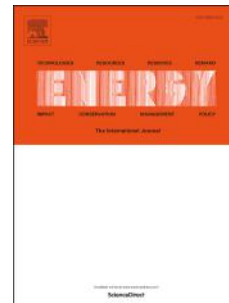


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Enhancing wave energy conversion in oscillating water column devices using breather valve-based pneumatic regulation: A CFD study

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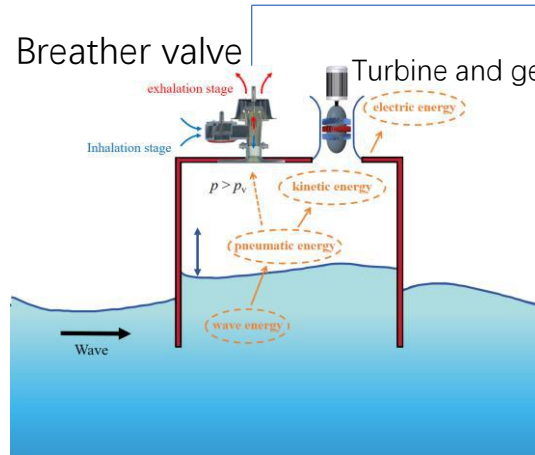
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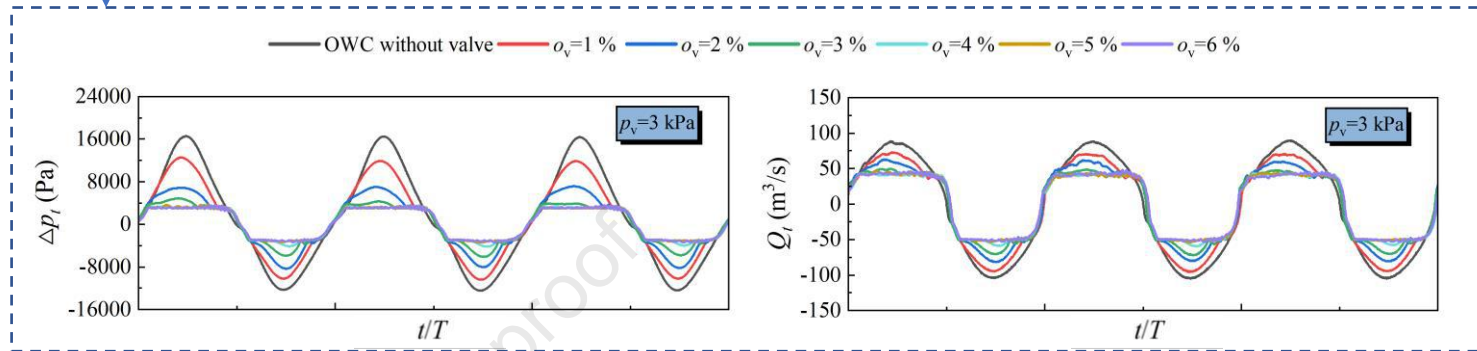
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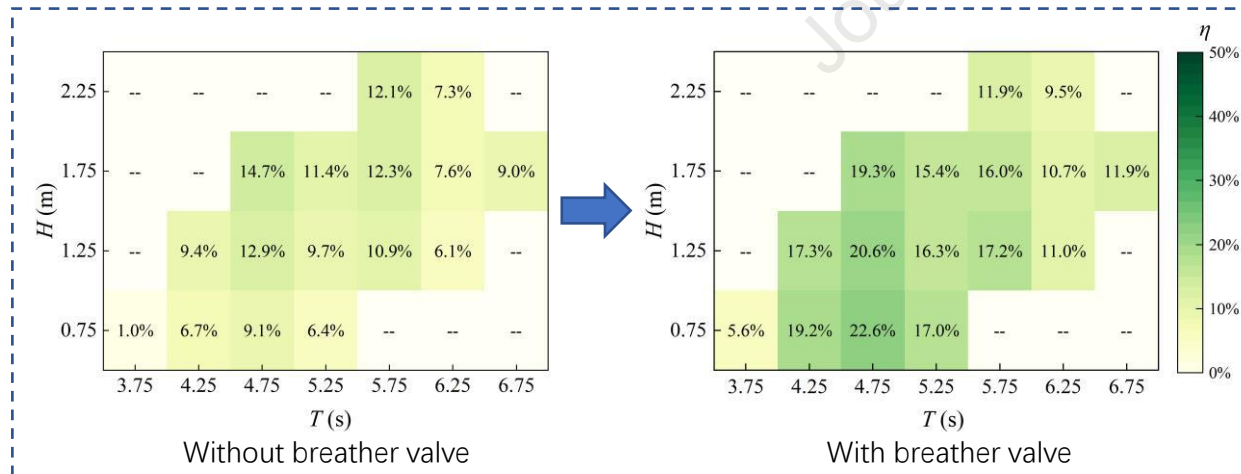
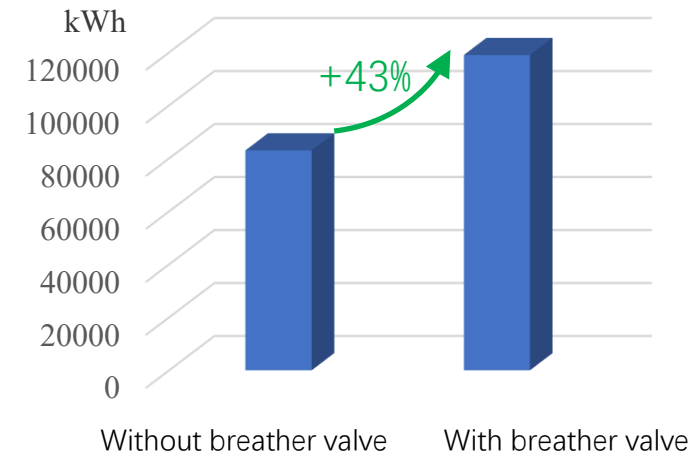
Regulate chamber pressure and airflow rate under high wave conditions



Reduce the required generator rated capacity (from 740 kW to 100 kW)

Improve operational efficiency during normal wave conditions

Increase annual energy production



Enhancing wave energy conversion in oscillating water column devices using breather valve-based pneumatic regulation: A CFD study

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Abstract

This study investigates the hydrodynamic and energy conversion performance of a cylindrical oscillating water column (OWC) device integrated with a breather valve for bidirectional pneumatic regulation. The primary objective is to suppress peak power output under high wave conditions and reduce the required generator rated capacity, thereby improving the load factor and operational efficiency during normal wave conditions. A three-dimensional computational fluid dynamics (CFD) is developed to simulate steady-state and transient flow characteristics, incorporating the nonlinear behavior of the breather valve. Parametric analyses are conducted to evaluate the effects of valve threshold pressure (3–12 kPa) and opening ratio (1%–6%) under regular wave conditions. Results reveal that the valve's pressure and flow regulation capabilities increase with the opening ratio, though this effect gradually saturates. Moreover, for a given threshold, a minimum opening ratio is required to achieve stable pressure relief, which decreases with increasing threshold pressure. The optimal configuration (3 kPa threshold with 5% opening ratio) achieves substantial performance improvements compared to a conventional OWC without a breather valve. Specifically, the rated generator capacity is reduced by 87% (from 740 kW to 100 kW), average generator efficiency increases by 50% (from 60.8% to 90.9%), and average wave-to-electricity conversion efficiency improves by 46% (from 10.3% to 15%). Additionally, annual energy production increases by 43%, from 83,000 kWh to 119,000 kWh. These findings highlight the breather valve's effectiveness in stabilizing pneumatic power output and enhancing the overall efficiency of OWC systems.

Keywords: Wave energy; OWC; Pressure regulation; Breather valve; Annual energy production.

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1. Introduction

As the foundation of modern human life, electricity has faced increasing challenges of shortage in the past few decades. The depletion of fossil energy resources, coupled with the growing challenges of climate change and pollution, has underscored the urgent need for renewable wave energy[1, 2]. To harness wave energy, researchers have invented a series of wave energy converters (WECs), including typical types such as oscillating water column (OWC)[3-6], oscillating body (OB)[7-9], raft-type[10, 11], oscillating wave surge converter (OWSC), and overtopping devices[12].

Among these diverse WECs, the OWC devices were developed earliest and are considered one of the most promising technologies due to their simple structure and high reliability. To thoroughly evaluate OWC performance, extensive theoretical, experimental, and numerical studies have been conducted by researchers to optimize its efficiency[13-18]. Despite these efforts, the commercial application of OWC WECs has not yet been realized. One major challenge lies in their poor performance in real marine environments, where multiple wave conditions with significantly varying wave power levels are encountered. Under extreme sea conditions, the device's power generation is significantly higher than under normal sea conditions. However, since the generator cannot operate above its rated power for prolonged periods, the peak power during extreme sea states becomes a rigid constraint on the generator's rated capacity. Consequently, the rated power determined based on extreme conditions is far higher than the power generated under normal conditions, resulting in the generator's load factor remaining below 0.1 for extended periods. When the load factor falls below 0.1, the generator's efficiency decreases sharply, leading to prolonged periods of low-efficiency operation under normal sea conditions. This issue has been observed in the long-term operation of the well-known oscillating water column (OWC) power plants such as PICO and Mutriku[19, 20]. Exploring methods to overcome the existing limitations of OWC WECs remains a critical research frontier.

To address the above challenges, Falcão and Justino[21] first proposed using a relief valve to regulate the airflow velocity through the Wells turbine under extreme wave conditions. They proposed two installation configurations: one where the valve is installed in series with the turbine in the duct connecting the air chamber to the atmosphere, and another where the valve is install in parallel with the

turbine, controlling airflow actively or passively. Falcão and Rodrigues[22] developed a stochastic method evaluating the series valve configuration, revealing a slight increase in the average output power of a Wells turbine. Subsequently, Falcão[23] later demonstrated that an appropriately controlled relief valve can increase annual energy production by approximately 37%. Carrelhas et al. [24] proposed a control algorithm for a high-speed series valve in OWC to dissipate excess pneumatic energy, validated under real wave conditions at the Mutriku wave power plant. This study demonstrated the potential of phase control and peak shaving strategies. Similarly, Rosati et al. [25] found that a series throttle valve can generally improve turbine efficiency; however, unilateral installation induced non-axisymmetric airflow downstream of the valve, reducing turbine performance in one flow direction.

Falcão et al.[26] investigated the performance of OWC system with controlled bypass valves, instead of the previously studied series configuration, and achieved an approximately 25% increase in annual energy production. This study also analyzed the impact of valve quantity, valve response time, signal noise levels, and valve control algorithms on energy generation. Furthermore, Josset and Clément[27] compared the performance of the Wells turbine under regular and irregular wave conditions when connected in series with a throttle valve and a bypass valve, respectively. They found that the bypass configuration consistently achieved optimal efficiency and observed significant asymmetry in pressure response during the intake and exhaust stages. To address issues of low energy generation at the Pico OWC device, Monk et al. [28] introduced a passive valve on top of an active parallel bypass valve, modifying the chamber pressure distribution and reducing pressure skewness. This modification led to an efficiency increase of up to 30% compared to the system's optimal performance without the passive valve. Previous studies have primarily focused on unidirectional bypass valves for airflow regulation[29, 30], demonstrating potential for improving annual power generation in OWC systems. However, limited research has explored the bidirectional air pressure regulation of an integrated exhalation-inhalation bypass valve, referred to as breather valve in this study.

As shown in Fig. 1, this study introduces a breather valve to enable bidirectional air pressure regulation in OWC systems, effectively mitigating peak power under high wave conditions. The breather valve operates as a passive device: when the instantaneous chamber pressure exceeds a predefined

threshold, the valve automatically opens to discharge excess air, and it closes once the pressure drops below the threshold. In this way, the valve achieves regulation through a self-activated feedback mechanism, without requiring external control. This approach enhances generator efficiency under typical wave conditions by reducing the installed capacity, which increases load factor. Additionally, a sensitivity analysis is performed to assess the influence of breather valve parameters on OWC performance, providing insights into the mechanism by which air pressure regulation affects energy conversion efficiency. This study also evaluates the impact of breather valve parameters on both installed capacity and annual energy production under real-world wave conditions.

