a) presents the optimal five-OWC array layout for Case 1, which was achieved through the real-time wave field reassessment based on a feed-forward process. The positions of the individual OWC devices in the array are determined by leveraging the multi-location wave energy-concentration effect generated by the parabolic wave energy concentrator, as well as the interactive hydrodynamic coupling between OWC devices and the concentrated wave field. The diameters of the OWC devices are tailored to the wave energy concentrating effect at their relating positions. Specially, the primary OWC was designed with a diameter of 1.5 m, as the theoretical focal point exhibits the strongest wave energy concentrating effect. In contrast, the secondary and tertiary OWC devices were set to a diameter of 1.0 m, considering the weaker wave energy concentrating effect at their corresponding focal positions [65]. In Case 2, an inner chamber was nested inside the primary OWC, thereby transforming the conventional single-chamber configuration of the primary OWC device into a dual-chamber structural design, as depicted in Fig. 5(b). As listed in Table 4, both the inner and outer chambers adopt the optimized dimensions and orifice ratios [66]. The

Table 3

Incident wave conditions.

Wave height H (m)	0.15			
Wave period T (s)	1.4	1.6	1.7	1.8
	2.0	2.4	2.6	

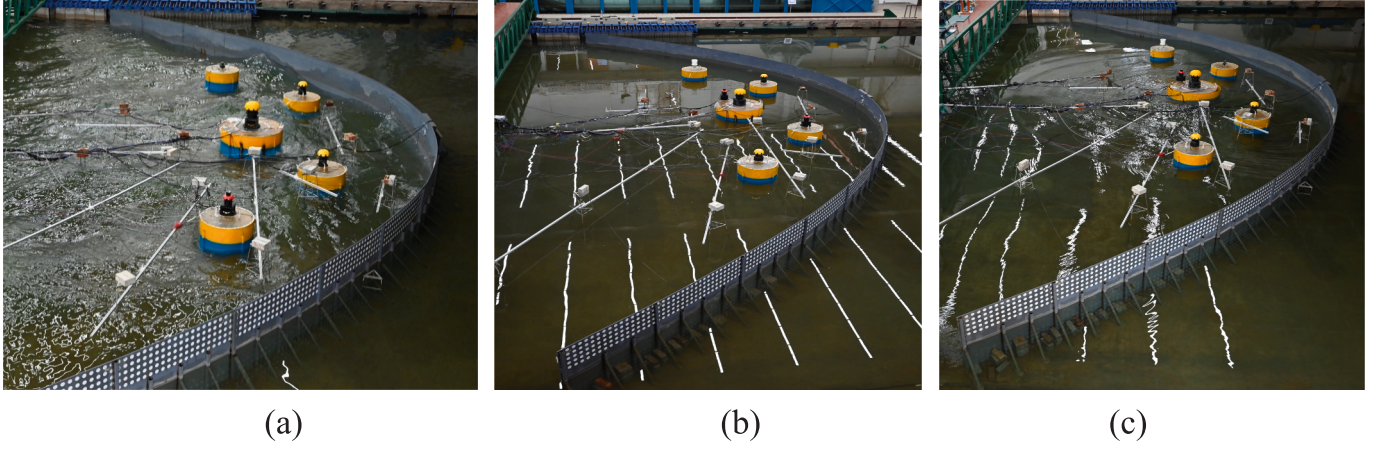


Fig. 5. Photo of three cases in the experiment: (a) Case 1, (b) Case 2, (c) Case 3.

Table 4

Physical parameters of the devices in the experiment.

Item	Notation [unit]	Value
Still water		
Depth	h (m)	0.8
Parabolic wave energy concentrator		
Chord length	l (m)	25
Theoretical focal distance	L_f (m)	4.22
Height	h_p (m)	1.5
Parabolic wave energy concentrator unit		
Width	W (m)	2
Thickness	t_1 (mm)	4
Piece	N	17
OWC device		
Height	h_1 (m)	0.6
Draft	h_2 (m)	0.2
Diameter	D (m)	1.5/1
Orifice ratio	R (%)	2.5
Thickness	t_2 (mm)	10
Dual-chamber OWC device		
Inner chamber diameter	D_1 (m)	0.78
Inner chamber thickness	t_3 (mm)	10
Inner chamber orifice ratio	R_1 (%)	1.5
Outer chamber orifice ratio	R_2 (%)	1.5
PTO system		
Rated power	P_{rated} (W)	300/75/50
Porous device		
Hole diameters	d_1 (mm)	18.2
Porosity	E (%)	10
Diameter	D_2 (m)	1.7
Square support columns		
Width	W_s (cm)	5
Length	l_s (cm)	5
Height	h_s (m)	1.2

inner chamber was fabricated from an acrylic cylinder with a thickness of 10 mm and a diameter of 0.78 m. Moreover, the orifice ratio of both chambers was set to 1.5%, with a uniform height of 0.6 m and a draft height of 0.2 m for both chambers.

Building on Case 2, the porous device was ultimately integrated with the primary OWC in Case 3, thereby developing a multi-feature energy-concentrated OWC array system, as shown in Fig. 5(c). The detailed parameters of the porous device are also presented in Table 4. The diameter of the porous device was set to 1.7 m, which is coaxially sleeved on the outer side of the primary OWC. The porosity and hole diameter of the porous device were set to 10% and 18.2 mm, which were selected based on the previous experimental research on a cylindrical OWC integrated with a porous annulus under wave-concentrating conditions [67]. The results showed that this porous device could effectively reduce the horizontal wave force acting on the

cylindrical OWC while maintaining the generated electrical power under wave-concentrating conditions. Therefore, the same porosity and hole diameter were adopted in the present study as a previously validated initial design for balancing load mitigation and energy-capture performance.

3.2. Characterization and measurement

Fig. 6(a) shows the conversion process of the electrical energy, together with the employed power measurement scheme. In the experimental investigation presented in this paper, all OWC devices utilised an identical PTO system composed of a unidirectional impulse air turbine and a rated-power PMSG. This uniform PTO configuration enables a fair comparison among the three structural cases. It is worth noting that although the OWC device operates through both inhalation and exhalation phases during wave energy capture, the turbine operates in a unidirectional rotation mode. Consequently, power generation can only be achieved in the exhalation phase, while no electric energy is

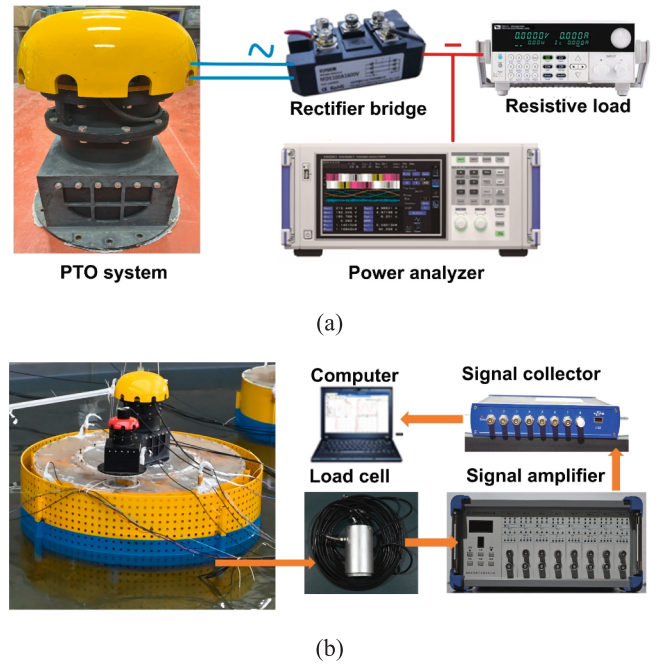


Fig. 6. Physical model experiments setup and measurement methodology: (a) power measurement methodology and testing equipment, (b) wave force measurement methodology and testing equipment.

produced during the inhalation phase. Moreover, the turbine employed in the secondary energy conversion stage of the investigation was not downscaled according to Froude scaling laws at the power scaling factor precludes this. The purpose of utilizing the turbine was solely to investigate the WtW efficiency in the laboratory experiment. This efficiency was not extrapolated to full-scale conditions.

The rated power of the PMSG is determined by the wave energy concentrating effect associated with the power capacity of the OWC device. Accordingly, the primary OWC positioned at the focal point was equipped with the PMSG of 300 W, while the secondary and tertiary OWCs adopt PMSGs with rated powers of 75 W and 50 W, respectively. In Case 2 and Case 3, the inner chamber of the primary OWC was still equipped with a PMSG with a rated power of 300 W, while an additional PMSG with a rated power of 75 W was installed for the outer chamber. The alternating current generated by the PMSG in the PTO system was rectified into direct current through a three-phase rectifier bridge. Furthermore, an IT8511A + Programmable DC Electronic Load was employed to connect resistive loads of 3 Ω , 10 Ω , and 15 Ω [68] to each circuit, which were matched with the PMSGs with rated powers of 300 W, 75 W, and 50 W, respectively. The selection of the resistive loads was based on the rated power levels of the PMSGs and the previous investigation of resistive-load effects on the OWC WtW conversion process [69]. Moreover, before the formal tests in the present study, preliminary load-screening experiments were also conducted for the PMSGs with different rated powers. The electrical power output under several candidate resistive loads was compared, and the loads that provided relatively stable and high average power output for each PMSG were selected.

