A Wave Focusing Device for OWC Wave Energy Convertor

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***Abstract-* Oscillating Water Column (OWC) device has been widely employed in the wave energy conversion. Wave Focusing Device (WFD) is proposed to improve the operating performance of OWC chamber. In the present paper, a 3D Numerical Wave Tank (NWT) using two-phase VOF model is utilized to simulate the generation and propagation of incident regular waves. The NWT consists of the continuity equation, the Reynolds-averaged Navier-Stokes equations and the two-phase VOF functions. The standard k-ε turbulence model, the finite volume method, NITA-PISO algorithm and dynamic mesh technique are employed to generate the regular waves. The effects of WFD on the operating performance of OWC chamber are investigated numerically.**

I. INTRODUCTION

Wave energy is one of the most promising forms of ocean renewable sources because of its high energy density. The Oscillating Water Column (OWC) device has been widely employed in the wave energy conversion. It comprises a partially submerged air chamber with an opening in the front skirt, and the water column exposes to the incident wave field through the underwater opening. Waves can force the water column in the chamber to oscillate in the same manner as a simple piston, which will produce the bi-directional air flow through the air turbine in the duct. Capable of operating in the reversing flow conditions, the Wells turbine or the impulse turbine linked to the electric generator in the air duct, is generally used to convert the pneumatic energy into the mechanical energy.

A number of efforts have been made to study the performance of OWC air chamber. Ref. [1] was first to develop the analyzing theory of OWC wave energy absorption. Physical model with different bottom slopes was constructed and tested in a wave tank under regular wave conditions Ref. [2]. Reference [3] studied the air chamber performance under incident wave heights and nozzle ratios experimentally. Ref. [4] performed an experiment concentrating on the effects of several shape parameters of OWC chamber in wave energy absorbing capability. Ref. [5] presented a boundary element method to study the influence of coastal topography and the harbor shape on the oscillations of the OWC plant. Reference [6] calculated the motions and time-mean horizontal drift forces of floating backward-bent duct buoy wave energy absorbers in regular waves taking account of the oscillating surface pressure due to the pressure drop in the air chamber above the oscillating water column within the scope of the linear wave theory. Reference [7] applied the low order boundary element method for efficient hydrodynamic modeling of generic bottom mounted OWC power plants to estimate the annual performance of the wave energy plant on Pico Island.

The development and utilization of OWC wave energy convertor are restricted by the low converting efficiency during converting wave energy to pneumatic energy. It is necessary to find some ways to improve the converting and absorbing efficiency. It has been found theoretically and experimentally since the early 1980s that the wave energy absorption process can be enhanced by extending the chamber structure by protruding (natural or man-made) walls in the direction of waves, forming a harbor or a collector. Wave focusing device (WFD) is proposed to be one of the useful techniques to extend the wave crest line the front skirt faces. More wave energy is to be absorbed by the OWC air chamber.

In the present paper, a 3D numerical wave tank using two-phase VOF model based on the commercial CFD code Fluent V 6.2.16 is utilized to simulate the generation and propagation of incident regular waves which have been validated by the corresponding experimental data. The effects of wave focusing device on the operating performance of OWC chamber are investigated numerically.

II. NUMERICAL WAVE TANK

The 3D regular incident waves are generated by the piston motion of the wave making plate at one end of the flume. The fluids are assumed to be incompressible and immiscible. At the interface of two fluids, no phase change and no-slip between fluids are assumed. The continuity equations and Reynolds Averaged Navier-Stokes (RANS) equations are employed in the present numerical model. The standard k-ε model, which is widely used in engineering application, is applied to close the above system of equations and employed to describe the turbulence phenomenon in the water and air dynamic motions.

The interface tracking between air and water phases is accomplished by the Volume of Fluid (VOF) method as Ref. [8]. The volume fractions of water and air in the computational cell sum to unity. In addition, the face fluxes through the computational cells are obtained as the geometric reconstruction approach. The interface between two fluids is calculated by the piecewise-linear scheme in Ref. [9], which assumes the linear slope in each cell.

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The motion of the piston wave maker is determined and controlled precisely by the sinusoidal equations. The periods of the piston motion equal to the incident wave periods.