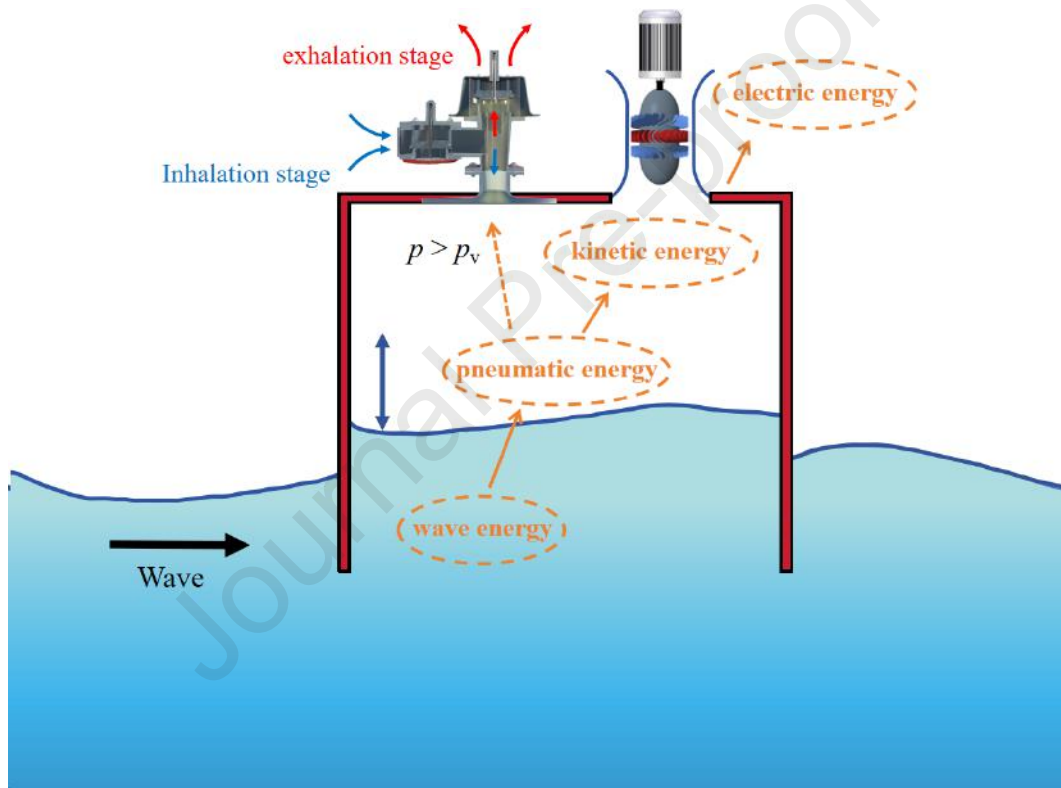


Fig. 1. Schematic of OWC device with a breather valve.

The article is structured as follows: Section 2 presents a CFD model coupling OWC system, breather valve, wave and air. Section 3 demonstrates steady-state and transient-state characteristics of OWC with breather valve and also presents a comparative analysis of the OWC with and without the breather valves. Finally, in Section 4, primary conclusions derived from this investigation are summarized.

2. CFD model

2.1. Governing equations

As the investigated OWC device is large in scale, the compressibility of air cannot be neglected in predicting its wave energy conversion performance, so the compressible model solver is employed in this study[31, 32]. This study employs a porous media approach to simulate the local pressure drop induced by the breather valve, significantly reducing computational cost. The compressible fluid motion is described by solving the three-dimensional compressible Reynolds-averaged Navier-Stokes (RANS) equations with the addition of porous media source terms. The governing equations are formulated as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) + \nabla \cdot (\rho u_s) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = f_i + f_b + \rho g - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] + \frac{\partial}{\partial x_j}(-\rho \overline{u'_i u'_j}) \quad (2)$$

In the equations, ρ is the fluid density; u_i is the mean flow velocity in the i direction; u_s is the apparent velocity in the porous media region; f_i is the external force acting on the fluid in the i direction, excluding gravity and porous media resistance; f_b is the pressure drop in the porous media region; g is the gravitational acceleration; p is the relative pressure; μ is the dynamic viscosity of air; δ_{ij} is the Kronecker delta; and $-\rho \overline{u'_i u'_j}$ is the Reynolds stress. f_b is calculated based on the apparent velocity u_s and the porous inertial resistance tensor $\mathbf{P}$ as

$$f_b = -\mathbf{P} \cdot |u_s| \quad (3)$$

In this study, the breather valve is modeled as a passive pressure-regulation device. Its operation is governed by a predefined pressure threshold p_v . p_v is determined based on the peak chamber pressure observed under high wave conditions in the absence of a valve. When the instantaneous chamber pressure exceeds p_v , the valve is considered open, and $\mathbf{P}$ is set to zero, allowing air to be discharged

through the valve. Conversely, when the chamber pressure falls below p_v , the valve is considered closed, and $\mathbf{P}$ is set to a sufficiently large value ($1 \times 10^8 \text{ kg/m}^4$) to effectively block airflow. In this way, the valve automatically regulates chamber pressure through a passive feedback mechanism without requiring external control. $-\overline{\rho u'_i u'_j}$ is expressed in terms of the mean velocity gradients as

$$-\overline{\rho u'_i u'_j} = \mu_t \left(\frac{\partial u_j}{\partial x_k} + \frac{\partial u_k}{\partial x_j} \right) - \frac{2}{3} \delta_{jk} \left(\rho K + \mu_t \frac{\partial u_k}{\partial x_j} \right) \quad (4)$$

where μ_t is the turbulent viscosity, calculated based on the SST K- Ω turbulence model; and K is the turbulent kinetic energy.

The equation for an ideal gas is used to describe the gas:

$$(p + p_{atm})V = \rho_g R T_a \quad (5)$$

where p_{atm} is the standard atmospheric pressure; V is the air volume; ρ_g is the gas density; R is the molar gas constant; T_a is the absolute temperature of the gas. In our study, the air in the OWC chamber is modeled as an ideal gas undergoing an isentropic compressible process, which is a common assumption in OWC thermodynamic modeling when heat exchange with the surroundings is negligible over the short timescale of wave-induced oscillations. The capture of the fluid interface is completed using the volume of fluid (VOF) method[33], and a high-resolution interface capture method is used for precise capture of the free surface. α is defined as the liquid volume fraction in each computational cell; if the cell is completely occupied by liquid, $\alpha = 1$; and if the cell is completely occupied by gas, $\alpha = 0$. Therefore, the free surface is located where $0 < \alpha < 1$, and satisfies the following volume fraction transport equation:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (u\alpha) + \nabla \cdot u_c \alpha (1 - \alpha) = 0 \quad (6)$$

where u_c is the compressive velocity of the interface; and the density and viscosity can be obtained through the following equations:

$$\rho = \rho_w \alpha + \rho_a (1 - \alpha), \mu = \mu_w \alpha + \mu_a (1 - \alpha) \quad (7)$$

where ρ_w is the density of water, setting at 998 kg/m³; ρ_a is the density of air; μ_w is the viscosity of water; μ_a is the viscosity of air. In this study, water is an incompressible liquid. The model uses the SIMPLE method to couple velocity and pressure, and a second-order implicit time discretization scheme, a Gaussian-LSQ gradient discretization scheme, and a second-order upwind convection term discretization scheme. By specifying appropriate boundary and initial conditions, the above equations can be numerically solved.

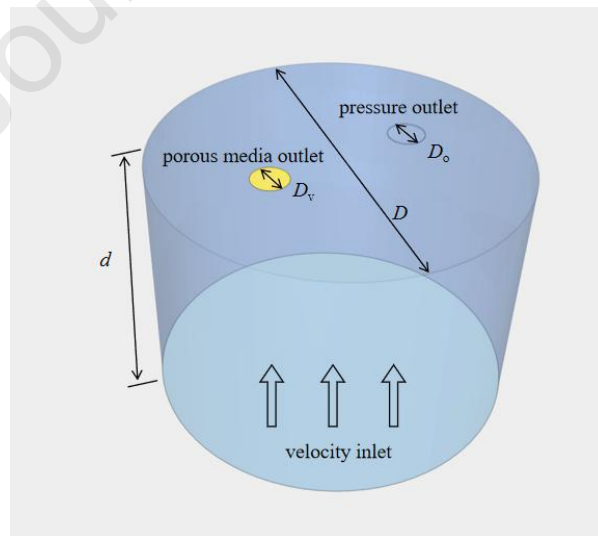
2.2. Computational model setup

The CFD model in this paper is divided into a steady-state model and a transient model. The two types of CFD simulations are employed to achieve different objectives. The steady-state simulations are used to efficiently examine the regulation effect of the breather valve on chamber pressure and orifice flow rate under constant inflow conditions. These results provide a preliminary assessment of suitable opening ratios and threshold pressures, which serves as the basis for the parameter settings in the subsequent transient simulations. In contrast, the transient simulations are carried out for the complete OWC-breather valve-generator system subjected to incident wave forcing. The objective of these simulations is to capture the dynamic coupling among wave excitation, chamber pressure oscillation, valve regulation, and generator output, thereby enabling a detailed investigation of the effect of the breather valve on overall system performance. The steady-state model is shown in Fig. 2 (a), with the computational domain being a cylindrical OWC. The lower base is set as a velocity inlet boundary with a constant flow rate input. At the top of the cylinder, there are two outlets: one is a pressure outlet with an area equal to 1% of the cylinder's cross-sectional area to simulate the PTO system[34]. The other is a porous media outlet simulating the breather valve, with an opening area that ranges from 1% to 6% of the cylinder's cross-sectional area, increasing by 1% increments. This area ratio is defined as σ_v .

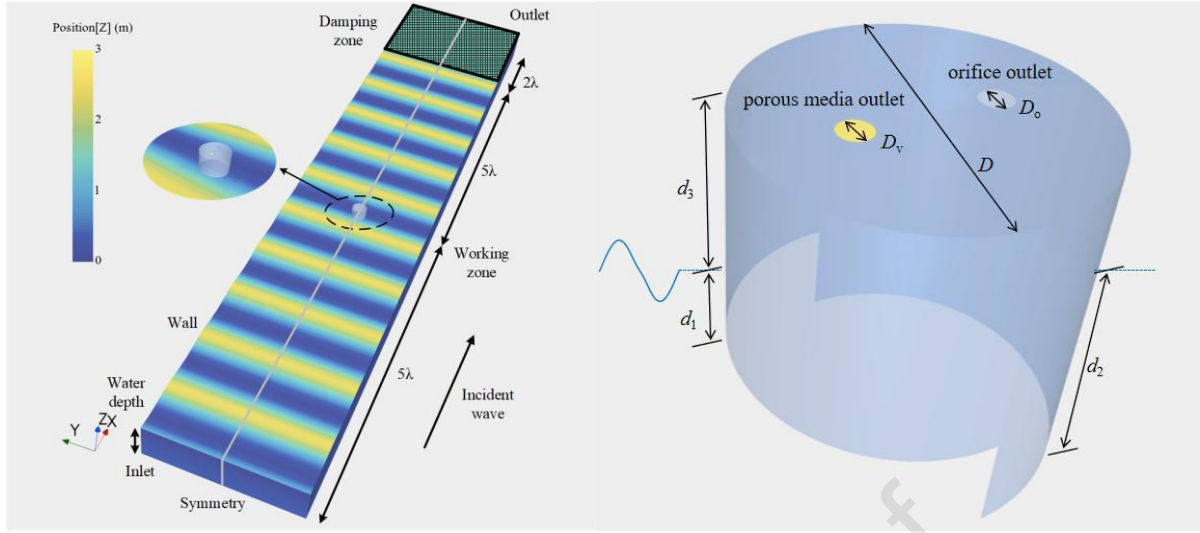
In transient calculations, the total length of the numerical wave tank(NWT) is adjusted according to the studied wave conditions, kept constant at 12 wavelengths (5 wavelengths upstream of the OWC and 7 downstream, including a 2-wavelength damping zone). The NWT is 60 m wide (5 times the OWC

diameter) and 50 m high, with a water phase height set to 30 m based on the average depth at the study site, and the gas phase height of 20 m.