Finally, the electrical power output of the OWC devices was measured using a PW6001 series power analyzer. It should be noted that the turbine, generator units and fixed resistive loads were not intended to represent a fully scaled PTO system. Similar to previous laboratory-scale OWC WtW experiments [33], the PTO system was solely used to provide a consistent energy conversion and measurement platform for comparing the three cases. The measured WtW efficiencies are therefore interpreted as laboratory-scale comparative indicators, and are not directly extrapolated to full-scale performance.

As illustrated in Fig. 6(b), an annular porous device was installed concentrically around the exterior of the OWC during the experiment. Load cells were mounted at the base of the OWC structure. The acquired signals were first amplified by a signal amplifier, then processed by the signal conditioner, and finally recorded by a monitoring computer.

Fig. 7 presents the optimal layout of the five-OWC array, where the secondary and tertiary OWC devices are symmetrically distributed about the central axis of the parabolic wave energy concentrator, as well as the arrangement of the YWH200-D wave gauges employed in the experiment to characterize wave field variation within the concave opening

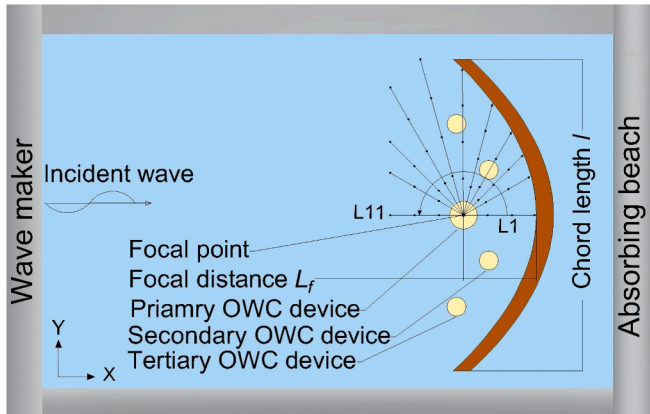


Fig. 7. Schematic of the optimal five-OWC array layout and wave gauge arrangement in the wave field.

region of the concentrator. A total of 39 wave gauges were divided into 11 groups and labeled counterclockwise as L1, L2, ..., L11. These wave gauges were strategically deployed in a radial pattern centered at the focal point, with an angular interval of $\pi/12$ rad and uniform spacing along the radial direction.

Fig. 8 depicts the equipment arrangements for the single and dual-chamber OWC device. As shown in Fig. 8(a), three wave gauges were employed to monitor the variation in the elevation of the free surface inside the OWC chamber. Two CY200 pressure sensors were used to measure the pneumatic pressure within each OWC chamber. For the dual-chamber OWC device, an additional three wave gauges and two pressure sensors were deployed to simultaneously monitor the variations in both chambers, as shown in Fig. 8(b). Four KD6005 load cells were used to record the wave forces acting on the OWC device. The wave force signals measured during the experiment exhibit two directions. The positive signal was defined as consistent with the propagation direction of the incident waves, while the negative signal was defined as opposite to this direction. Accordingly, positive wave force signals were primarily measured under the action of incident waves, whereas negative signals are mainly obtained under the action of waves reflected from the parabolic wave energy concentrator. The wave force acting on the OWC device was defined as the average value of the sum of positive and negative force signals. And the dimensionless horizontal wave force F^* is defined as

$$F^* = F_x / \rho g A h_2, \quad (2)$$

where F_x is the measured horizontal wave force, ρ is the water density, g is gravitational acceleration, A is the incident wave amplitude, and h_2 is the draft height of the OWC device.

3.3. Calculation method of Wave-to-Wire efficiency

In this study, the peak and average power output (P_{peak} , P_{ave}) of each OWC device were measured using the power analyzer. The incident wave power of each OWC device in the array is denoted as P_{in} , which is defined as the local incident wave energy flux arriving at the OWC chamber itself, rather than the total wave energy intercepted by the entire parabolic concentrator. This definition follows the commonly adopted efficiency calculation method for OWC devices arranged in front of breakwaters or integrated with coastal structures, where the input power is evaluated using the characteristic chamber width of the OWC device rather than the full length of the auxiliary wave-field-modifying structure [58,59,70,71], because these peripheral structures only alter the local wave field without changing the inherent wave-to-electricity conversion process of the OWC device. Therefore, the P_{in} is calculated by

$$P_{\text{in}} = P_w w, \quad (3)$$

where w is the characteristic width of the OWC chamber, and P_w is the average energy flux per unit width of the incident wave, computed by

$$P_w = \frac{1}{2} \rho g A^2 C_g, \quad (4)$$

where g is the gravitational acceleration and ρ is the water density; A is the incident wave amplitude and C_g is the group velocity of the incident wave, determined from

$$C_g = \frac{\sqrt{gk \tanh kh}}{2k} \left(1 + \frac{2kh}{\sinh 2kh} \right), \quad (5)$$

where k is the wave number and h is the still water depth.

Thus, the average Wave-to-Wire conversion efficiency of each OWC, and the total conversion efficiency of the OWC array, are calculated by

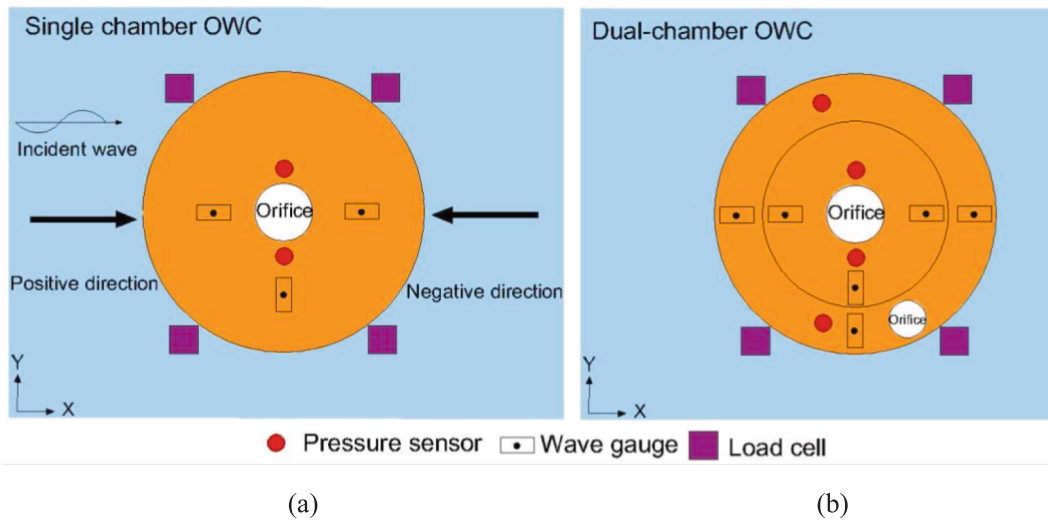


Fig. 8. Schematic of the equipment arrangement on the OWC device: (a) single chamber OWC, (b) dual-chamber OWC.

$$\eta = \frac{P_{ave}}{P_{in}}, \eta_{total} = \frac{\sum P_{ave,i}}{\sum P_{in,i}} (i = 1, 2, 3), \quad (6)$$

in which the input and output power are doubled for $i = 2$ or 3 , owing to the inclusion of two secondary and/or two tertiary OWC devices. Furthermore, the WtW efficiency reported in this study should be interpreted as the local OWC-level wave energy conversion efficiency under the wave-energy-concentrated condition.

3.4. Experimental repeatability and uncertainty analysis

3.4.1. Repeatability analysis

Repeatability analysis was conducted to assess the repeatability of the experimental measurements. Each test condition in the present experimental campaign was repeated three times under the same wave condition and experimental configuration. For each repeated run, the same steady-state time window was used to calculate the average power output, WtW efficiency, and horizontal wave force. The mean value, standard deviation, and coefficient of variation were then calculated for each quantity. To keep the presentation concise, several representative test conditions are selected and summarized in Table 5. These representative results demonstrate the repeatability of the measured power output, WtW efficiency, and horizontal wave force. The same

Table 5
Repeatability analysis of representative test cases.

Test Case	Wave condition	Quantity	Mean value	Standard Deviation	Coefficient of variation
Case 1	$H = 0.15$ m, $T = 1.4$ s	Total average power output (W)	8.3	0.15	1.80
Case 2			16.5	0.16	0.97
Case 3			17.8	0.25	1.41
Case 1	$H = 0.15$ m, $T = 1.4$ s	Total WtW efficiency (%)	4.4	0.08	1.81
Case 2			8.7	0.08	0.92
Case 3			9.4	0.30	3.19
Case 1	$H = 0.15$ m, $T = 1.7$ s	Dimensionless horizontal wave force	1.38	0.02	1.45
Case 2			1.46	0.01	0.68
Case 3			1.42	0.03	2.11

repeatability-processing procedure was applied to all remaining test conditions. These results indicate good repeatability and stability of the experimental setup and measurement procedure. The relatively small coefficients of variation indicate that the experimental results are repeatable.

3.4.2. Uncertainty analysis

To ensure the reliability of the experimental results, calibration and uncertainty analysis were conducted for the main measured quantities, including wave elevation, chamber pressure, horizontal wave force, and electrical power output. Before the formal experiments, all sensors were calibrated according to their corresponding measurement ranges. The wave gauges were calibrated using a multi-point static water-level calibration method. The pressure sensors were calibrated by applying known pressure differences and checking the zero-offset and linear response. The load cells were calibrated using known standard loads. The power analyzer was checked using known voltage, current signals and standard resistive loads before the electrical power measurements.

