Hydrodynamic Performance of an OWC Wave Energy Converter with Triple Chambers in Waves

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1 INTRODUCTION

An oscillating water column (OWC) device is a promising wave energy converter (WEC) to utilize ocean wave energy resources (Falcão and Henriques, 2016). The OWC chamber absorbs the kinetic energy of ocean waves, so its shape has a significant effect on the energy conversion performance. Recently, various studies on breakwater-WEC integration technology have been conducted to reduce the cost of OWC-WEC chamber construction and improve economic feasibility (Torre-Enciso et al., 2009; Arena et al., 2017; Kim et al., 2022). In the present study, the hydrodynamic performance of a multi-OWC chamber is investigated experimentally, focusing on its hydrodynamic behavior and energy conversion characteristics. A series of model tests were conducted for single- and triple-OWC chambers in the two-dimensional wave tank. The orifice was applied to induce a turbine-chamber interaction owing to the pressure drop. It was found that the triple OWC chamber improves the converted pneumatic power by reducing the sloshing motion of the internal fluid compared to the single OWC chamber (Kim and Nam, 2021). A numerical investigation was also conducted to simulate the hydrodynamic problem for a multiple OWC chamber. The validity of the present numerical method was examined by comparing it with the experimental data. Furthermore, numerical simulations were conducted on the breakwater-integrated multiple OWC chambers to investigate improving the hydrodynamic energy conversion performance.

2 EXPERIMENTAL AND NUMERICAL METHOD

2.1 Experimental setup

The physical model tests were carried out in a two-dimensional wave tank at the Korea Research Institute of Ships and Ocean Engineering (KRISO). OWC chamber models, which were made of 15mm thick acrylic material, were considered to investigate the hydrodynamic behavior and energy conversion performance of the single and triple OWC chambers. For each chamber model, an air duct and orifice were installed on the chamber top for the turbine-chamber interaction due to the pressure variation from the reciprocating airflow. Figure 1 shows the experimental models of the single- and triple-OWC chamber installed in the two-dimensional wave tank. The dimensions of the wave tank are as follows: length 25.6 m, breadth 0.56 m, and water depth 0.55 m. The triple OWC chamber was designed by dividing the inner area of a single OWC chamber into three independent chambers along the wave propagation direction. Three wave gauges measured the surface elevations inside the chamber. The airflow speed was directly measured at the orifice using a hot-wire anemometer which directly converts the heat loss into the absolute value of airflow speed. A pressure variation inside the chamber was directly measured using a piezoelectric pressure gauge.

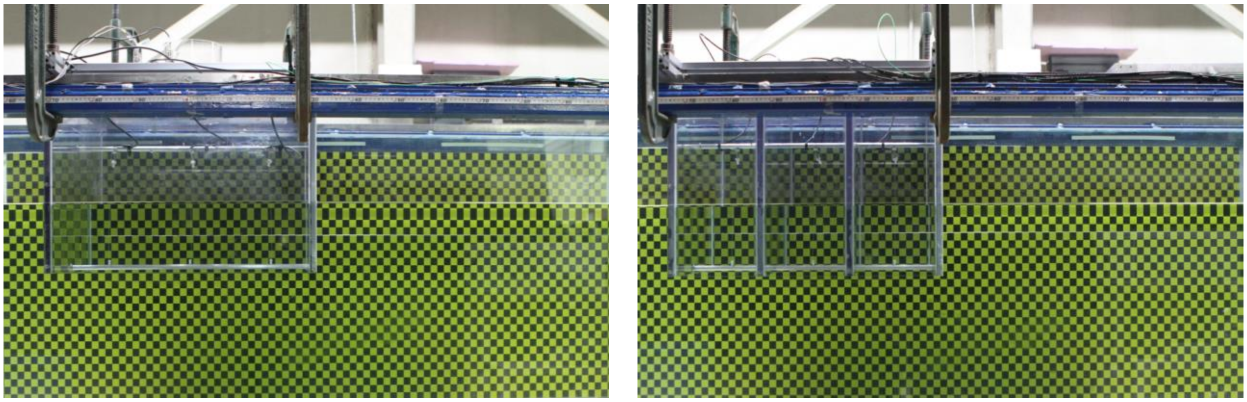


Figure 1: Experimental model of single- and triple-OWC chamber in two-dimensional wave flume