The mesh for the numerical model is generated using the built-in automatic meshing function in STAR-CCM+. The base cell size for the entire computational domain is 6 m, with further refinement in the free surface region and around the OWC structure to ensure accuracy. At least 60 cells are allocated per wavelength in the x-direction and 30 cells in the y-direction of the free surface zone. Additionally, at least 20 cells per wave height are allocated in the z-direction. The cell sizes of NWT in this study are in accordance with the recommended values[10, 35, 36]. Temporal discretization employs a time step of 1/1000 of the wave period. The boundary conditions are set as follows: The left and right sides of the NWT correspond to the inlet and pressure outlet boundaries, respectively, along the x-axis. The top boundary is set to constant pressure (equal to atmospheric pressure), and the bottom and sides are set to no-slip wall boundaries. Considering the symmetry of the model about the xOz plane, a symmetry boundary condition is applied at the xOz plane to reduce computational costs, assuming symmetric flow and pressure fields across this plane. In addition to the wave elevation, the water particle velocities at the inlet boundary are prescribed according to the fifth-order Stokes wave theory[37], with further details provided in [10].



(a)



(b)

Fig. 2. Schematic of model setup: (a) steady-state model; (b) transient model.

The OWC WEC investigated in transient simulations is shown in Fig. 2 (b). Similar to the steady-state model, the structure comprises a cylindrical chamber with 12 m diameter and 0.01 m wall thickness. A coaxial tube-sector support with a diameter equal to that of the OWC is installed at the bottom to enhance wave energy absorption following recommendations from references^[38, 39]. The front wall draft(d_1) is maintained at $H/2$ to ensure aerodynamic seal integrity, while the rear wall draft (d_2) is configured as $0.3D+d_1$. Two outlets are also defined at the top of the OWC chamber. One is an orifice outlet, with an area equal to 1% of the cylinder's cross-sectional area, representing the PTO system. The other is a porous media outlet, modeling the breather valve, with σ_v varying from 1% to 6%, in 1% increments, similar to the steady-state setup. For transient simulation, the breather valve threshold is governed through parametric control of the porous inertial resistance tensor. Given the peak pressure of 16.5 kPa observed in the OWC without a breather valve, four distinct thresholds (3, 6, 9, and 12 kPa) are implemented for comparative analysis.

To investigate the effects of pressure regulation in OWC under real wave conditions, this study uses the wave conditions at 18°30'N, 111°10'E, near Wanning in Hainan Province, China, as the basis for the incident wave input. This region exhibits high wave energy density and experiences significant typhoon activity. Wave data from the past year were collected, and the top 16 most frequently occurring

wave conditions (accounting for over 80% of the total occurrence probability), along with a high wave condition, are summarized in Table 1. This study considers only the effects of regular waves, assuming that the wave heights and periods of the regular waves are consistent with those listed in Table 1 and are used as input conditions for the numerical model.

Table 1. Wave condition parameters.

Wave conditions	Wave period T (s)	Wave height H (m)	Probability of occurrence (%)	Annual occurrence hours (h)
Normal wave conditions	3.75	0.75	6.62	580
	4.25	0.75	9.91	868
	4.75	0.75	5.92	519
	5.25	0.75	3.54	310
	4.25	1.25	9.45	828
	4.75	1.25	11.5	1007
	5.25	1.25	7.13	625
	5.75	1.25	4.1	359
	6.25	1.25	1.95	171
	4.75	1.75	2.23	196
	5.25	1.75	3.92	343
	5.75	1.75	4.17	365
	6.25	1.75	2.47	216
	6.75	1.75	1.96	172
	5.75	2.25	3.84	336
	6.25	2.25	1.76	154
High wave condition	8.75	5.75	0.07	6

2.3. Energy conversion assessment method

To evaluate the energy conversion efficiency of the OWC, a series of assessment methods are introduced. The efficiency of converting wave energy to pneumatic energy in one wave condition is calculated as

$$\eta_1 = \frac{\overline{P_{\text{pneu}}}}{\overline{P_{\text{in}}}} \times 100\% = \frac{\frac{1}{NT} \int_{t_0}^{t_0+NT} \Delta p_i Q_i dt}{\frac{1}{4k} \rho_w g A^2 \omega \left(1 + \frac{2kh}{\sinh 2kh} \right) D} \times 100\% \quad (8)$$

where $\overline{P_{\text{pneu}}}$ is the average pneumatic power within a wave period; $\overline{P_{\text{in}}}$ is the average incident wave power within a wave period; N is the number of wave periods considered in the calculation; T is the wave period; Δp_i is the instantaneous pressure difference in the air chamber relative to the atmosphere; Q_i is the instantaneous airflow rate through the turbine; ρ_w is the density of water; A is the amplitude of the incident wave; ω is the wave frequency; and k is the wave number. The average pneumatic efficiency ($\overline{\eta_1}$) of the OWC across a range of normal wave conditions evaluated as

$$\overline{\eta_1} = \frac{\sum_{i=1}^n \overline{P_{\text{pneu}_i}} \cdot \omega_i}{\sum_{i=1}^n \overline{P_{\text{in}_i}} \cdot \omega_i} \times 100\% \quad (9)$$

where ω_i is the occurrence probability of the normal wave condition of i .

Air turbines are devices that convert pneumatic energy into the mechanical kinetic energy of the rotor, and the efficiency under one wave condition is calculated as

$$\eta_2 = \frac{\overline{P_{\text{rotor}}}}{\overline{P_{\text{pneu}}}} \quad (10)$$

where $\overline{P_{\text{rotor}}}$ is average rotational kinetic energy of the turbine within a wave period. In this work, the air turbine efficiency η_2 is approximated by a constant value of 50%, as suggested in previous studies [40-42]. This assumption is based on experimental and numerical studies [43, 44], which reported that the average efficiency of Wells and impulse turbines typically falls in the range of 40–60% under oscillating flow conditions. The breather valve primarily affects the amplitude of the chamber pressure, while the bidirectional oscillatory airflow pattern remains unchanged. Therefore, the valve is not expected to significantly alter the time-averaged turbine efficiency. Although this simplification is reasonable for evaluating the relative impact of valve parameters on overall OWC performance, we acknowledge that a fully coupled turbine–valve analysis would provide more comprehensive insight.

This will be considered in future work. Additionally, the efficiency of the generator is expressed through the relationship between the instantaneous mechanical kinetic energy of the turbine P_{rotor} and the rated power of the generator P_{rated} [45, 46]. By defining the generator load coefficient $C_l = P_{\text{rotor}} / P_{\text{rated}}$, the calculation formula for the generator efficiency is as

$$\eta_3 = \begin{cases} \left(\sum_{n=1}^8 D_n C_l^n - 0.035 \right) \times 100\%, C_l < 0.4 \\ 95\%, C_l \geq 0.4 \end{cases} \quad (11)$$

where D_n is coefficient constant, $D_1 = 27.7$, $D_2 = -402.9$, $D_3 = 3299.4$, $D_4 = -154290$, $D_5 = 39739.1$, $D_6 = -47813.9$, $D_7 = 7218.6$, $D_8 = 23320.7$. The average generator efficiency ($\overline{\eta_3}$) of OWC across a range of normal wave conditions is evaluated as

$$\overline{\eta_3} = \frac{\sum_{i=1}^n \overline{P_{\text{out}_i}} \cdot \omega_i}{\sum_{i=1}^n \overline{P_{\text{rotor}_i}} \cdot \omega_i} \times 100\% \quad (12)$$

where $\overline{P_{\text{out}}}$ is average output power of the generator within a wave period. It is worth note that the determination of generator rated capacity(installed capacity) fundamentally governs the wave energy conversion efficiency across all wave conditions for OWC. Henriques[47] proposed setting the rated capacity as twice the expected average annual power extraction, which often leads to generator overload during highly energetic sea states. Babarit[48] recommend using a value 20 times the device's annual mean absorbed power as a baseline value, which results in a low load factor and consequently low efficiency of the generator. Sheng[40] established an annual conversion efficiency of 0.3 as a reference criterion, without considering generator overload. This study introduces a novel method for determining the generator rated capacity based on the peak instantaneous mechanical kinetic energy of the air turbine under high wave condition. The core principle ensures that the generator operates within safe load thresholds during the high wave condition.

Based on the above assumptions, the wave-to-electricity conversion efficiency calculation formula of the OWC under one wave condition is

$$\eta = \eta_1 \cdot \eta_2 \cdot \eta_3 \quad (13)$$

The output power of the generator can be expressed as

$$\overline{P_{\text{out}}} = \eta \cdot \overline{P_{\text{in}}} \quad (14)$$

The average wave-to-electricity conversion efficiency ($\bar{\eta}$) across a range of normal wave conditions is calculated as

$$\bar{\eta} = \frac{\sum_{i=1}^n \overline{P_{\text{out}_i}} \cdot \omega_i}{\sum_{i=1}^n \overline{P_{\text{in}_i}} \cdot \omega_i} \times 100\% \quad (15)$$

The power generation for each sea state is calculated as

$$E_{\text{out}_i} = \overline{P_{\text{out}_i}} \cdot h_i \quad (16)$$

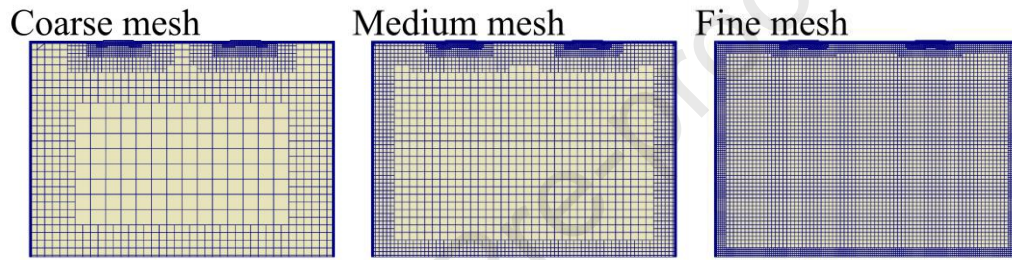
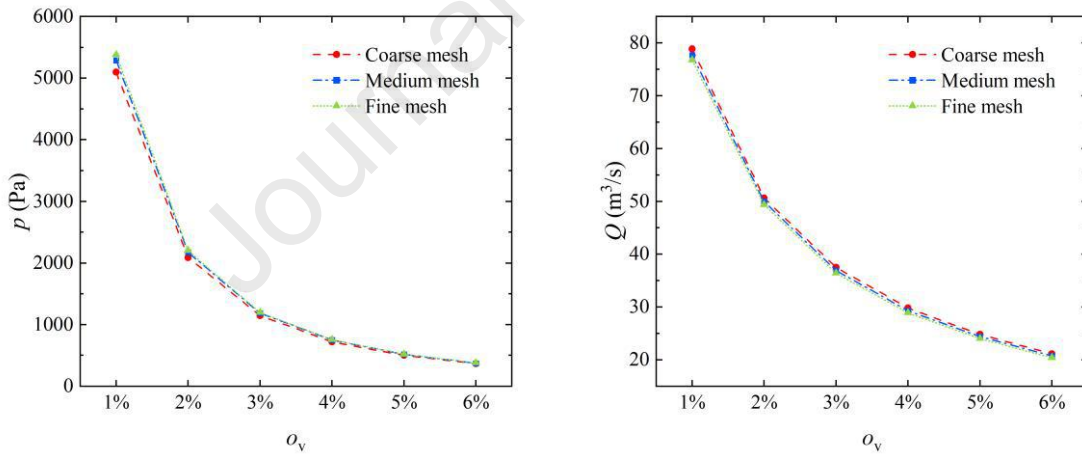
Where h_i is the annual occurrence hours for the i -th wave condition. The annual energy production (AEP) is calculated as