The main directly measured quantities in this study include wave height, chamber pressure, horizontal wave force, and electrical output power. The instrument uncertainty of each directly measured quantity was estimated from the manufacturer-specified accuracy. When the accuracy was given as a maximum error range, it was treated as the half-width of a rectangular distribution and converted into standard uncertainty by

$$u = a/\sqrt{3}, \quad (7)$$

where a is the maximum error bound. Table 6 presents the uncertainties of the corresponding measurements.

The uncertainties of the derived quantities, including total average power output, WtW efficiency, and wave force, were evaluated using standard uncertainty propagation. This approach is consistent with the uncertainty treatment commonly used in experimental OWC studies. The combined standard uncertainty u_A was calculated as

Table 6
Uncertainty of the main instruments.

Measured quantity	Instrument	Standard uncertainty
Wave height	Wave gauge	0.7 mm
Chamber pressure	Pressure sensor	0.025 kPa
Horizontal wave force	Load cell	7.5 N
Dimensionless horizontal wave force		0.05
Electrical power	Power analyzer	0.075 W

$$uA = \left[\left(\frac{\partial A}{\partial B_1} uB_1 \right)^2 + \left(\frac{\partial A}{\partial B_2} uB_2 \right)^2 + \dots + \left(\frac{\partial A}{\partial B_n} uB_n \right)^2 \right]^{\frac{1}{2}}, \quad (8)$$

where A is derived quantity; $B_1, B_2, \dots, B_n$ are independent measured variables with standard uncertainties $uB_1, uB_2, \dots, uB_n$. To compare the uncertainty levels of different quantities with different units, the relative uncertainty of each quantity was calculated as the ratio of its standard uncertainty to the corresponding measured value and further calculated as

$$ur, A = uA/A \times 100\%. \quad (9)$$

The uncertainty results in Table 7 were further compared with the main reported performance improvements. The relative uncertainties of total average power output and WtW efficiency are within 0.42%-0.90% for the representative high-frequency condition. These values are much smaller than the maximum WtW efficiency improvements reported in this study, namely 98.8% for Case 2 relative to Case 1 and 113.6% for Case 3 relative to Case 1. In addition, the average WtW efficiency of the fully integrated system reaches 50.0%, while the relative uncertainty of the WtW efficiency calculation remains below 1% in the representative uncertainty analysis. This indicates that the reported efficiency enhancement is much larger than the estimated uncertainty level. For the wave force results, the relative uncertainties of the dimensionless horizontal wave force are 1.4%-1.9% under the representative condition. These uncertainty levels are substantially smaller than the maximum wave force reduction of 24.1%. Therefore, the reported wave force mitigation effect is distinguishable from the uncertainty associated with force measurement and normalization. Overall, the uncertainty analysis supports the reliability of the main conclusions regarding WtW efficiency enhancement and wave force reduction.

4. Results and discussions

4.1. Frequency-broadening wave-energy capture characteristic of the array system

The combined effect of incident waves and multi-directional reflected waves generated by the parabolic wave energy concentrator gives rise to additional high-frequency harmonic waves at the focal location. Consequently, the waves impinging on the OWC devices installed at the focal points, especially the primary OWC, are no longer unidirectional and monochromatic, but multi-directional and multi-frequency. This results in the coexistence of wave crests and troughs of different frequencies inside the OWC chamber, causing the internal water column to oscillate in a sloshing mode, as shown in the cross-sectional view of Fig. 9(a). Under this condition, the air volume inside the chamber experiences simultaneous compression and decompression, a phenomenon that significantly degrades the efficient conversion from wave energy to pneumatic power. To overcome this inherent limitation, the dual-chamber OWC configuration is proposed and implemented in the primary OWC of the five-OWC array system, as illustrated in Fig. 9

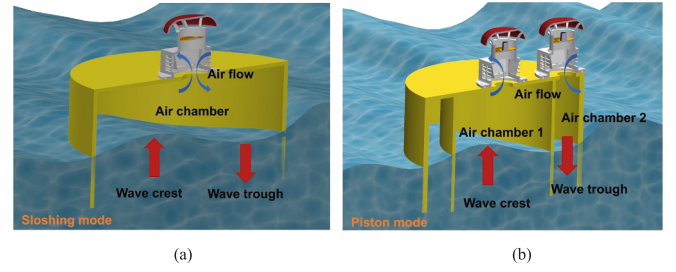


Fig. 9. Frequency-broadening wave-energy-capture mechanism of the dual-chamber OWC device: (a) free surface state within the single-chamber OWC, (b) free surface states within the dual-chamber OWC.

(b). The dual-chamber structure decouples the two distinct water column motions observed in the single-chamber OWC device, confining the water column oscillation in each chamber to a piston-mode, which is highly favorable for efficient energy conversion.

Fig. 10(a) and (b) compare the average power output of the single-chamber primary OWC in Case 1 and the dual-chamber primary OWC in Case 2, as well as the total average power output of the five-OWC array for both Cases, at a wave height of $H = 0.15$ m. It can be seen that the power outputs for both cases show similar trends with varying wave periods. Notably, under all tested wave period conditions, the power output of the primary OWC accounts for a substantial proportion of the total power in each Case, with the maximum contribution exceeding 33.3%. Compared with Case 1, the adoption of the dual-chamber structure in Case 2 improves the motion mode of the water column within the OWC chamber, leading to higher power output from the primary OWC over the entire range of wave periods. This improvement is especially significant under high-frequency wave conditions. For example, at $T = 1.4$ s, the average power of the primary OWC increases from 7.7 W to 11.8 W, corresponding to a relative improvement of 53.2%. Benefiting from the enhanced power output of the primary OWC, the total average power output is also significantly increased across all tested wave periods, with the maximum relative enhancement of 98.8%. The positive effect of the dual-chamber structure is also reflected in the WtW efficiency. As shown in Fig. 10(c), the dual-chamber structure allows the primary OWC in Case 2 to capture and convert more wave energy efficiently, thereby improving its average WtW efficiency. Consequently, the total average WtW efficiency of Case 2 is increased by more than 10.7%, with a maximum enhancement of 98.8%. These results further confirm that the dual-chamber structure can enhance the high-efficiency power output of individual OWC device and OWC array systems, enabling a frequency-broadening effect under the tested regular wave conditions.

To further elucidate the underlying mechanism responsible for in the broadband energy capture enabled by the dual-chamber structure, Fig. 11 presents the spectral analysis at each stage of the wave-energy-conversion chain for the single-chamber primary OWC in Case 1 and the dual-chamber primary OWC in Case 2. As clearly shown in Fig. 11 (a), the sloshing motion of the water column inside the single-chamber primary OWC generates multiple high-order harmonic components in both the free surface-elevation spectrum and the chamber air pressure spectrum. In contrast, the electrical power spectrum only exhibits a noticeable amplitude at the fundamental frequency. For instance, the dimensionless amplitude of the free-surface elevation spectrum within the single-chamber primary OWC device reaches 0.29 at $\omega/\omega_0 = 2$. This amplitude decreases to 0.28 in the air pressure spectrum following pneumatic conversion, and further drops to 0.02 in the final electrical power spectrum. This observation indicates that the high-order harmonic components cannot contribute to efficient energy conversion. This phenomenon arises from the enhanced wave non-linearity induced by the sloshing motion of the internal water column, which appears as higher harmonics in the free surface oscillation.

Table 7

Relative uncertainty results for derived quantities.

Test Case	Wave conditions	Quantity	Value	Relative uncertainty (%)
Case 1	$H = 0.15$ m, $T = 1.4$ s	Total average power output (W)	8.3	0.90
Case 2			16.5	0.45
Case 3			17.8	0.42
Case 1	$H = 0.15$ m, $T = 1.7$ s	WtW efficiency (%)	46.1	0.90
Case 2			51.1	0.45
Case 3			50.0	0.42
Case 1	$H = 0.15$ m, $T = 1.6$ s	Dimensionless horizontal wave force	3.53	1.4
Case 2			2.74	1.8
Case 3			2.68	1.9