2.2 Numerical model

The hydrodynamic problem of an OWC chamber was solved based on the linear potential theory with the assumption of an inviscid and incompressible fluid and irrotational flow. The governing equation of the potential flow is the Laplace equation, and the velocity potential can be defined in the fluid domain surrounding the OWC chamber. The airflow produced by the OWC motion inside the chamber can only pass through an orifice installed in the air duct. In this case, the pressure variation inside the OWC chamber (p_c) should be considered to solve the turbine-chamber interaction problem. The following equation shows the modified dynamic free-surface boundary condition for the region inside the OWC chamber.

$$\frac{\partial \phi}{\partial t} = -g\zeta - \frac{p_d}{\rho_a} \tag{1}$$

$$p_d = p_c - p_{atm.} = \gamma V|V| \tag{2}$$

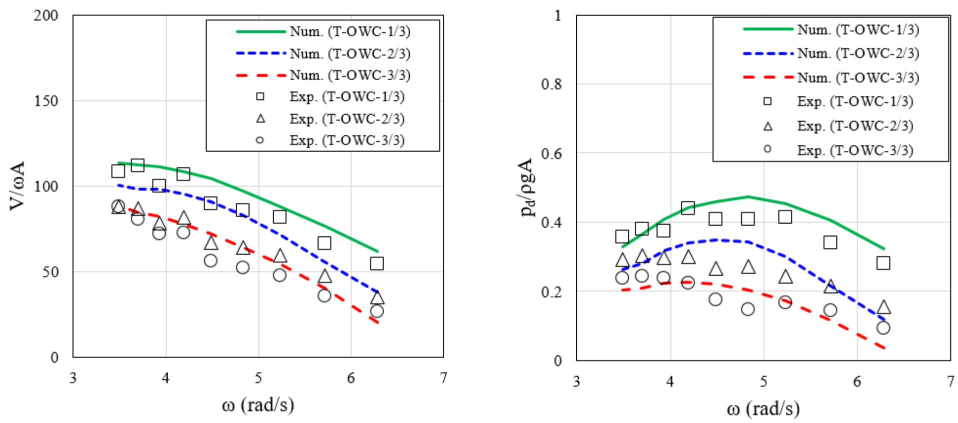
A numerical orifice model was considered with an empirical quadratic pressure drop function in Eq. (2). A nonlinear pressure drop coefficient (γ) was derived by the least square method for the experimental data. The finite element method was applied to address the boundary value problem. The weak formulation of the governing equation can be obtained by applying integration by parts with test functions ψ as follows.

$$\iiint_{\Omega} \nabla\phi \cdot \nabla\psi \mathrm{d}V - \iint_{\partial\Omega} \frac{\partial \phi}{\partial n} \psi \mathrm{d}S = 0 \tag{3}$$

After the fluid domain is discretized using a finite number of elements, the velocity potential function and wave elevation can be approximated as a linear summation of the continuous and differentiable test functions.

3 RESULTS & DISCUSSION

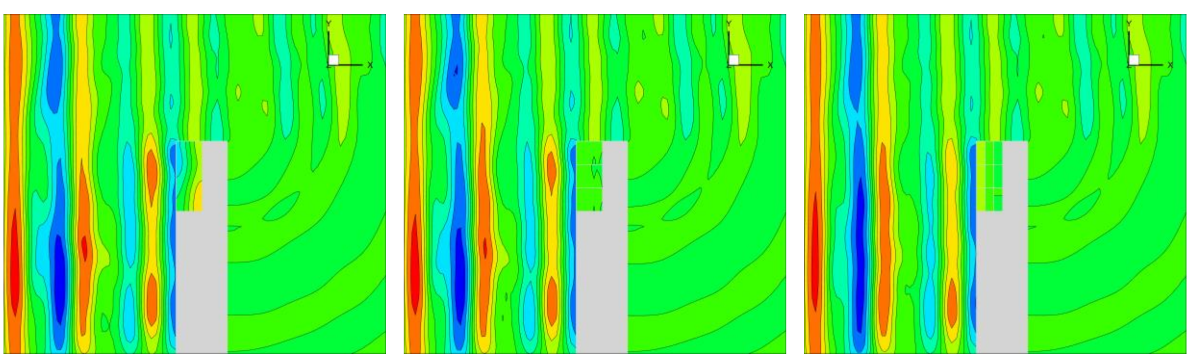
To validate the present numerical method, the airflow speed and pressure drop of the triple-OWC chamber are compared in Figure 2. The pneumatic response of the front chamber shows a good agreement between the numerical and experimental data. The energy conversion performance of the rear chamber was lower than that of the front chamber. The overestimation of these numerical results is due to the limitations of the potential flow theory assumptions regarding the wave energy loss around the complex geometry of the multi-chamber structure.