$$AEP = \sum_{i=1}^n E_{\text{out}_i} \quad (17)$$

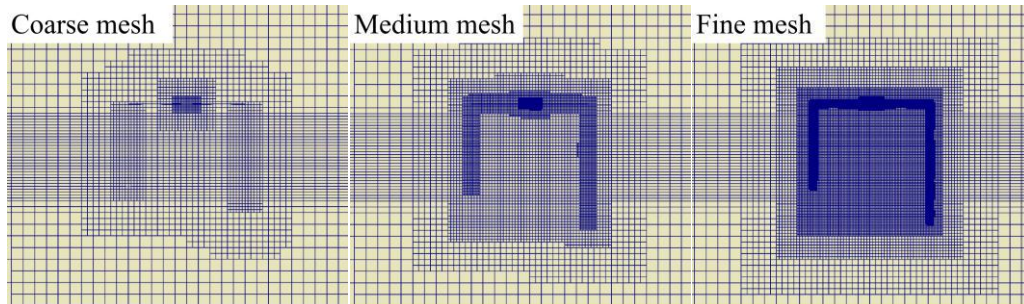
2.4. Model validation

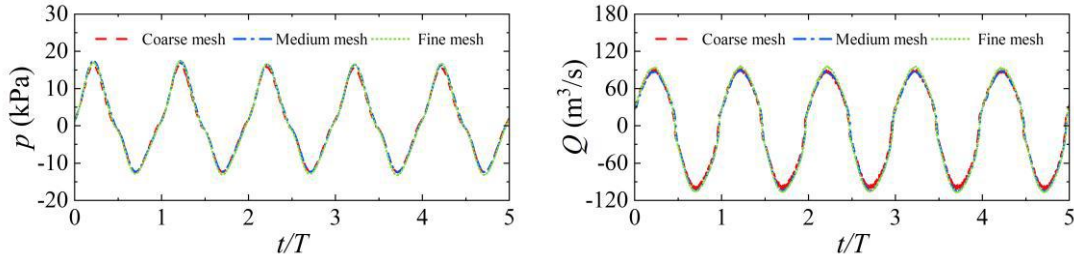
The current work is primarily conducted within the framework of CFD. Mesh sensitivity analyses are conducted for both the steady-state and transient models, as shown in Fig. 3. For the steady-state model, three mesh resolutions are considered: coarse (0.07 million cells), medium (0.25 million cells), and fine (1.05 million cells). The inlet velocity is set to 1.3 m/s, and the ϕ_v of the breather valve ranges from 1% to 6%. For the transient model, the mesh resolutions include coarse (1.24 million cells), medium (1.43 million cells), and fine (2.28 million cells). Fig. 3 (a) shows that for the steady-state model, when the mesh number increases from 0.07 million to 1.05 million, the maximum relative errors for chamber pressure and orifice flow volume are 5.27% and 3.37%, respectively, and the average relative errors are 4.17% and 2.90%, respectively. When the mesh number increases from 0.25 million to 1.05 million, the maximum relative errors for chamber pressure and orifice flow rate are 1.69% and 1.50%,

respectively, and the average relative errors are 1.02% and 1.36%, respectively. Fig. 3 (b) shows that for the transient model, when the mesh number increases from 1.24 million to 1.43 million, the R^2 values for chamber pressure and orifice flow rate are 0.987 and 0.989, respectively. These values are within the commonly accepted tolerance of 5% in CFD analyses. When the mesh number increases from 1.43 million to 2.28 million, the R^2 values for chamber pressure and orifice flow rate are 0.997 and 0.998, respectively. These results indicate that both the medium mesh steady-state model and the transient model have converged. Balancing the accuracy of the calculation results with computational costs, the medium mesh is selected for subsequent simulations.



(a)





(b)

Fig. 3. Mesh convergence: (a) steady-state model ; (b) transient model .

Furthermore, the experimental results of Li et al.[14] are used for validation. As shown in Fig. 4 (a), the experimental model includes a cylindrical fixed OWC device with a structure similar to that in this study. The device has an inner radius of 0.188 m and two openings: the upper opening with an opening ratio of 1.25% allows the airflow to pass through; the lower opening allows wave propagation, with an opening angle of $2/3\pi$. The OWC is placed in a tank that is 60 m long, 3 m wide, 1.5 m high, and has a water depth of 0.95 m. As shown in Fig. 4 (b), both the orifice model and the porous media model are used to simulate the effect of the turbine. The porous inertial resistance tensor is set to 0 in the porous media model to replicate the behavior of an orifice. Fig. 5 compares the numerical results from both models with the experimental results [14]. Under the wave condition of $kh=1.00$, the orifice model yields R^2 values of 0.984 for free surface elevation and 0.959 for pressure, while the porous media model yields R^2 values of 0.983 and 0.953, respectively. For $kh=1.41$, the orifice model achieves R^2 values of 0.977 for free surface elevation and 0.974 for pressure, while the porous media model achieves R^2 values of 0.967 and 0.976, respectively. The results indicate that the numerical model results agree well with the experimental data, validating the accuracy of the numerical model. In addition, these results confirm that the porous media method with zero resistance can accurately reproduce the physical behavior of an orifice.

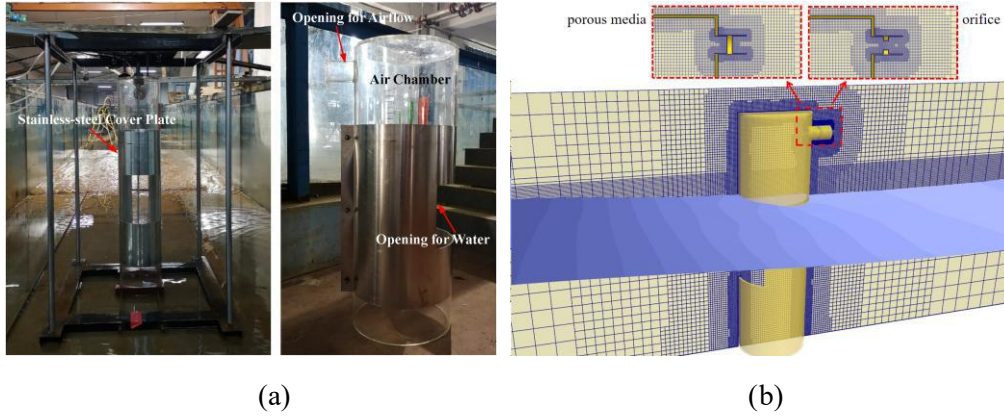


Fig. 4. Experimental and numerical models: (a) experimental; (b) numerical model.

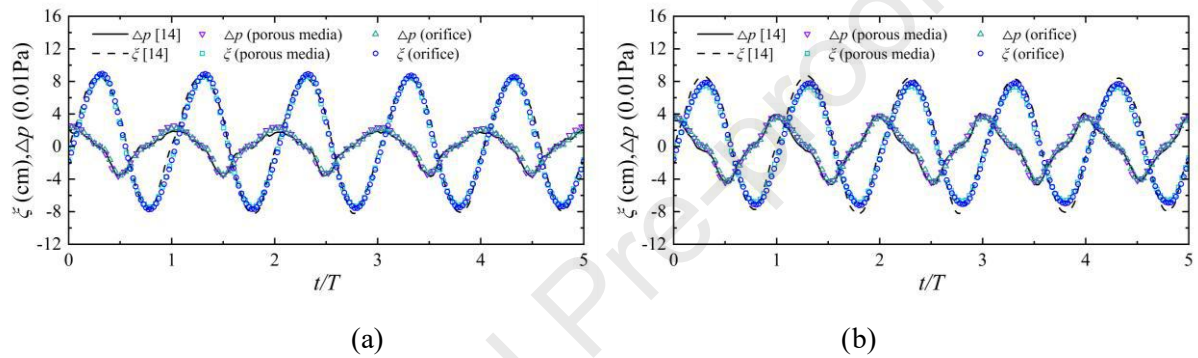


Fig. 5. Comparison of numerical results with experimental data: (a) $kh=1.00$; (b) $kh=1.41$.

3. Results and discussion

3.1. Effect of breather valve on air pressure regulation under constant airflow

This section aims to explore the steady-state performance of OWC with a breather valve of different opening ratios. Through the input of constant airflow, we systematically evaluate the pressure regulation effect of the breather valve on the chamber pressure and orifice flow rate reduction capabilities, thereby informing valve selection for OWC in regular wave conditions of the transient model. Approximately 50 calculations are performed, covering an inlet flow velocity (v_{in}) range from 0.8m/s to 1.5m/s, which almost encompasses the inlet flow velocity that may occur under high wave condition in transient calculations. The α_v of the breather valve ranges from 1% to 6%.

The pressure reduction ratio (PRR) and flow rate reduction ratio (FRR) are defined as the relative reductions in chamber pressure and airflow rate through the turbine, respectively, in the OWC system

with a breather valve, compared to the system without one. Fig. 6 presents the variations of PRR and FRR with v_{in} under multiple σ_v . The results indicate that the breather valve has a stronger effect on reducing chamber pressure than on reducing the airflow rate, as PRR is consistently higher than FRR under the same operating conditions. For a given v_{in} , both PRR and FRR increase with increasing σ_v . However, their rates of increase diminish as σ_v becomes larger. Specifically, when σ_v increases from 1% to 2%, the average PRR across different v_{in} values increases from 83% to 93%, and the average FRR increases from 58% to 73%. In contrast, increasing σ_v from 5% to 6% results in only a marginal increase in PRR (from 98.3% to 98.7%), and FRR (86.6% to 88.6%). Moreover, as v_{in} increases, the pressure regulation performance of the valve gradually enhances. This can be attributed to the enhanced flow relief capacity provided by the breather valve. In the configuration without a breather valve, all airflow must exit through the orifice, whose flow resistance increases nonlinearly with velocity. As v_{in} increases, the kinetic energy of the incoming air leads to a more rapid accumulation of pressure within the chamber due to the limited discharge capacity of a single orifice. The introduction of a second outlet—modeled as a breather valve—offers an additional discharge path, which becomes increasingly effective at relieving pressure under high-flow conditions. This dual-outlet configuration reduces the overall flow resistance and mitigates pressure buildup more effectively than the single-outlet case. As a result, PRR becomes more pronounced at higher v_{in} .

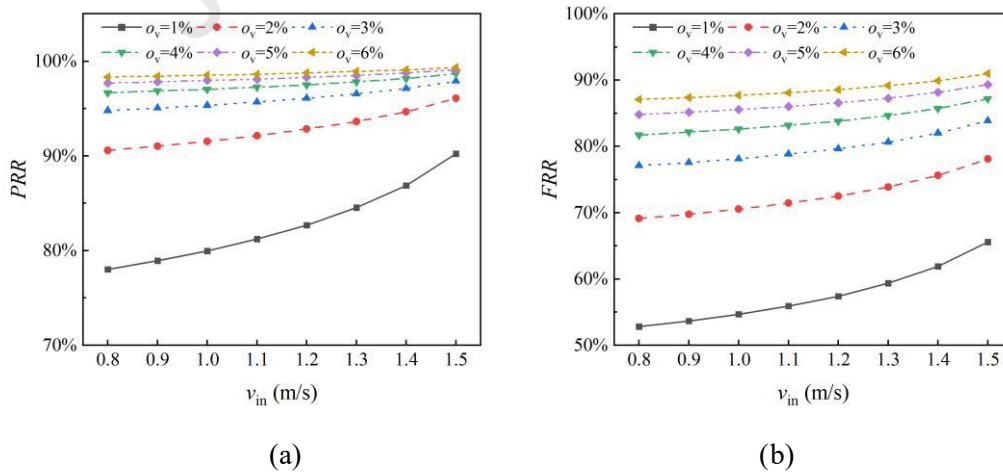


Fig. 6. Variation of PRR and FRR with v_{in} under multiple σ_v : (a) PRR ; (b) FRR .