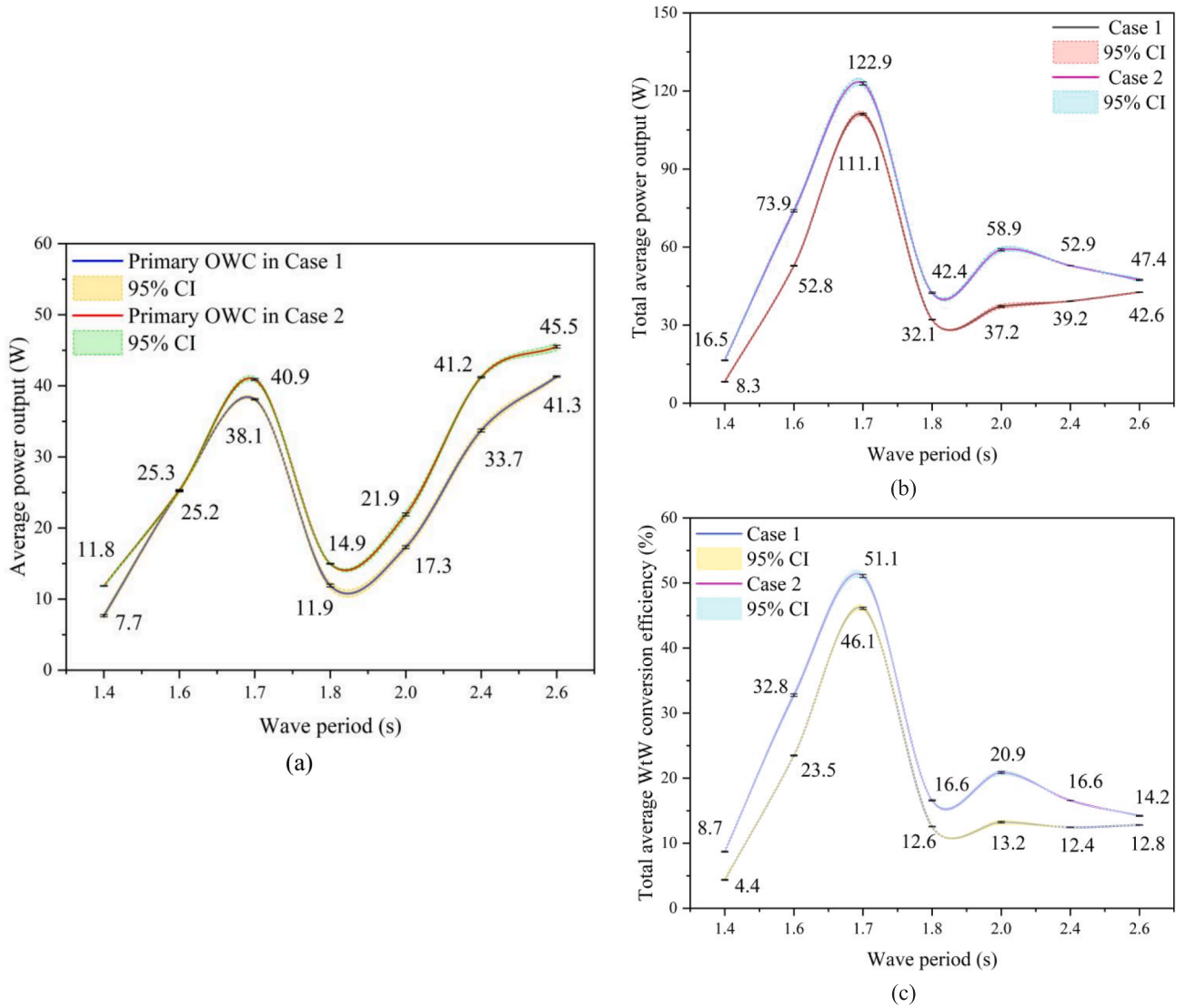


Fig. 10. Comparative analysis of the wave-energy-harvesting performance between the Case 1 and Case 2 at $H = 0.15$ m: (a) average power output of the primary OWC; (b) total average power output; (c) total average WtW efficiency.

After integrating the dual-chamber structure into the primary OWC in Case 2, the dimensionless amplitude of the free-surface elevation spectrum (Fig. 11(b)) for Chamber 1 increases from 0.71 to 0.81 at the fundamental frequency, while the dimensionless amplitude of the air pressure spectrum (Fig. 11(c)) rises from 1.35 to 1.36, in comparison with the single-chamber primary OWC. Although the relative improvement in Chamber 1 is modest, Chamber 2 delivers additional contributions, with the dimensionless amplitudes of its free-surface elevation and air pressure spectra reaching 0.41 and 1.61, respectively. This result demonstrates that the dual-chamber structure constrains the water column motion and gradually transfers energy from the high-order harmonic components to the fundamental frequency. It should be noted that this process does not represent a direct linear conversion of high-order harmonic waves into fundamental frequency waves. Rather, the dual-chamber configuration spatially constrains the free-surface motion and suppresses sloshing-dominated nonlinear oscillations, thereby promoting a more coherent piston-mode response. As a result, a larger proportion of the water column motion and air pressure fluctuation is concentrated near the fundamental frequency, which is more effectively converted by the PTO system. Consequently, the dimensionless amplitude of the power spectrum (Fig. 11(d)) for dual-chamber primary OWC increases significantly to 0.39, three times that of the single-chamber

primary OWC. This energy transfer mechanism enables the dual-chamber OWC device to achieve a broader efficiency-bandwidth for wave energy capture compared to its single-chamber OWC counterpart.

4.2. Wave force reduction characteristic of the array system

The parabolic wave energy concentrator not only achieves the quantitative improvement in the power output and energy conversion efficiency of the OWC device, but also imposes greater wave forces on the OWC device. As the core power-generating component in the array layout, the primary OWC achieves high power output while enduring the maximum wave force. In addition, the integration of the dual-chamber structure increases the force-bearing area of the primary OWC, resulting in larger wave forces acting on the device. This phenomenon poses a considerable challenge to the structural survivability of the primary OWC device, rendering it difficult to balance two key objectives: high-efficiency power output and long-term structural survivability. To address this issue, the porous device is integrated with the primary OWC, which dissipates wave energy through frictional losses at its permeable interface. As shown in Fig. 12(a), in the absence of the porous device, the wave run-up elevation at the exterior of the OWC chamber reaches H_1 . When the porous device is introduced as shown in

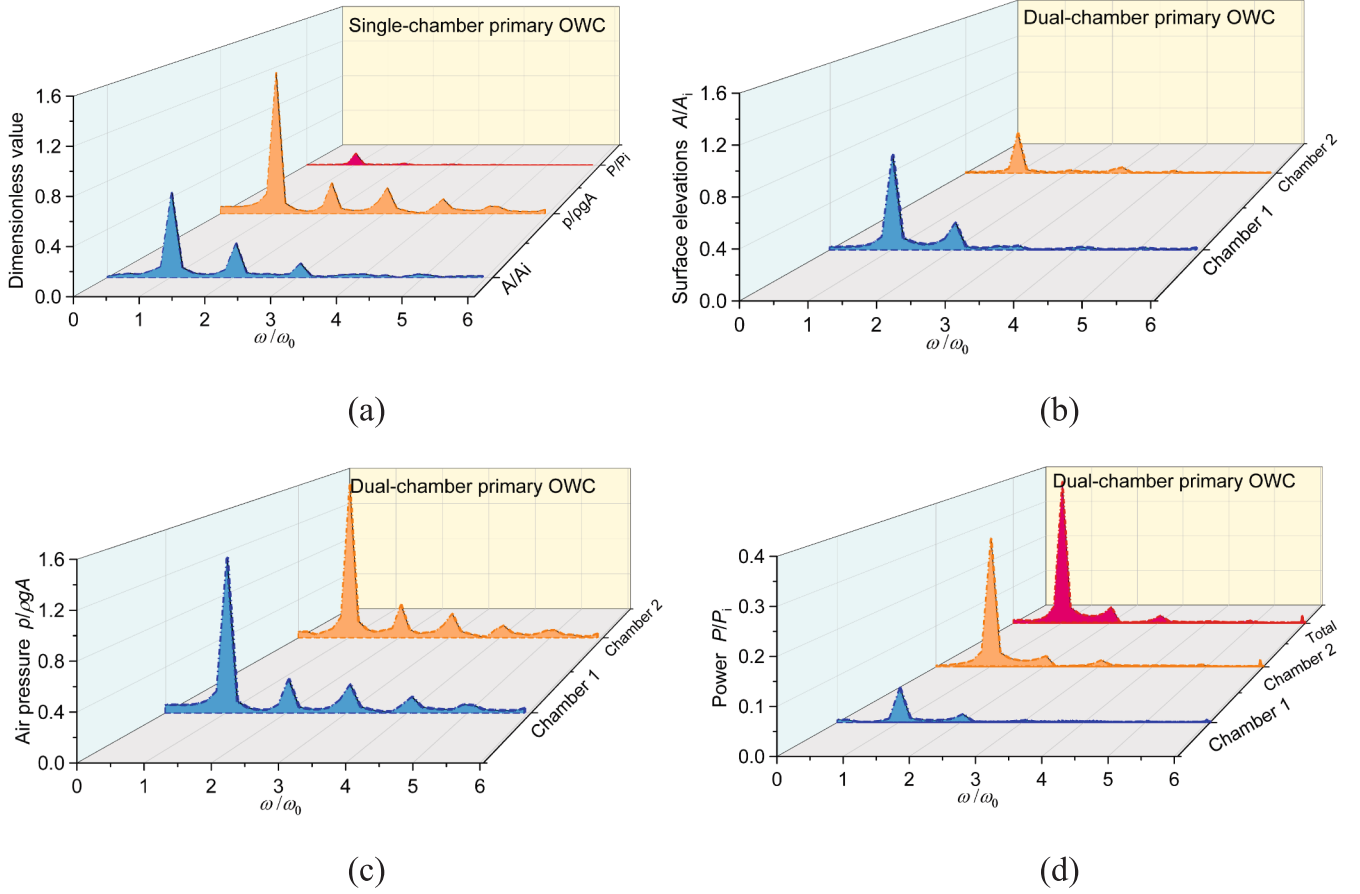


Fig. 11. Spectral analysis of each stage in the wave-energy-conversion process for the primary OWC in Case 1 and Case 2 at $H = 0.15$ m, $T = 1.7$ s: (a) single-chamber primary OWC in Case 1, (b) free surface elevation spectrum of the dual-chamber primary OWC in Case 2, (c) air pressure spectrum of the dual-chamber primary OWC in Case 2, (d) power spectrum of the dual-chamber primary OWC in Case 2.