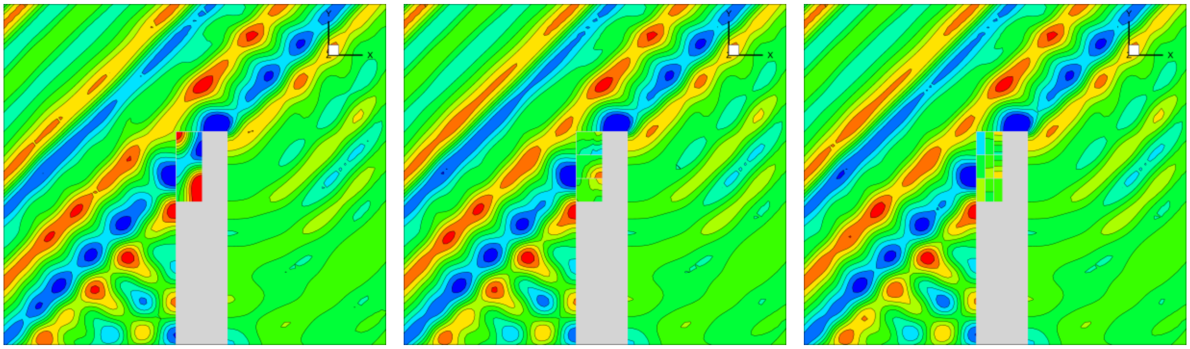
(a) airflow speed (b) air pressure

Figure 2: Comparison of the airflow speed and air pressure of the triple-OWC chamber in regular waves

Figure 3 shows the wave field around the breakwater-integrated OWC-WEC with single- and multi-chamber in irregular waves. The sloshing fluid motion is observed inside the single-OWC chamber in left side of Figure 3. Such a sloshing motion inside the single-OWC chamber was converted into a piston-type motion of each water column with a different phase in the case of multi-OWC chamber, which reduces the hydrodynamic energy loss in the net airflow rate. Figure 4 shows a comparison of pneumatic power between breakwater-integrated OWC-WEC with single- and multi-chamber under the head sea and oblique sea conditions. Three irregular wave conditions were considered in the numerical simulation; W#1 (H_s=0.5m, T_p=4.7s), W#2 (H_s=1.0m, T_p=5.3s), W#3 (H_s=1.5m, T_p=6.1s). The energy conversion performance of the multi-OWC chamber (XY) divided in the cross section of breakwater was better than other chambers. In particular, it can be found that a multi-chamber significantly improves the hydrodynamic energy conversion performance in oblique waves.

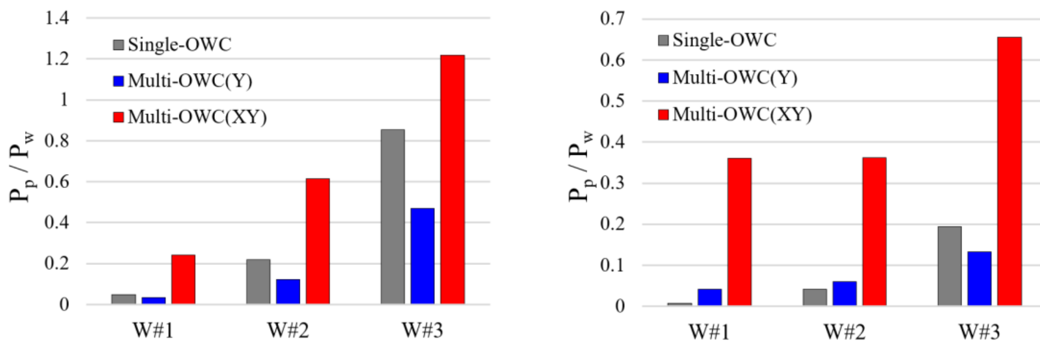


(a) head sea



(b) oblique sea

Figure 3: Comparison of wave field around breakwater-integrated OWC-WEC in irregular wave; (left) single-, (central) multi(Y)-, and (right) multi(XY)-OWC chamber



(a) head sea (b) oblique sea

Figure 4: Comparison of the pneumatic power between single- and multi-OWC chamber in irregular waves

4 CONCLUSIONS

In this study, the hydrodynamic performance of a multi-OWC chamber was investigated experimentally and numerically. It is found that the multi-OWC chamber improves the hydrodynamic energy conversion performance by reducing the sloshing fluid motion in waves. It is also confirmed from the numerical simulations that these improvements were effective under irregular wave conditions, particularly significant under oblique waves. In future research, we plan to investigate the practical arrangement of multi-chambers and frequency band expansion in terms of energy conversion performance.

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