3.2. Performance of OWC with breather valve under regular waves

Based on the above analysis, the effects of breather valve on reducing the chamber pressure and flow rate in the OWC system have been demonstrated. To further evaluate the performance of the OWC with a breather valve and to identify an optimal configuration for enhancing its annual energy production, a cylindrical OWC device equipped with a breather valve is modeled in the NWT, as shown in Fig. 2 (b). The breather valve is installed in parallel with the orifice channel and functions to regulate the pneumatic power based on the instantaneous air chamber pressure.

Under high wave condition ($T = 8.75$ s, $H = 5.75$ m, as listed in Table 1), the peak pressure of the OWC without a breather valve is 16.5 kPa. To investigate the effect of the breather valve, four breather valve thresholds ($p_v = 3$ kPa, 6 kPa, 9 kPa and 12 kPa) are tested. Fig. 7 illustrates the variations in peak pressure reduction ratio (PRR_p) and peak flow rate reduction ratio (FRR_p) with respect to o_v under different p_v values for the high wave condition. The results confirm that the breather valve exhibits a more pronounced effect on reducing the chamber pressure than on reducing the airflow rate, which is consistent with predictions from the steady-state model. Specifically, PRR_p ranges from 20% to 80%, while FRR_p remains within 0% to 50%, highlighting the breather valve's primary function in pressure regulation. Furthermore, the pressure regulation performance of the breather valve is closely related to o_v . For a given p_v , both PRR_p and FRR_p increase with o_v and then tend to stabilize beyond a certain point. In addition, a lower p_v requires a larger minimum o_v to achieve stable pressure regulation, and the associated PRR_p is correspondingly higher. When p_v values are 3 kPa, 6 kPa, 9 kPa, and 12 kPa, the pressure regulation performance stabilizes at o_v values of 5%, 4%, 3%, and 2%, respectively. At these o_v values, the instantaneous pressure and flow rate curves exhibit distinct plateau characteristics. Specifically, at $p_v = 3$ kPa and $o_v = 5\%$, the OWC system achieves a PRR_p of 80% and an FRR_p of 50%.

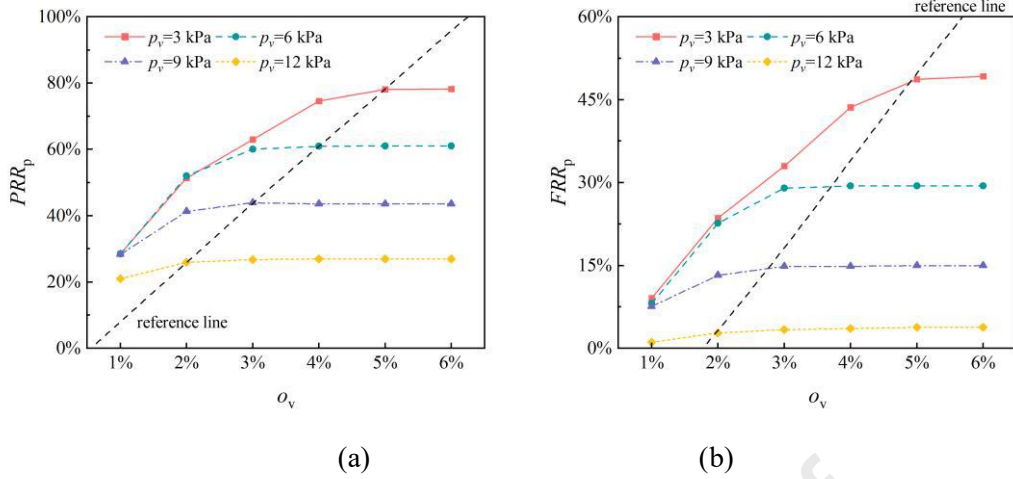


Fig. 7. Variations of PRR_p and FRR_p with o_v under different p_v values for $T = 8.75$ s, $H = 5.75$ m: (a) PRR_p ; (b) FRR_p .

Fig. 8 compares Δp_t and Q_t of the OWC device with and without breather valve under the high wave condition. The results indicate that under the time-harmonic excitation of regular incident waves, both Δp_t and Q_t exhibit cyclic oscillation patterns. For the OWC without a breather valve, the Δp_t and Q_t curves display noticeable asymmetry, a phenomenon also reported by Marjani et al. [49]. One contributing factor to this phenomenon is the nonlinear effects of the fifth-order Stokes wave, which features steep crests and flat troughs. As a result, both horizontal and vertical fluid velocities at the crest are significantly greater than those at the trough. This leads to a markedly higher momentum of the OWC oscillating water column during the upward phase compared to the downward phase, leading to asymmetric oscillations in both Δp_t and Q_t . In the case of the OWC with a breather valve, as Δp_t gradually increases from 0 and reaches the preset p_v , the breather valve opens to release pressure. This action leads to varying degrees of reduction in both pressure and flow rate, depending on the valve settings. Notably, at $p_v = 3$ kPa and $o_v = 5\%$, both the Δp_t and Q_t curves exhibit distinct plateau features. This pressure release mechanism helps smooth out the oscillations and contributes to a more stable and continuous pneumatic power output.

— OWC without valve — $o_v=1\%$ — $o_v=2\%$ — $o_v=3\%$ — $o_v=4\%$ — $o_v=5\%$ — $o_v=6\%$

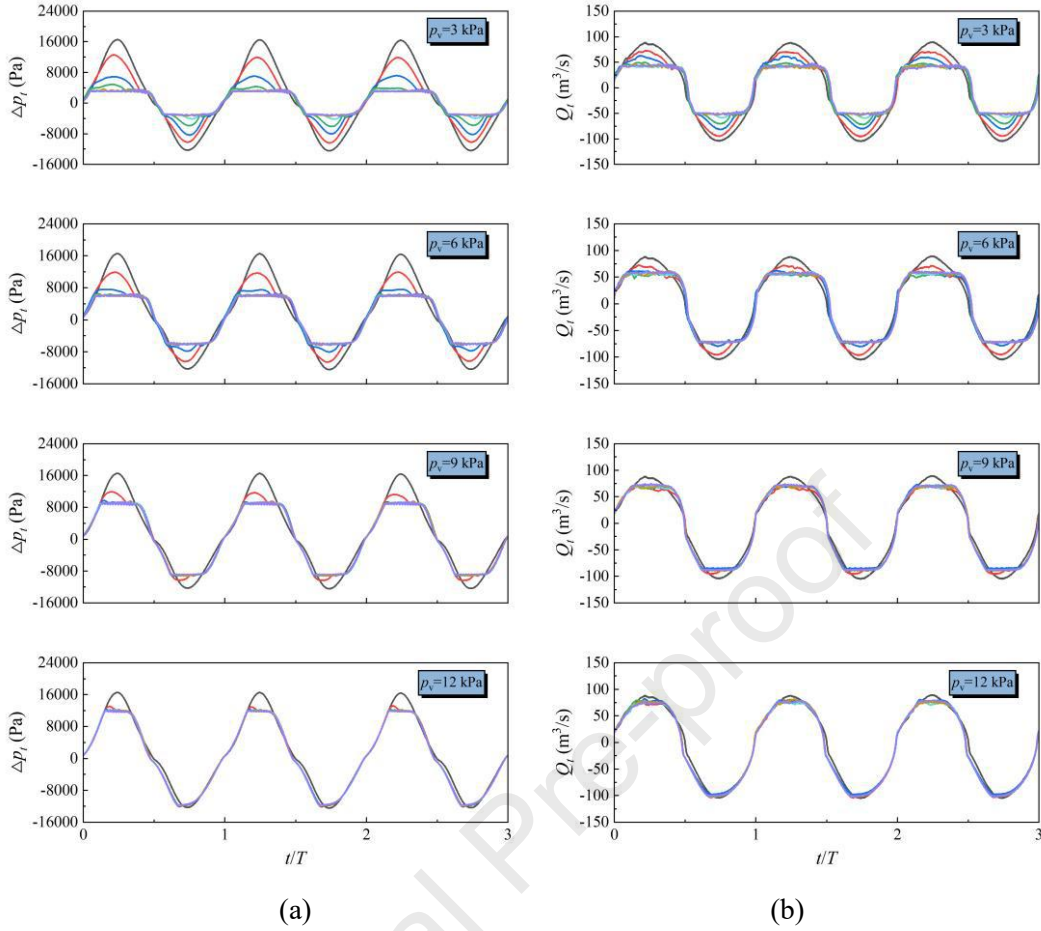


Fig. 8. Comparison of OWC performance with and without breather valve for $T = 8.75$ s, $H = 5.75$ m:
(a) Δp ; (b) Q .

Fig. 9 presents the symmetric interface pressure distribution diagrams of OWC with and without a breather valve ($p_v = 3$ kPa, $\sigma_v = 5\%$) under the high wave condition at four representative moments within one period. At $t = T/4$, the incident wave crest arrives at the front wall of the OWC, and the inflow velocity reaches its maximum in both devices. Correspondingly, the chamber pressure reaches its positive peak. In the case of the OWC with a breather valve, the chamber pressure exceeds p_v , causing the breather valve to open and maintain the chamber pressure at 3 kPa during the exhalation phase. At this moment, the free surface inside the chamber of the device with the breather valve is significantly higher than that of the device without one. This phenomenon can be attributed to the reduced damping effect introduced by the breather valve, which lowers resistance to free surface displacement and enhances the oscillation amplitude. At $t = T/2$, the water flow velocity in the OWC channel gradually

decreases, leading to a reduction in chamber pressure. In the OWC without a breather valve, the chamber pressure approaches 0. Meanwhile, in the OWC with a breather valve, the breather valve closes as the pressure falls below p_v , thereby altering the damping characteristics of the system. As water continues to be discharged from the channel, the chamber pressure transitions into negative values. At $t = 3T/4$, when the incident wave trough arrives at the front wall of the OWC, the outflow velocity of the channel reaches its maximum for both devices, and the chamber pressure attains its negative peak. For the OWC with a breather valve, this initiates the inhalation phase, with the value maintaining the pressure at -3 kPa. Moreover, in contrast to the condition at $t = T/4$, the free surface in the chamber of the breather valve-equipped OWC is now significantly lower than that of the OWC without breather valve. At $t = T$, the water flow velocity in the channel of the OWC without a breather valve decreases to 0, and the chamber pressure increases from a negative value to approach 0. In the case of the OWC with a breather valve, the water flow direction in the channel reverses from outflow to inflow, and the chamber pressure increases from a negative to a positive value.