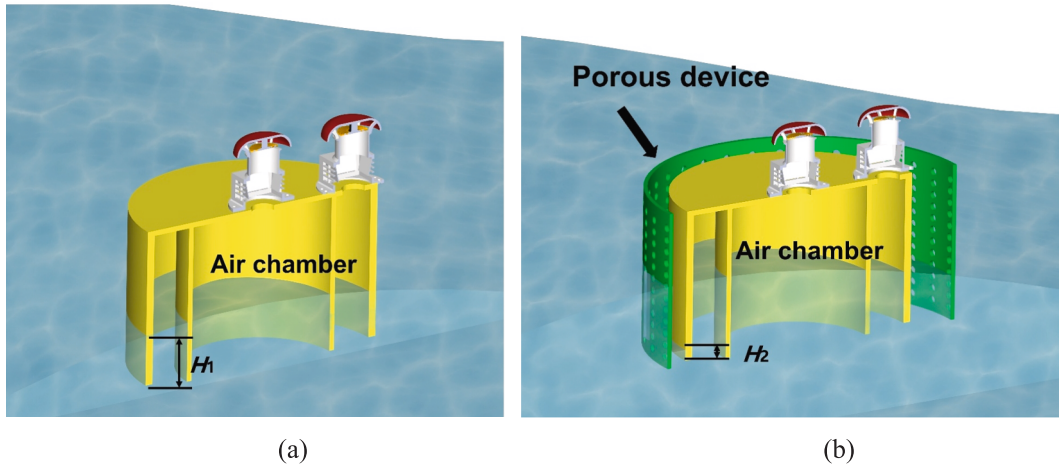


Fig. 12. Wave force reduction mechanism of the porous device: (a) free-surface run-up outside the OWC chamber wall without the porous device, (b) free-surface run-up height outside the OWC chamber wall with the porous device.

Fig. 12(b), the wave run-up elevation reduces to H_2 due to the energy dissipation effect of the porous device, thereby reducing the load acting on the OWC chamber. It should be noted that the comparison between wave run-up elevation H_1 and H_2 is solely intended to demonstrate the wave force reduction effect of the porous device and carries no explicit numerical significance.

Fig. 13 presents the time history curves of the dimensionless

horizontal wave force acting on the primary OWC for Cases 1–3 at $T = 1.7$ s. In all three cases, the positive dimensionless horizontal wave force on the primary OWC is significantly smaller than the negative force. This phenomenon occurs because the incident waves propagate unidirectionally, which is consistent with the defined positive direction, whereas the reflected waves generated by the parabolic wave energy concentrator propagate in multiple directions. Consequently, the negative

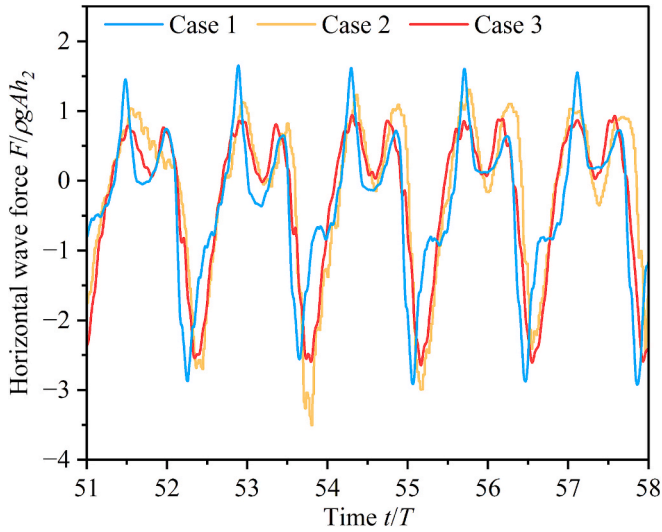


Fig. 13. Time histories of the dimensionless horizontal wave force on the primary OWC in Cases 1–3 at $H = 0.15$ m, $T = 1.7$ s.

dimensionless horizontal wave force induced by the reflected waves is notably larger than the positive horizontal dimensionless wave force induced by incident waves. A comprehensive comparison of Cases 1–3 further reveals that the integration of the porous device exerts a favorable effect in reducing both the positive and negative horizontal wave forces acting on the primary OWC.

The porous device primarily dissipates energy from high-frequency waves, while the wave energy absorbed by OWC devices is predominantly derived from relatively low-frequency waves [72]. Consequently, the integration of the porous device provides a promising strategy to reduce the wave forces on the OWC device without significantly compromising the wave-energy-capture performance. To further illustrate the effect of the porous device, Fig. 14 illustrates the dimensionless horizontal wave forces acting on the primary OWC for Cases 1–3. Furthermore, the results of Case 2 and Case 3 by normalizing against Case

1 are also provided to show a clearer quantitative comparison. Notably, the primary OWC in Case 2 adopts the dual-chamber structure but is not equipped with the porous device.

For Cases 1–3, the wave force acting on the primary OWC reaches a trough at $T = 1.7$ s, which is attributed to the concentration of wave energy inside the primary OWC chamber. Under other wave periods, variations in wavelength alter the wave energy concentrating position, leading to a significant increase in the horizontal wave force acting on the primary OWC. Compared with Case 1, the introduction of the dual-chamber structure in Case 2 increases the force-bearing area of the primary OWC, resulting in a higher horizontal wave force. However, under high-frequency wave conditions ($T = 1.4$ s and 1.6 s), the dimensionless wave force on the primary OWC decreases by 11.3% and 22.4%, respectively. This reduction arises the transition of the internal water column motion from the sloshing mode to the piston mode induced by the dual-chamber structure, which effectively mitigates the wave force generated by the oscillating water column and thus significantly reduces the horizontal force on the primary OWC.

To further mitigate the adverse effect of the increased horizontal wave force on the primary OWC under low-frequency wave conditions induced by the introduction of the dual-chamber structure in Case 2, the primary OWC device in Case 3 is further integrated with a porous device. Compared with Case 2, the addition of the porous device can reduce the horizontal wave force acting on the primary OWC across all tested wave periods. At $T = 1.4$ and 1.6 s, the wave force decreases further by 10.8% and 2.2%, respectively. For other wave periods, the maximum wave force reduction reaches 17.8% at $T = 2.0$ s. Consequently, the force-bearing characteristics of the primary OWC in Case 3 are maintained or even superior to those in Case 1. Combined with the wave-energy-harvesting performance of the three cases and the result of case 2 and 3 by normalizing against Case 1 presented in Fig. 15, the beneficial effect of introducing the porous device can be further clearly demonstrated.

It is evident that the introduction of the dual-chamber structure in Case 2 achieves a prominent enhancement in the total average power output and WtW efficiency of the OWC array, especially under high-frequency wave conditions. The comparison between Case 2 and Case 1 reflects the isolated effect of the dual-chamber configuration, with the maximum relative improvement in total average WtW efficiency