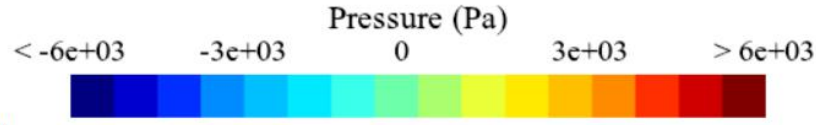
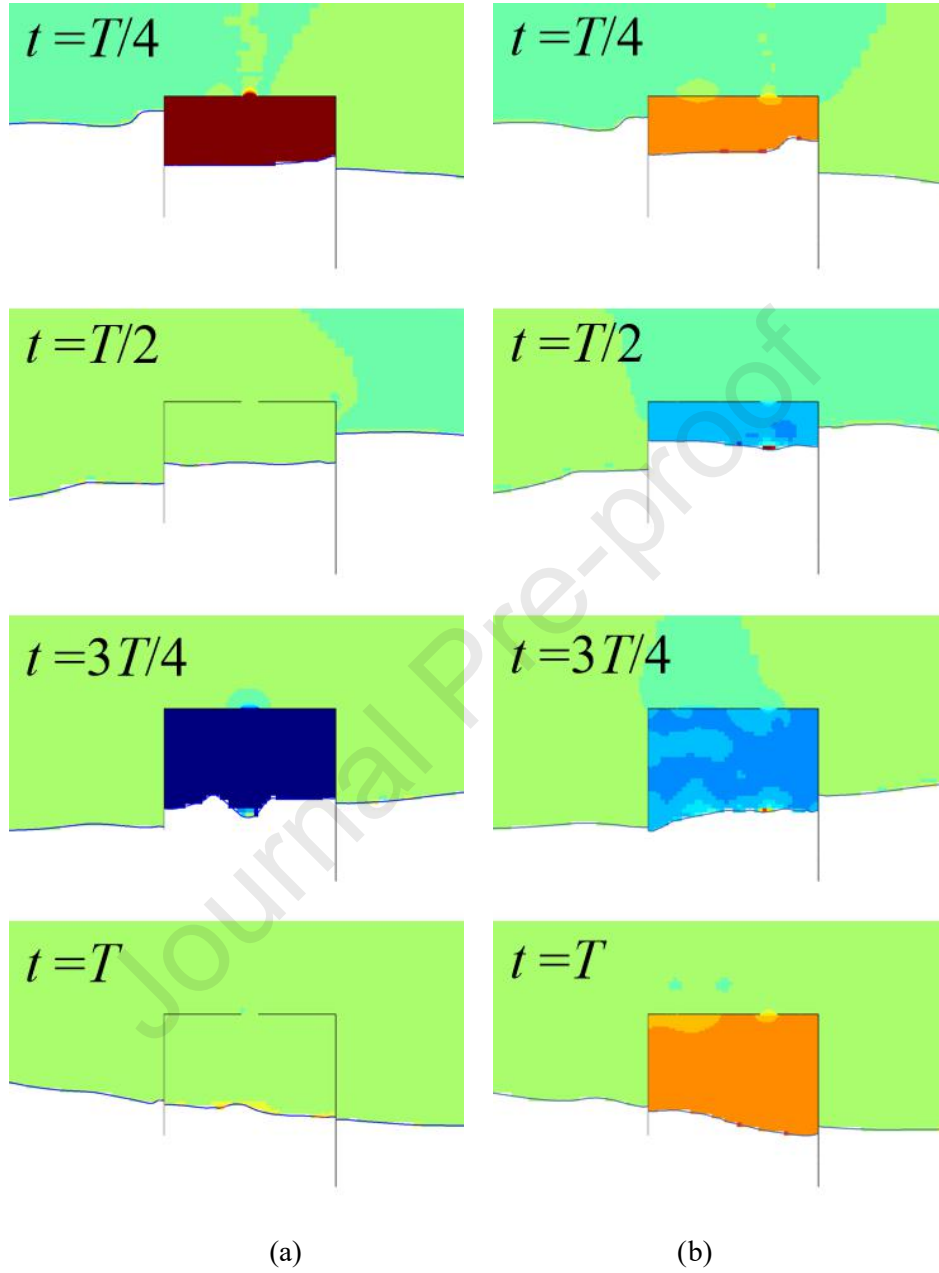


Fig. 9. Symmetric interface pressure distribution diagrams of OWC devices at typical moments for $T = 8.75$ s, $H = 5.75$ m: (a) without breather valve; (b) with breather valve ($p_v = 3$ kPa, $o_v = 5\%$).

Fig. 10 presents the variations of $\bar{\eta}_1$, $\bar{\eta}_3$, and $\bar{\eta}$ with o_v for different p_v , under the normal wave conditions listed in Table 1. $\bar{\eta}_2$ is assumed to be 50%, based on findings reported in previous studies^[40].

^{43]} and is therefore not discussed further here. As shown in Fig. 10 (a), $\bar{\eta}_1$ remains highly consistent across different p_v values, with only the case of $p_v = 3$ kPa exhibiting a slight decrease. This indicates that, under most normal wave conditions, the chamber pressure does not exceed 3 kPa, resulting in minimal influence of the breather valve on pneumatic performance. In contrast, Fig. 10 (b) and (c) show that both $\bar{\eta}_3$ and $\bar{\eta}$ gradually increase with decreasing p_v and increasing o_v . When $p_v = 3$ kPa and $o_v = 5\%$, both performance indicators stabilize at 91% and 15%, respectively. Compared to the baseline OWC without a breather valve ($\bar{\eta}_3 = 60.8\%$ and $\bar{\eta} = 10.3\%$), this represents significant improvements of 50% and 46%, respectively. This enhancement can be attributed to the peak-shaving control of the breather valve. In this study, the rated power of the generator is determined based on the peak instantaneous output power under high wave condition. By mitigating pressure extremes, the breather valve enables safer operation even with a lower rated power, thereby preventing generator overload during high wave condition and finally improving the average generator efficiency under normal wave conditions. In conclusion, given the need for OWC to operate reliably under complex and variable sea states, the use of a breather valve for pressure regulation proves effective in enhancing overall system performance.

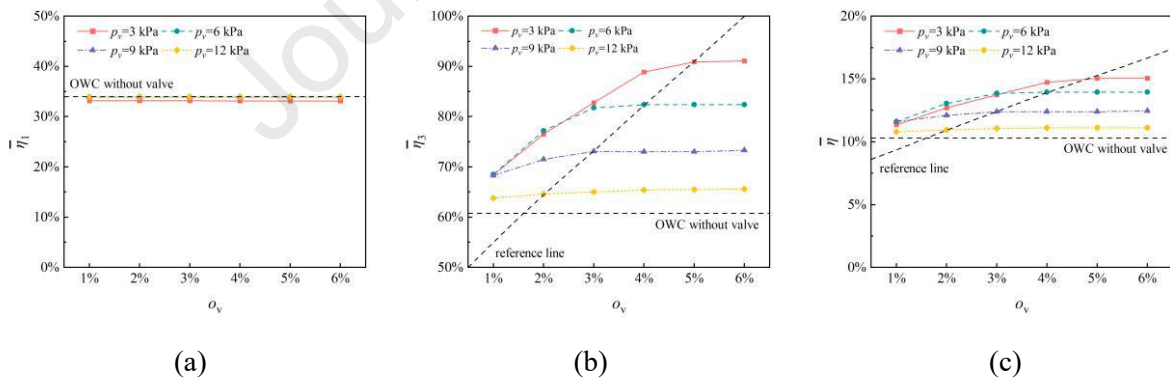


Fig. 10. Variations of $\bar{\eta}_1$, $\bar{\eta}_3$, and $\bar{\eta}$ with o_v for different p_v under normal wave conditions: (a) $\bar{\eta}_1$; (b) $\bar{\eta}_3$; (c) $\bar{\eta}$.

3.3. Comparison of energy conversion performance between OWC with breather valve and without valve

3.3.1. Energy conversion efficiency

Fig. 11 compare the instantaneous efficiencies $\eta_1(t)$, $\eta_3(t)$, and $\eta(t)$ across the three energy conversion stage of the OWC system under the high wave condition ($T = 8.75$ s, $H = 5.75$ m). The implementation of a breather valve ($p_v = 3$ kPa, $o_v = 5\%$) significantly reduces Δp_t and Q_t . Specifically, the peak $\eta_1(t)$ decreases from 36.4% (without breather valve) to 4.7% (with breather valve), and η_1 decreases from 15.5% to 3%. Conversely, η_3 increases from 93.9% to 94.8%, while η declines from 7.3% to 1.4%. These result in a decrease in P_{rated} from 740 kW to 100 kW, representing an 86% reduction.

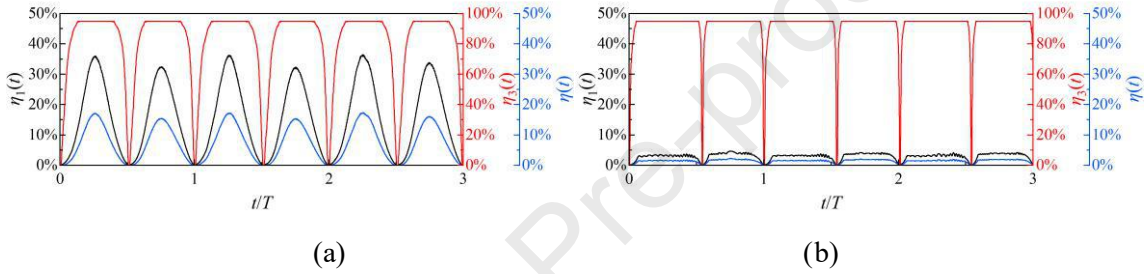


Fig. 11. $\eta_1(t)$, $\eta_3(t)$, and $\eta(t)$ of both OWC devices under the high wave condition ($T = 8.75$ s, $H = 5.75$ m): (a) without breather valve; (b) with a breather valve ($p_v = 3$ kPa, $o_v = 5\%$).

Fig. 12 shows the instantaneous efficiencies $\eta_1(t)$, $\eta_3(t)$, and $\eta(t)$ under a typical normal wave condition ($T=4.75$ s and $H=1.25$ m), which corresponds to the wave condition with the highest occurrence probability. The results indicate that the breather valve ($p_v = 3$ kPa, $o_v = 5\%$) significantly improves the generator's operating condition, increasing C_l (as defined in Eq.(11)) from 0.0156 (without breather valve) to 0.193 (with breather valve). This substantial improvement in C_l is primarily attributed to the reduction in P_{rated} from 740 kW to 100 kW, as discussed earlier. Consequently, η_3 rises from 57.4% to 91.7%, while η improves from 12.9% to 20.6%, representing relative improvements of approximately 60% in both metrics.

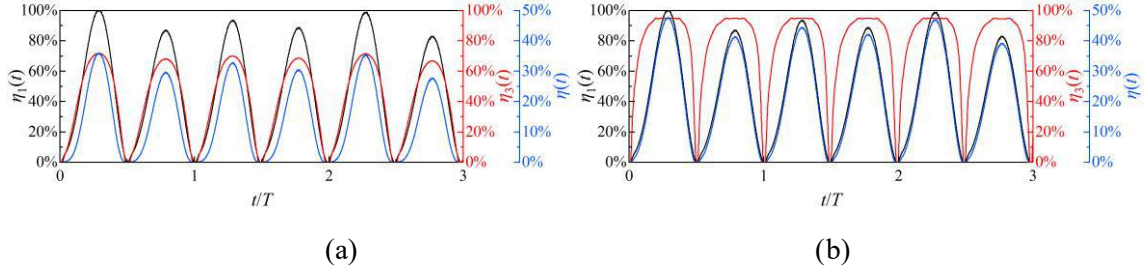


Fig. 12. $\eta_1(t)$, $\eta_3(t)$, and $\eta(t)$ of both OWC devices under a typical normal wave condition ($T=4.75$ s, $H=1.25$ m): (a) without breather valve; (b) with a breather valve ($p_v = 3$ kPa, $o_v = 5\%$).

To systematically analyze the impact of the breather valve on the multi-stage energy conversion efficiencies of the OWC under a range of normal wave conditions (listed in Table 1), Fig. 13, Fig. 14, and Fig. 15 respectively present the η_1 , η_3 , and η matrices for both OWC systems with and without a breather valve ($p_v = 3$ kPa, $o_v = 5\%$). Fig. 13 shows that the breather valve has a minor impact on the η_1 under normal wave conditions. On average, the $\bar{\eta}_1$ of the OWC without a breather valve is 33.9%, compared to 33.1% for the OWC with a breather valve, indicating only a marginal 0.8% decrease. Noticeable deviations are observed at wave conditions of $T=5.75$ s, $H=2.25$ m and $T=6.25$ s, $H=2.25$ m. These exceptions are attributed to the higher incident wave energy at these wave conditions, which elevates the chamber pressure beyond p_v and triggers periodic activation of the breather valve. This observation underscores the importance of p_v optimization in improving the OWC performance. If p_v is set below its optimal value, premature activation may occur under moderate sea states, thereby diminishing pneumatic efficiency and ultimately reducing the overall wave-to-electricity conversion performance.