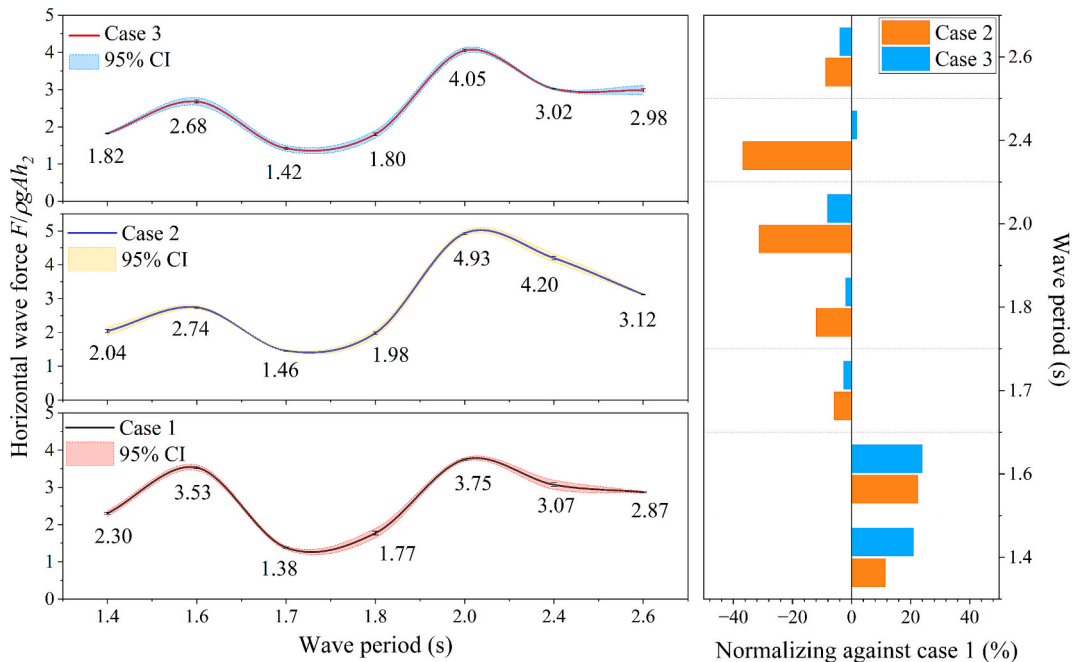
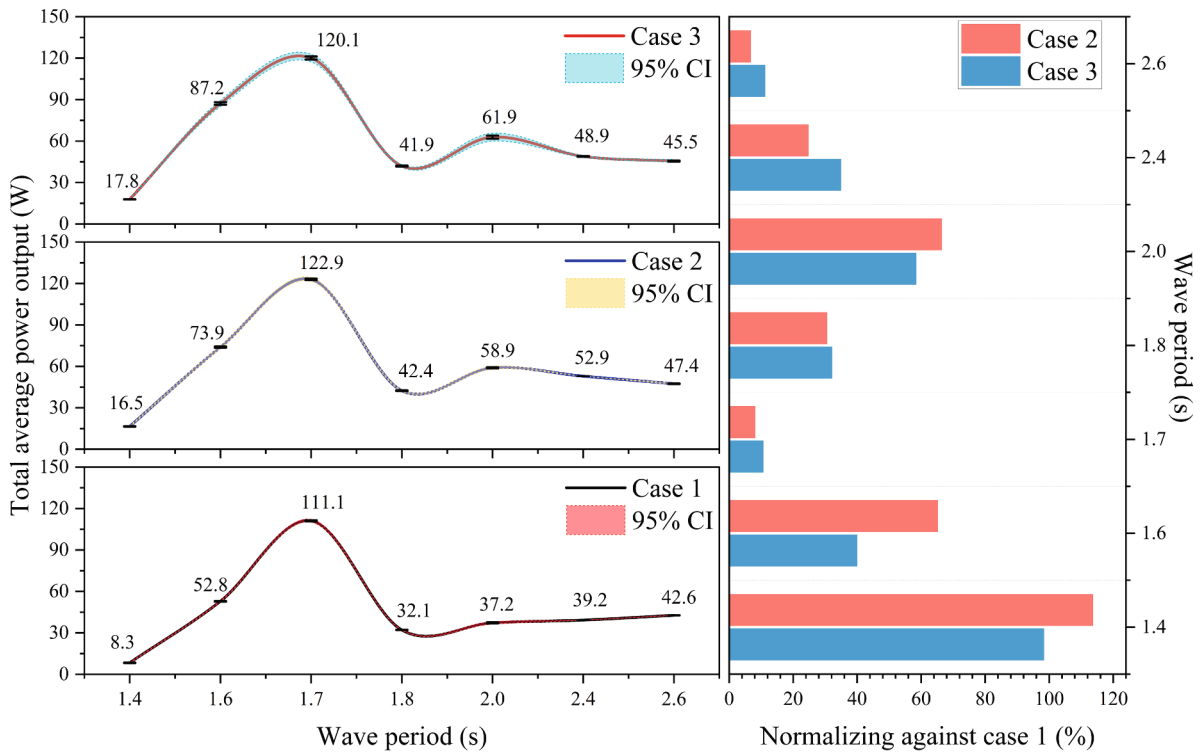
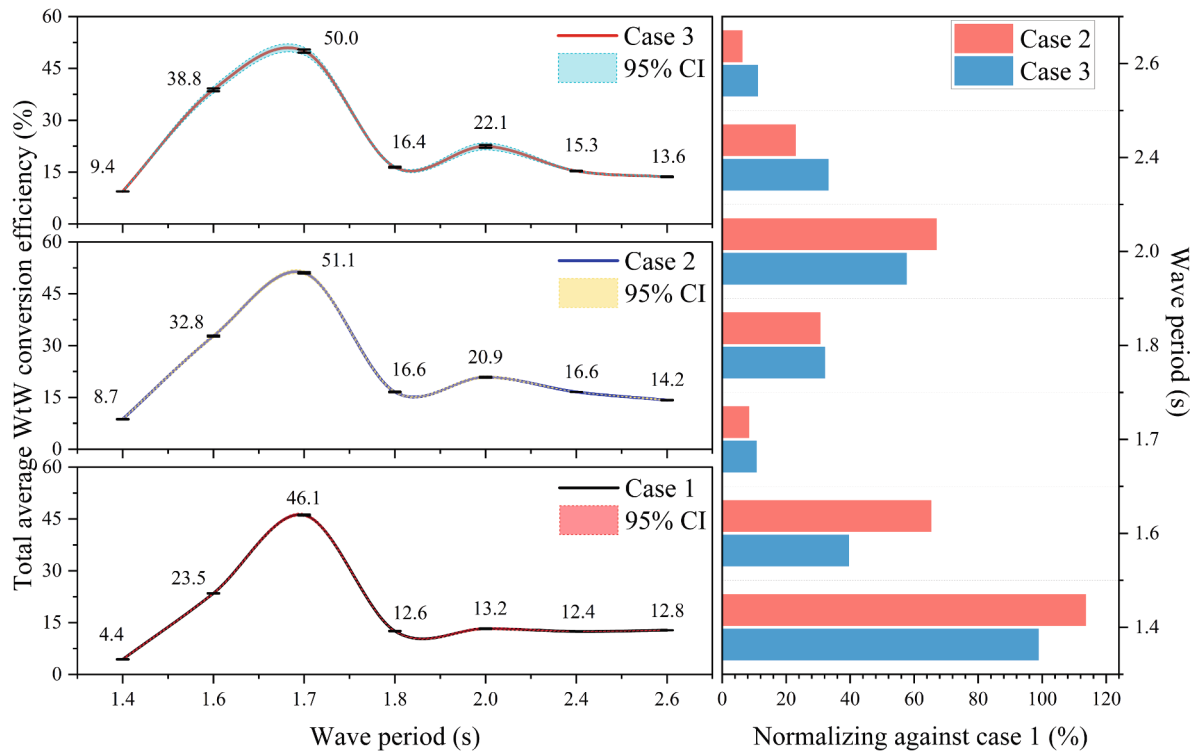


Fig. 14. Comparison of dimensionless horizontal wave force acting on the primary OWC device in Cases 1–3, and the result of Case 2 & 3 by normalizing against Case 1.



(a)



(b)

Fig. 15. Comparison of wave energy harvesting performance of Cases 1–3 at $H = 0.15$ m, and the result of Case 2 & 3 by normalizing against Case 1: (a) total average power output, (b) total average WtW efficiency.

reaching 98.8%. Meanwhile, the horizontal wave force acting on the primary OWC is reduced under high-frequency conditions, owing to the improved internal water-column motion regulated by the dual-chamber configuration. However, the simultaneous improvement in wave energy harvesting performance and reduction of wave force cannot be well achieved under low-frequency wave conditions. This inherent limitation is mainly attributed to the fact that the dual-chamber structure introduces additional force-bearing area. Moreover, this issue is resolved by introducing the porous device in Case 3. As shown in Fig. 15, Case 3 represents the complete multi-feature system, combining the dual-chamber structure and porous device in the primary OWC. Compared with the baseline five-OWC array in Case 1, Case 3 achieves a maximum relative improvement of 113.6% in total average WtW efficiency under the tested wave period conditions. This value corresponds to the comparison between Case 3 and Case 1, and therefore reflects the overall enhancement of the fully integrated system rather than the isolated contribution of the dual-chamber structure. At the same time, the porous device reduces the horizontal wave force acting on the primary OWC, allowing Case 3 to maintain force-bearing characteristics comparable to those of Case 1. Therefore, the porous device preserves the energy-harvesting advantage of the dual-chamber configuration while improving structural survivability, leading to a synergistic balance between high-efficiency energy capture and wave force mitigation, thus significantly improving the survivability and economic viability of the OWC array system.

To further clarify the contribution of the minor OWC components to the overall array performance, the average power output and power contribution ratio of each OWC component in Case 3 are summarized in Table 8. It can be observed that the primary OWC generally remains the dominant energy harvesting component because it is located at the strongest focal region generated by the parabolic wave energy concentrator. Over the tested wave period range, the primary OWC provides the largest contribution to the total array power output, especially at $T = 1.4$ s, 2.4 s, and 2.6 s, where its contribution ratios reach 73.5%, 80.9%, and 94.9%, respectively.

Nevertheless, the secondary and tertiary OWCs also make non-negligible contributions to the total power output under several wave period conditions. For example, at $T = 1.6$ – 1.8 s, the secondary and tertiary OWCs together contribute more than 60% of the total power output, indicating that the minor OWCs can effectively harvest wave energy from the secondary and tertiary energy-concentrated regions formed by the parabolic concentrator. Therefore, these minor OWC

components are not merely auxiliary structures, but active wave-energy-harvesting units that improve the total power output of the array system. In addition to their power contribution, the secondary and tertiary OWCs can also participate in the wave-induced force redistribution within the array. This force distribution effect is beneficial for improving the structural survivability of the primary OWC, especially when combined with the porous device introduced in Case 3.

From an engineering perspective, the individual power contribution information in Table 8 provides a useful basis for future techno-economic assessment of the proposed array system. The additional power obtained from the secondary and tertiary OWCs should be weighed against the increased costs associated with extra chambers, PTO units, installation, operation, and maintenance. It should be noted that the present study focuses primarily on experimentally demonstrating the advantages of the multi-feature energy-concentrated OWC array system, especially the beneficial effects of the dual-chamber structure and porous device on energy-capture enhancement and wave force mitigation. A detailed economic feasibility analysis, including cost-benefit evaluation and levelized cost assessment, will be conducted in future work.

4.3. Engineering implications and scale-up limitations

The proposed multi-feature energy-concentrated OWC array system provides a potential engineering pathway for improving wave energy utilization in low-energy-density coastal regions. However, several practical issues should be considered before full-scale deployment.

The full-scale parabolic wave energy concentrator would require sufficient structural stiffness and foundation stability to withstand long-term cyclic wave loading and occasional extreme wave impacts. The parabolic concentrator can be designed as a modular, semi-submersible pontoon system that can be interconnected for deep-sea conditions. For nearshore or offshore conditions, its construction form may be integrated with breakwaters, harbor protection structures, or nearshore bottom-mounted foundations to reduce additional infrastructure cost. Nevertheless, structural strength, fatigue life, scour protection, and installation tolerance should be carefully evaluated.