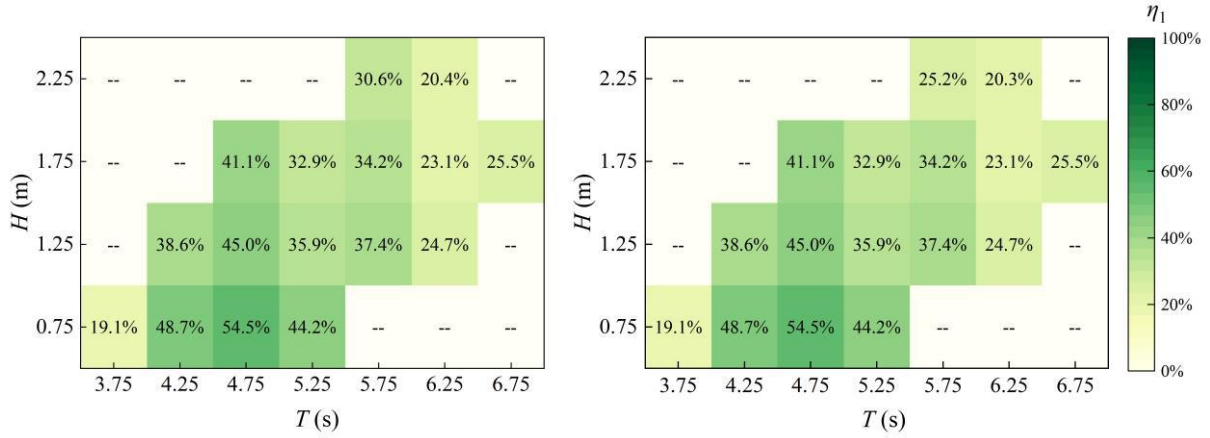


Fig. 13. η_1 matrix of the OWC devices under normal wave conditions: (a) without breather valve; (b) with a breather valve ($p_v = 3$ kPa, $\sigma_v = 5\%$).

Fig. 14 reveals that the OWC with a breather valve exhibits significantly higher η_3 under normal wave conditions compared to the OWC without a breather valve. On average, the $\overline{\eta_3}$ of the OWC with and without a breather valve is 90.9% and 60.8%, respectively, indicating a 50% improvement with the inclusion of the valve. Specifically, the η_3 of the OWC with the breather valve ranges from 58.3% to 94.3%, whereas the OWC without breather valve operates within a lower range of 10% to 79%. Furthermore, the variation in η_3 decreases from 69% (without breather valve) to 36% (with breather valve), corresponding to a reduction of approximately 48%. These results indicate that the appropriate configuration of the breather valve not only enhances generator efficiency but also significantly improves its operational stability across a wide range of wave conditions, thereby boosting the overall adaptability and performance of the OWC system. In addition to the observed improvements in generator efficiency, it is important to consider the interaction between the breather valve and generator optimization. While conventional approaches to enhancing generator performance—such as variable-speed operation, advanced PTO control strategies, or integration with energy storage—focus on active electrical regulation[19, 50, 51], the breather valve offers a complementary, passive mechanism that modulates the pneumatic load before it reaches the generator. By mitigating extreme pressure fluctuations, the valve reduces peak loading and allows the generator to operate closer to its optimal

efficiency range during typical sea states. Consequently, the breather valve can enable the use of a smaller-rated generator without sacrificing average annual energy production, potentially lowering system cost and improving long-term reliability. This synergy suggests that passive pneumatic regulation and generator optimization need not be mutually exclusive; rather, combining both strategies could maximize overall OWC performance, balancing structural simplicity with advanced electrical control to achieve higher annual energy yield.

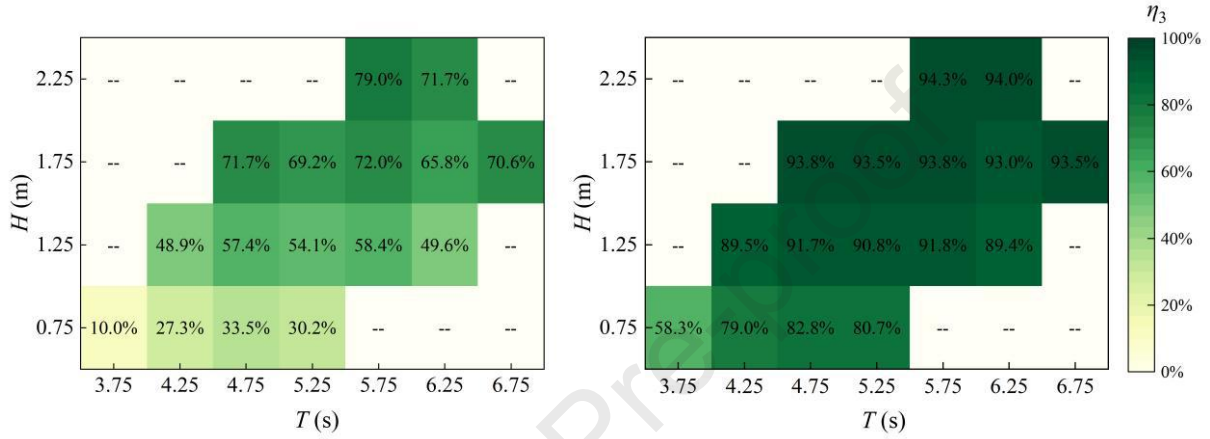


Fig. 14. η_3 matrix of OWC devices under normal wave conditions: (a) without breather valve; (b) with a breather valve ($p_v = 3$ kPa, $\sigma_v = 5\%$).

Fig. 15 demonstrates that the OWC with a breather valve achieves a η range of 5.6% to 22.6%, with a fluctuation range of 17%, under normal wave conditions. In contrast, the OWC without a breather valve exhibits a narrower and lower η range of 1%–14.7%, with a fluctuation range of 13.7%. On average, the $\bar{\eta}$ of the system without a breather valve is 10.3%, while the system with a breather valve reaches 15%, representing an improvement of approximately 46%. Notably, under the typical wave condition interval with a 47% annual occurrence probability ($4.25 \text{ s} \leq T \leq 5.25 \text{ s}$, $0.75 \text{ m} \leq H \leq 1.25 \text{ m}$), the OWC with a breather valve exhibits a remarkable $\bar{\eta}$ of 18.8%. These findings further confirm the effectiveness of the breather valve in enhancing the overall energy conversion performance of the OWC system under realistic sea states.

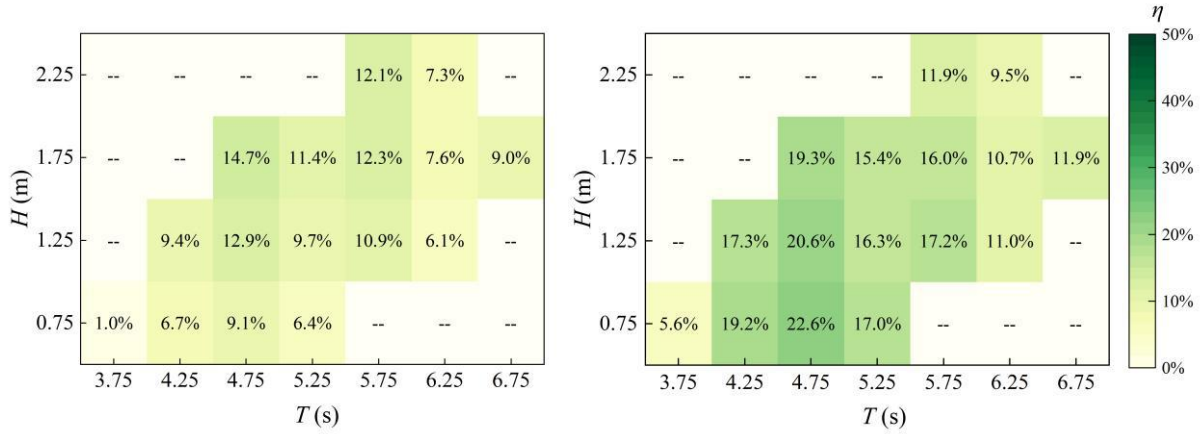


Fig. 15. η matrix of OWC devices under normal wave conditions: (a) without breather valve; (b) with a breather valve ($p_v = 3$ kPa, $o_v = 5\%$).

3.3.2. Annual energy production

This section analyzes the impact of air pressure regulation on the annual energy generation performance of the OWC devices. Fig. 16 and Fig. 17 respectively illustrate the $\overline{P}_{out}$ and E_{out} matrices for both OWC systems with and without a breather valve ($p_v = 3$ kPa, $o_v = 5\%$) under the normal wave conditions. The OWC with the breather valve demonstrates significantly higher $\overline{P}_{out}$ and E_{out} across most wave conditions compared to system without a breather valve. An exception occurs at the wave condition $T=5.75$ s, $H=2.25$ m, where frequent activation of the breather valve results in excessive release of pneumatic energy, leading to a reduction in pneumatic efficiency. Although the generator efficiency increases under this condition, the overall wave-to-electricity conversion efficiency decreases, as shown in Fig. 13–15, ultimately reducing the system's power output. Despite this exception, the OWC with a breather valve achieves an *AEP* of 119,000 kWh, which is 43% higher than the 83,000 kWh generated by the system without a breather valve.

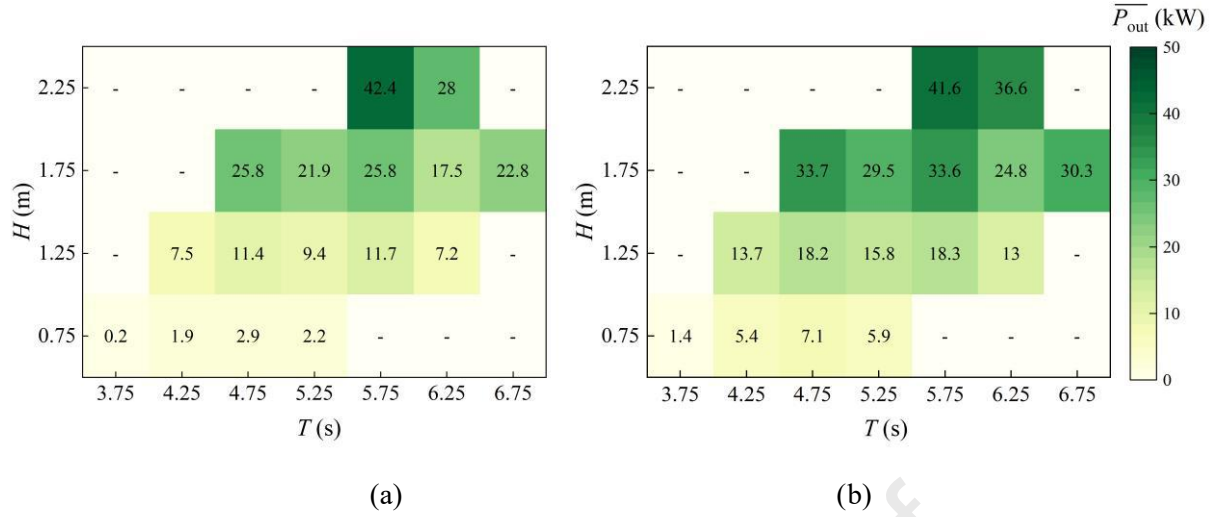


Fig. 16. $\overline{P}_{out}$ matrix of both OWC devices under normal wave conditions: (a) without breather valve; (b) with a breather valve ($p_v = 3$ kPa, $o_v = 5\%$).

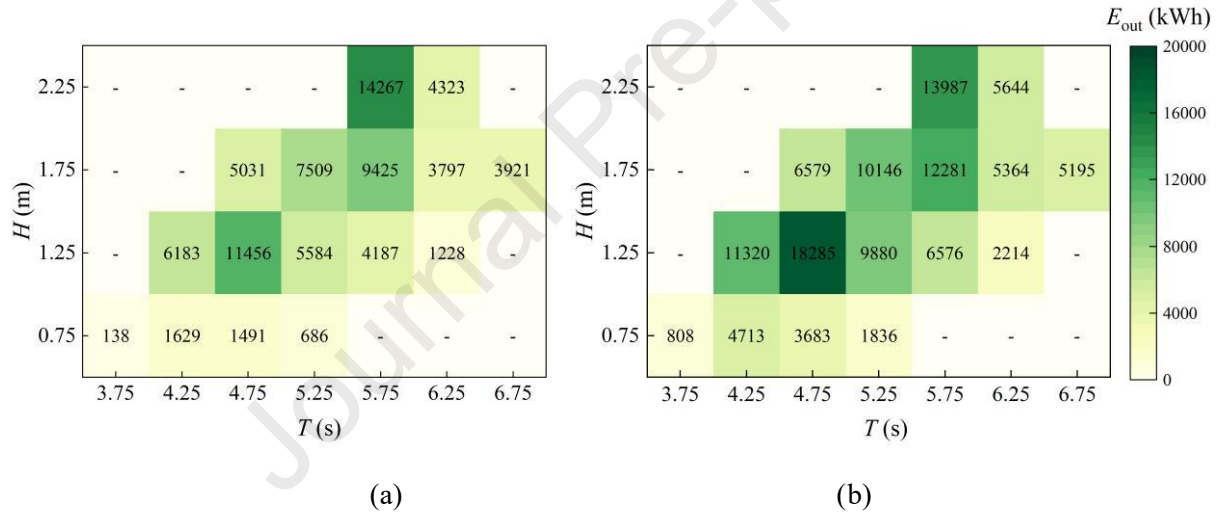


Fig. 17. E_{out} matrix of both OWC devices under normal wave conditions: (a) without breather valve; (b) with a breather valve ($p_v = 3$ kPa, $o_v = 5\%$).

Fig. 18 presents the improvements in AEP and reductions in P_{rated} for OWC systems with different p_v and o_v . The results indicate that when $o_v > 3\%$, both AEP increment and P_{rated} reduction exhibit consistent upward trends as p_v decreases from 12 kPa to 3 kPa. However, when $o_v \leq 3\%$, both AEP increment and P_{rated} reduction first increase and then decline with decreasing p_v . The 3 kPa threshold closely approximates the peak instantaneous chamber pressure of the OWC without a breather valve

under normal wave conditions. At this threshold, the breather valve effectively regulates the chamber pressure, alleviating the generator's peak output power during high wave events. As a result, the required installed capacity is reduced, and the generator operates with a higher load factor under normal sea states, thereby enhancing generator efficiency and increasing overall annual energy production. However, further reductions in p_v can lead to premature valve activation, which adversely impacts pneumatic energy conversion during moderate sea states, ultimately lowering the overall annual energy production. In conclusion, the breather valve configuration with $p_v = 3$ kPa and $o_v = 5\%$ is identified as optimal. Under this setup, the OWC achieves an AEP of 119,000 kWh (a 43% increase over the 83,000 kWh produced without a breather valve) and a P_{rated} of 100 kW (an 86% reduction from the 740 kW required in the valve-free configuration).

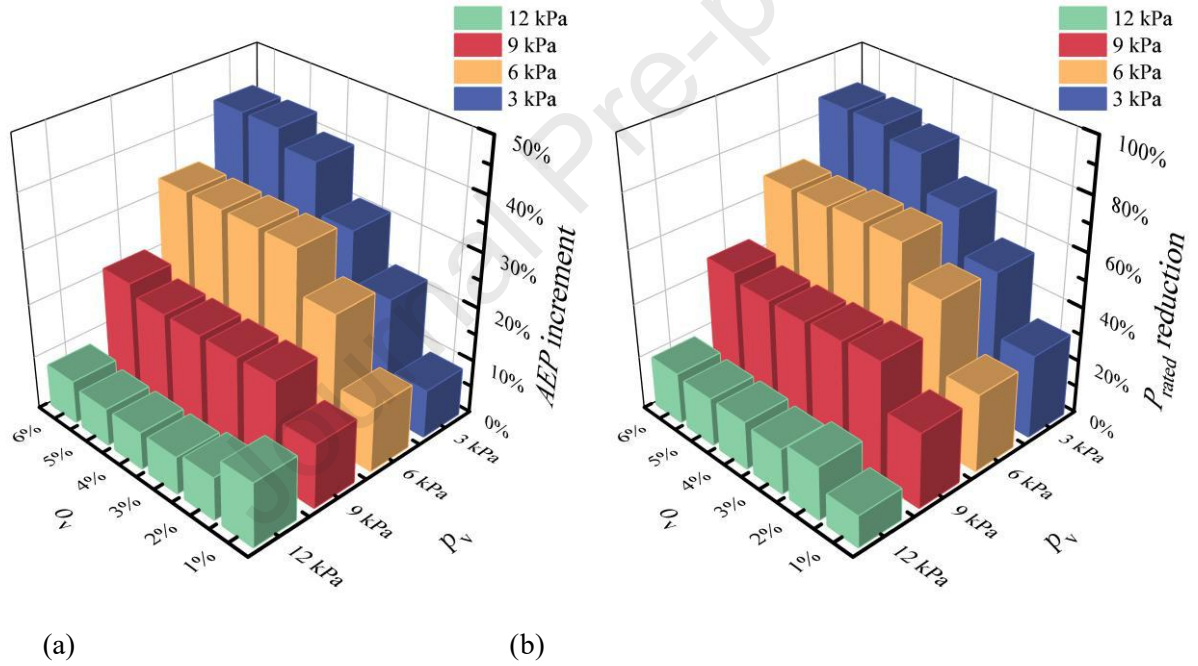


Fig. 18. AEP increment and P_{rated} reduction for OWC systems with various p_v and o_v , relative to the baseline system without a valve: (a) AEP increment ; (b) P_{rated} reduction.

Compared with previous studies focusing mainly on turbine design or generator control strategies, the present work introduces a novel approach by incorporating a breather valve for pneumatic regulation. The unique contributions of this study are as follows: (i) a systematic parametric investigation of

threshold pressure and valve opening ratio, which has not been addressed in earlier research; (ii) demonstration that the breather valve, although exerting little influence on first-order pneumatic conversion efficiency, substantially improves generator efficiency and annual energy production; (iii) development of a validated CFD-based chamber–valve–generator coupling model; and (iv) highlighting the engineering advantages of the breather valve as a passive, low-cost, and reliable complement to active generator control. These findings provide new methodological insights and practical guidance for enhancing the performance of OWC wave energy converters.

4. Conclusions

This study proposes a pneumatic regulation method for OWC devices using breather valves. The primary objective is to suppress peak power output under high wave conditions and reduce the required generator rated capacity, thereby improving the load factor and operational efficiency during normal wave conditions. Validated numerical models are employed to investigate the influence of breather valve on multi-stage energy conversion in OWC devices, as well as on annual energy production. The main conclusions can be drawn as follows:

1) Under constant inlet flow velocity conditions, the pressure reduction ratio and flow rate reduction ratio of OWC with breather valve increase with valve opening ratio. However, the rate of increase diminishes as the opening ratio becomes larger. Additionally, the valve's pressure regulation capability becomes more pronounced at higher inlet velocities.

2) Under regular wave conditions, at a constant threshold pressure, increasing the breather valve opening ratio initially enhances peak pressure and flow rate reduction before reaching a plateau. The opening ratio required for stable pressure relief depends on the valve threshold: lower thresholds demand larger opening ratios, accompanied by enhanced pressure regulation performance. Specifically, stable pressure relief is achieved at opening ratios of 5%, 4%, 3%, and 2% for thresholds of 3 kPa, 6 kPa, 9 kPa, and 12kPa, respectively. Notably, with a properly configured breather valve, the temporal curves of pressure and flow rate exhibit distinct plateau characteristics, facilitating smoother and more stable power output.

3) The configuration with a 3 kPa threshold and 5% opening ratio is identified as optimal under the examined wave conditions. Compared to the OWC without a breather valve, the optimized system achieves a substantially reduced installed capacity of 100 kW—an 86% reduction from 740 kW. The average generator efficiency increases by 50%, from 60.8% to 90.9%, while the average wave-to-electricity conversion efficiency improves by 46%, rising from 10.3% to 15%. This configuration also yields a 43% increase in annual energy production, from 83,000 kWh to 119,000 kWh.

In the present study, turbine efficiency is assumed to be a constant 50%, which introduces a discrepancy from actual operating conditions. Future work will focus on investigating the hydrodynamic performance and wave energy conversion efficiency of OWC systems with the breather valve under irregular wave conditions, incorporating more realistic turbine behavior.

Acknowledgements

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Nomenclature

A	Amplitude of the incident wave
AEP	Annual energy production
C_l	Generator load coefficient
D	Diameter of the OWC
D_n	Coefficient constant
D_o	Diameter of the orifice region
D_v	Diameter of the porous media region
d_1	Front wall draft of OWC
d_2	Rear wall draft of OWC

614	d_3	Distance from the top of the front wall to the horizontal plane
615	E_{out}	Power generation for each sea state
616	f_b	Pressure drop in the porous media
617	f_i	External force acting on the fluid in the i direction
618	FRR	Flow reduction ratio
619	FRR_p	Peak flow reduction ratio
620	g	Gravitational acceleration
621	H	Wave height
622	h	Waters depth
623	K	Turbulent kinetic energy
624	k	Wave number
625	N	Number of wave periods considered in the calculation
626	α_v	Area ratio of the breather valve opening to the cylinder's cross-sectional area
627	p	Relative pressure
628	p_v	Pressure threshold beyond which the breather valve begins to open
629	$\mathbf{P}$	Porous inertial resistance tensor
630	p_{atm}	Standard atmospheric pressure
631	$\overline{P_{\text{in}}}$	Average incident wave power within a wave period
632	$\overline{P_{\text{out}}}$	Average output power of the generator within a wave period
633	$\overline{P_{\text{pneu}}}$	Average pneumatic power within a wave period
634	P_{rated}	Rated power of the generator
635	P_{rotor}	Instantaneous mechanical kinetic energy of the turbine
636	$\overline{P_{\text{rotor}}}$	Average rotational kinetic energy of the turbine within a wave period
637	PRR	Pressure reduction ratio

638	PRR_p	Peak pressure reduction ratio
639	Q_t	Instantaneous airflow rate through the turbine
640	R	Molar gas constant
641	T	Wave period
642	T_a	Absolute temperature of the gas
643	T_t	Instantaneous torque of the turbine
644	t_0	Time at which the OWC's power output tends to stabilize
645	u_c	Compressive velocity of the interface
646	u_i	Mean flow velocity in the i direction
647	u_s	Apparent velocity in the porous media region region
648	v_{in}	Inlet flow velocity
649	α	Liquid volume fraction in each computational cell
650	ρ	Fluid density
651	ρ_g	Gas density
652	ρ_w	Density of water
653	ω	Wave frequency
654	ω_i	Occurrence probability of the normal wave condition of i
655	ω_t	Instantaneous rotational speed
656	μ	Dynamic viscosity of air
657	μ_t	Turbulent viscosity
658	λ	Wave length
659	δ_{ij}	Kronecker delta
660	$-\rho \overline{u'_i u'_j}$	Reynolds stress
661	ξ	Free surface displacement

662	η	Wave-to-electricity conversion efficiency
663	$\eta(t)$	Instantaneous wave-to-electricity conversion efficiency
664	$\bar{\eta}$	Average wave-to-electricity conversion efficiency across a range of normal wave
665		conditions
666	η_1	Pneumatic energy conversion efficiency
667	$\eta_1(t)$	Instantaneous pneumatic energy conversion efficiency
668	$\bar{\eta}_1$	Average pneumatic energy conversion efficiency across a range of normal wave
669		conditions
670	η_2	Mechanical kinetic energy conversion efficiency
671	η_3	Generator conversion efficiency
672	$\eta_3(t)$	Instantaneous generator conversion efficiency
673	$\bar{\eta}_3$	Average generator conversion efficiency across a range of normal wave conditions
674	Δp_t	Instantaneous pressure difference in the air chamber relative to the atmosphere

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Highlights:

- 1) A breather valve is integrated into an OWC device for pneumatic power regulation.
- 2) Valve threshold and opening ratio strongly influence pressure and flow stabilization.
- 3) Optimized configuration reduces generator capacity by 87% and boosts efficiency.
- 4) Annual energy production increases by 43% compared to a conventional OWC system.

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:



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