The porous device introduces additional engineering considerations. Although the porous device can reduce wave-induced loads on the primary OWC, its long-term performance may be affected by marine corrosion, biofouling, sediment deposition, and possible pore blockage. These effects may gradually change the effective porosity and weaken the designed load-mitigation function. Therefore, modular porous panels, anti-corrosion treatment, inspection access, and replaceable components should be considered in future engineering design. The dual-chamber OWC and multiple PTO units increase the complexity of operation and maintenance. The present laboratory-scale PTO system was mainly used to compare the relative performance of the tested cases under consistent conditions. At commercial scale, turbine-generator efficiency, PTO damping, load matching, air compressibility, and control strategy may significantly affect WtW performance. Therefore, optimized PTO design and full-scale turbine and generator matching are required before practical application.

Finally, the theoretical installed capacity of 1.57 MW estimated in this study should be regarded as a preliminary indicator based on idealized Froude-scale assumptions and representative sea state conditions. The present regular wave experiments cannot fully represent irregular sea states, multi-directional waves, or extreme storm-wave conditions. Full-scale application also requires economic assessment, including additional capital cost of the parabolic wave energy concentrator, minor OWC units, porous device, PTO systems, maintenance cost, and levelized cost of energy. Future work will therefore focus on irregular wave testing, multi wave height experiments, air-compressibility correction, PTO optimization, structural reliability assessment, and techno-economic evaluation.

Table 8
Wave energy harvesting performance of the OWC components in Case 3.

Wave period (s)	OWC component	Average power (W)	Power contribution ratio (%)
1.4	Primary	13.08	73.5
	Secondary	0.82	4.6
	Tertiary	3.90	21.9
1.6	Primary	34.60	39.7
	Secondary	27.20	31.2
	Tertiary	25.40	29.1
1.7	Primary	46.10	38.4
	Secondary	39.20	32.6
	Tertiary	34.80	29.0
1.8	Primary	16.58	39.6
	Secondary	12.90	30.8
	Tertiary	12.42	29.6
2.0	Primary	22.57	36.5
	Secondary	26.60	42.9
	Tertiary	12.73	20.6
2.4	Primary	39.60	80.9
	Secondary	8.64	17.7
	Tertiary	0.66	1.4
2.6	Primary	43.20	94.9
	Secondary	0.60	1.4
	Tertiary	1.7	3.7

5. Conclusions

This work advances OWC technology for high-efficiency ocean wave energy harvesting through four interconnected innovations, addressing critical bottlenecks in power output, bandwidth adaptability, structural survivability, and array-scale reliability. The central breakthrough lies in the passive reshaping of incident wavefields by the parabolic wave energy concentrator prior to energy extraction, which yields substantial enhancements in power output and WtW efficiency. Building on this foundation, the integration of the dual-chamber structure and the porous device enables the proposed multi-feature energy-concentrated OWC array system to achieve a minimum increase of 6.8% in total average power output and average WtW efficiency, with a maximum improvement of 113.6% relative to the baseline five-OWC array in Case 1. In addition, the maximum reduction in horizontal wave force acting on the primary OWC within the system reaches 24.1%.

The proposed array system demonstrates remarkable feasibility for high-efficiency wave energy harvesting in low-energy-density marine regions, such as the coastal waters of Guangdong Province, China (with a significant wave height of approximately 2 m and an average wave period ranging from 5 to 7 s). Based on idealized Froude-scale assumptions and representative sea-state conditions, the theoretical installed capacity is preliminarily estimated to be 1.57 MW. It should be noted that this value is regarded only as a preliminary indicator of potential full-scale capacity, rather than a validated full-scale power rating. Given that the present experimental campaign was conducted under a fixed incident wave height, direct extrapolation to the full spectrum of operational sea states, including low and extreme wave conditions which requires further systematic validation. Therefore, the full-scale prototype tests, together with systematic investigations under irregular and extreme sea states, are required in future work to verify the practical performance and engineering reliability of the proposed system.

Moreover, the multi-feature energy-concentrated OWC system also highlights the critical importance of balancing power output enhancement and wave forces mitigation in the design of wave energy exploitation systems. Consequently, the multi-feature energy-concentrated OWC array system provides a transformative approach for long-term and large-scale wave energy exploration facilitating grid-scale energy supply and significantly improving the commercial viability of wave energy as a renewable energy resource. This research not only advances OWC array technology but also lays a solid foundation for the practical application and industrialization of wave-energy-harvesting systems in low-energy-density coastal areas.

In this study, the introduction of the dual-chamber structure and porous device, as structural optimization strategies, is first applied to the energy-concentrated OWC array system, and the beneficial effects have been preliminarily validated. Future work will expand the range of investigated wave conditions and systematically explore the influences of key design variables, including geometric parameters and structural characteristics of multi-chamber and porous device, on the overall system performance. This is expected to further enhance the generality and engineering robustness of the multi-feature energy-concentrated OWC array system.

CRedit authorship contribution statement

Maokun Ge: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Guohu Xie:** Writing – review & editing. **Peiwen Cong:** Writing – review & editing. **Jianchun Zhao:** Writing – review & editing. **Zhenqiang Jiang:** Writing – review & editing, Project administration. **Dezhi Ning:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

- [1] Cui Y, Zhao H. Marine renewable energy project: the environmental implication and sustainable technology. *Ocean Coastal Manage* 2023;232:106415.
- [2] Adcock T, Draper S, Willden R, Vogel C. The fluid mechanics of tidal stream energy conversion. *Annu Rev Fluid Mech* 2020;53:1–24.
- [3] Astariz S, Iglesias G. The economics of wave energy: a review. *Renew Sustain Energy Rev* 2015;45:397–408.
- [4] Kamranzad B, Amarouche K, Akpinar A. Linking the long-term variability in global wave energy to swell climate and redefining suitable coasts for energy exploitation. *Sci Rep* 2022;12:14692.
- [5] Salter SH. Wave power. *Nature* 1974;249:720–4.
- [6] Wang X, Niu S, Yin Y, Yi F, You Z, Wang Z. Triboelectric nanogenerator based on fully enclosed rolling spherical structure for harvesting low-frequency water wave energy. *Adv Energy Mater* 2015;5(24):1501467.
- [7] Shao Z, Gao H, Liang B, Lee D. Potential, trend and economic assessments of global wave power. *Renew Energy* 2022;195:1087–102.
- [8] Unna PJH. Wave energy: sideways flow and losses by the shore. *Nature* 1946;158:635–6.
- [9] MUSGROVE PJ. Energy analysis of wave-power and wind-power systems. *Nature* 1976;262:206–207.
- [10] Gallutia D, Tahmasbi Fard M, Gutierrez Soto M, He J. Recent advances in wave energy conversion systems: from wave theory to devices and control strategies. *Ocean Eng* 2022;252:111105.
- [11] Korde UA, Ringwood J. *Hydrodynamic Control of Wave Energy Devices*. Cambridge University Press; 2016.
- [12] Gonzalez N, Serna-Torre P, Sánchez-Pérez PA, Davidson R, Murray B, Staadecker M, et al. Offshore wind and wave energy can reduce total installed capacity required in zero-emissions grids. *Nat Commun* 2024;15:6826.
- [13] Rtimi R, Sottolichio A, Tassi P, Bertier C, Le Brun M, Vandenhove M, et al. Three-dimensional hydrodynamic model of the Rance estuary (France) influenced by the world's second largest tidal power plant. *LHB* 2022;108(1):1–8.
- [14] Budar K, Falnes J. A resonant point absorber of ocean-wave power. *Nature* 1975;256:478–9.
- [15] Swift-Hook DT, Count BM, Glendenning I, Salter S. Characteristics of a rocking wave power device. *Nature* 1975;254:504–6.
- [16] López I, Andreu J, Ceballos S, Martínez De Alegría I, Kortabarria I. Review of wave energy technologies and the necessary power-equipment. *Renew Sustain Energy Rev* 2013;27:413–34.
- [17] Zhang Y, Zhao Y, Sun W, Li J. Ocean wave energy converters: technical principle, device realization, and performance evaluation. *Renew Sustain Energy Rev* 2021;141:110764.
- [18] Ning DZ, Wang RQ, Zou QP, Teng B. An experimental investigation of hydrodynamics of a fixed OWC Wave Energy Converter. *Appl Energy* 2016;168:636–48.
- [19] Medina-Lopez E, Allsop W, Dimakopoulos D, Bruce T. Conjectures on the failure of the OWC breakwater at Mutriku. In: *Proceedings of Coastal Structures*, 2015.
- [20] Pawitan KA, Dimakopoulos AS, Vicinanza D, Allsop W, Bruce T. A loading model for an OWC caisson based upon large-scale measurements. *Coast Eng* 2019;145:1–20.
- [21] Cheng Y, Du W, Dai S, Ji C, Collu M, Cocard M, et al. Hydrodynamic characteristics of a hybrid oscillating water column-oscillating buoy wave energy converter integrated into a π -type floating breakwater. *Renew Sustain Energy Rev* 2022;161:112299.
- [22] Cheng Y, Fu L, Dai S, Collu M, Ji C, Yuan Z, et al. Experimental and numerical investigation of WEC-type floating breakwaters: a single-pontoon oscillating buoy and a dual-pontoon oscillating water column. *Coast Eng* 2022;177:104188.
- [23] Guo B, Ringwood JV. Geometric optimisation of wave energy conversion devices: a survey. *Appl Energy* 2021;297:117100.
- [24] Falcão AFO, Henriques JCC, Gomes RPF, Portillo JCC. Theoretically based correction to model test results of OWC wave energy converters to account for air compressibility effect. *Renew Energy* 2022;198:41–50.

- [25] Abbasi R, Ketabdari MJ. Enhancement of OWC Wells turbine efficiency and performance using riblets covered blades, a numerical study. *Energ Conver Manage* 2022;254:115212.
- [26] Gadelho J, Guedes Soares C, Barajas G, Lara JL. CFD analysis of the PTO damping on the performance of an onshore dual chamber OWC. *Trends Maritime Technol Eng* 2022;2:381–9.
- [27] Zhang C, Ning D. Hydrodynamic study of a novel breakwater with parabolic openings for wave energy harvest. *Ocean Eng* 2019;182:540–51.
- [28] Zhang H, Tao A, Tu J, Su J, Xie S. The focusing waves induced by bragg resonance with V-shaped undulating bottom. *J Marine Sci Eng* 2021;9:708.
- [29] Hao J, Li J, Liu S, Wang L. Wave amplification caused by Bragg resonance on parabolic-type topography. *Ocean Eng* 2022;244:110442.
- [30] Xu J, Ning D, Mayon R, Zhao M. Hydrodynamic investigation of a parabolic breakwater for wave energy focusing. *Phys Fluids* 2023;35:097145.
- [31] Ranjan S, Manjul RR, Kumar S, Sharma DK. Comparative experimental study of rectangular and parabolic base oscillating water column devices under varying wave conditions. *Int Commun Heat Mass Transfer* 2026;175:111222.
- [32] Mayon R, Ning D, Zhang C, Chen L, Wang R. Wave energy capture by an omnidirectional point sink oscillating water column system. *Appl Energy* 2021;304:117795.
- [33] Mayon R, Ning D, Sun Y, Ding Z, Wang R, Zhou Y. Experimental investigation on a novel and hyper-efficient oscillating water column wave energy converter coupled with a parabolic breakwater. *Coast Eng* 2023;185:104360.
- [34] Liu Z, Xu C, Kim K, Li M. Experimental study on the overall performance of a model OWC system under the free-spinning mode in irregular waves. *Energy* 2022;250:123779.
- [35] He F, Leng J, Zhao X. An experimental investigation into the wave power extraction of a floating box-type breakwater with dual pneumatic chambers. *Appl Ocean Res* 2017;67:21–30.
- [36] Fu L, Ning D, Wang R, Mayon R. Numerical and experimental study on hydrodynamic performance of a land-based dual-chamber OWC device under irregular waves. *Renew Sustain Energy Rev* 2025;207:114895.
- [37] Zhao X, Zhang L, Li M, Johanning L. Experimental investigation on the hydrodynamic performance of a multi-chamber OWC-breakwater. *Renew Sustain Energy Rev* 2021;150:111512.
- [38] Fu L, Wang R, Kar P, Ning D. Experimental and numerical investigation of wave loads on land-based multi-chamber OWC converters. *Energy* 2024;310:133281.
- [39] Shalby M, Walker P, Dorrell DG. Modelling of the multi-chamber oscillating water column in regular waves at model scale. *Energy Procedia* 2017;136:316–22.
- [40] Fu L, Wang R, Ning D, Mayon R. Numerical investigation on the hydrodynamic performance of a land-based OWC system with multi-chamber modules. *Appl Ocean Res* 2023;141:103801.
- [41] Wang R, Ning D, Zou Q. Wave loads on a land-based dual-chamber Oscillating Water Column wave energy device. *Coast Eng* 2020;160:103744.
- [42] Zhou Y, Ning D, Liang D, Qiao D. Nonlinear wave loads on an offshore oscillating-water-column wave energy converter array. *Appl Ocean Res* 2022;118:103003.
- [43] Zheng S, Meylan MH, Greaves D, Iglesias G. Water-wave interaction with submerged porous elastic disks. *Phys Fluids* 2020;32:047106.
- [44] Gayathri R, Khan M, Behera H, Tsai C-C. Wave attenuation by a submerged circular porous membrane. *J Ocean Eng Sci* 2022.
- [45] Ning D, Zhao X, Teng B, Johanning L. Wave diffraction from a truncated cylinder with an upper porous sidewall and an inner column. *Ocean Eng* 2017;130:471–81.
- [46] Feichtner A, Mackay E, Tabor G, Thies PR, Johanning L, Ning D. Using a porous-media approach for CFD modelling of wave interaction with thin perforated structures. *J Ocean Eng Mar Energy* 2021;7:1–23.
- [47] Qiao D, Mackay E, Yan J, Feng C, Li B, Feichtner A, et al. Numerical simulation with a macroscopic CFD method and experimental analysis of wave interaction with fixed porous cylinder structures. *Mar Struct* 2021;80:103096.
- [48] Göteman M. Wave energy parks with point-absorbers of different dimensions. *J Fluids Struct* 2017;74:142–57.
- [49] Xie G, Zhao T, Ma Y, Ni W, Hu C. Investigation on the wave focusing effects and energy capture of Oscillating Water Column array. *Renew Energy* 2025;238:121901.
- [50] Nader JR, Zhu S, Cooper P, Stappenbelt B. A finite-element study of the efficiency of arrays of oscillating water column wave energy converters. *Ocean Eng* 2012;43:72–81.
- [51] Göteman M, McNatt C, Giassi M, Engström J, Isberg J. Arrays of Point-Absorbing Wave Energy Converters in Short-Crested Irregular Waves. *Energies* 2018;11:964.
- [52] Mayon R, Ning D, Xu J, Fu L. Oscillating water column wave energy converter arrays coupled with a parabolic-wall energy concentrator in regular and irregular wave conditions. *Coast Eng* 2024;192:104559.
- [53] Child BFM, Venugopal V. Optimal configurations of wave energy device arrays. *Ocean Eng* 2010;37:1402–17.
- [54] Huang S, Huang Z. Hydrodynamic performance of a row of closely-spaced bottom-sitting oscillating water columns. *Renew Energy* 2022;195:344–56.
- [55] Portillo JCC, Henriques J, Gomes R, Gato LMC, Falcao A. On the array of wave energy converters: The case of the coaxial-duct OWC, in: *Proceedings of the 37th International Conference on Ocean, Offshore and Arctic Engineering*, Madrid, Paper No. OMAE2018-78022.
- [56] Göteman M, Giassi M, Engström J, Isberg J. Advances and challenges in wave energy park optimization—a review. *Front Energy Res* 2020;8:26.
- [57] Bosma B, Brekken T, Lomonaco P, DuPont B, Sharp C, Batten B. Array modeling and testing of fixed OWC type wave energy converters. *Int Marine Energy J* 2020;3:137–43.
- [58] Mustapa MA, Yaakob OB, Ahmed YM, Rheem C-K, Koh KK, Adnan FA. Wave energy device and breakwater integration: a review. *Renew Sustain Energy Rev* 2017;77:43–58.
- [59] Samuel J, S A S, Sundar V. Performance of an array of oscillating water column devices integrated with an offshore detached breakwater. *Ocean Engineering* 2018;163.
- [60] Zhang D, Chen Z, Liu X, Yu H, Zeng W, Ying Y, et al. A coupled numerical framework for hybrid floating offshore wind turbine and oscillating water column wave energy converters. *Energ Conver Manage* 2022;267:115933.
- [61] Zhou Y, Ning D, Chen L, Mayon R, Zhang C. Experimental investigation on an OWC wave energy converter integrated into a floating offshore wind turbine. *Energ Conver Manage* 2023;276:116546.
- [62] Zhou Y, Geng J, Zhao X, Ning D, He Z. Nonlinear load analysis of an offshore triple-OWC platform. *Renew Energy* 2026;256:124704.
- [63] Wang C, Xu H, Zhang Y, Chen W. Hydrodynamic investigation on a three-unit oscillating water column array system deployed under different coastal scenarios. *Coast Eng* 2023;184:104345.
- [64] Wang C, Xu H, Zhang Y, Chen W. Power capture analysis of a five-unit oscillating water column array integrated into a breakwater in terms of flow field visualization. *Energ Conver Manage* 2023;293:117449.
- [65] Ning D, Ge M, Mayon R, Cong P, Ding Z, Sun Y. Experimental investigation on an energy-focused type OWC WEC array. *Appl Energy* 2026;404:127148.
- [66] Zhang X, Mayon R, Zhou F, Ning D. Experimental and numerical investigation on a novel dual-chamber OWC-WEC integrated with an energy-focusing breakwater. *Coast Eng* 2025;201:104814.
- [67] Zhuang Q, Ning D, Mayon R, Ye X, Lin H. Experimental investigation on a cylindrical OWC device integrated with a porous annulus in open-water and wave-concentrating conditions. *Energ Conver Manage* 2026;361:121596.
- [68] Ding Z, Ning D, Mayon R. Wave-to-wire model for an oscillating water column wave energy converter. *Appl Energy* 2025;377:124663.
- [69] Ning D, Ding Z, Mayon R, Ruan H, Fu Y. Experimental and numerical investigation of resistive load impact on oscillating water column wave energy converter integrated with a parabolic breakwater. *Energy* 2025;324:135960.
- [70] Konispoliatis DN. Performance of an array of oscillating water column devices in front of a fixed vertical breakwater. *J Marine Sci Eng* 2020;8:912.
- [71] Fox BN, Gomes RPF, Gato LMC. Analysis of oscillating-water-column wave energy converter configurations for integration into caisson breakwaters. *Appl Energy* 2021;295:117023.
- [72] Zhuang Q, Ning D, Mayon R, Zhou Y. Experimental and numerical investigation of a land-fixed breakwater-type wave energy converter: an OWC device and a porous plate. *Coast Eng* 2024;194:104614.