On the opening boundary, the Sommerfeld radiation boundary condition as in Ref. [10] is used to obtain the relation between the horizontal velocity component and the free surface elevation. The wave absorption can be performed by controlling the motion of the opening boundary within the velocities opposite to the water particles adjacent to the opening boundary on the x-direction.

The motion of the wave generating and absorbing boundaries can be achieved by defining UDF (User-Defined Function) programs. Fluent also provides the layering remeshing method in dynamic mesh model to govern the grid reconstruction adjacent to the moving boundaries. The geometries and meshes are created by the grid generation software Gambit V 2.2.

Second-order upwind discretization is employed for the convection terms. The pressure-velocity coupling is calculated by the NITA (None-Iterative Time Advancement) – PISO (Pressure Implicit with Splitting of Operators) algorithm compatible with VOF model, which requires only one global iteration per time step, and reduces solution time significantly.

In Fluent, the symmetry definition is applied for the wave making and absorbing boundaries. The bottom and chamber structures are set as the wall boundaries using no-slip conditions. The pressure outlet boundary is taken account for the top boundaries of the computational domain adjacent to the air phase (free in or outflow of air).

The grid independence and effects of time step has been tested in Ref. [11]. The computational results indicate that the numerical accuracy will be ensured when the grid size is less than $L/20$ and time step is less than $T/50$, where L denotes the wave length. In the present simulation, the grid sizes were modified case by case according to the wave length. The grid sizes, Δx in the x-direction were set around $L/50$, and Δy in the y-direction were set around $h/20$. The temporal time step was set to $T/100$ according to the incident wave period.

The capability of the numerical wave tank on the simulation of wave elevations, air pressure and air flow variation inside the chamber has been proved in Reference [12]. The numerical prediction of the operating performance of OWC chamber has shown good agreements with the corresponding experimental data.

III. Numerical Analysis of Wave Focusing Device

A. Wave Focusing Device and OWC Chamber

The schematic of the OWC air chamber with an cylinder duct installed at the center of the top cover is shown in Fig. 1 and Fig. 2, where l_{fc}=10.0m denotes the chamber width, d_s=3.0m the draft of the chamber skirt, l_s=1.0m the thickness of chamber skirt, l_d=1.8m the diameter of the cylinder duct, h_d =10.0m the length of the duct, chamber height h_e=33.0m, l_a=10.0m the distance from the center of the duct to the side edge of the chamber .

The schematic of Wave Focusing Device (WFD) is illustrated in Fig. 3. The WFD consists of two symmetrical vertical walls. One side of the vertical walls is connected with one corner of the front skirt of OWC air chamber, and the other end extends to the sea. The two vertical walls show bell-mouthed shape to the incident wave direction. When the incident waves arrive at the facility, the water surface will be enhanced during the propagation because of the effects of wave focusing device. The standing waves appear in front of the chamber and the amplitudes are evidently higher than the case of the chamber without WFD.

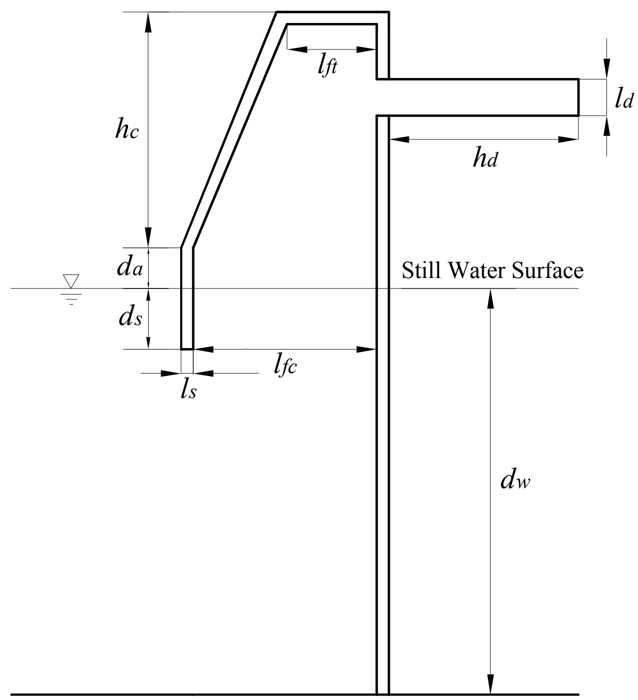

Figure 1. Side view for schematic of OWC chamber within two ducts installed on the side.

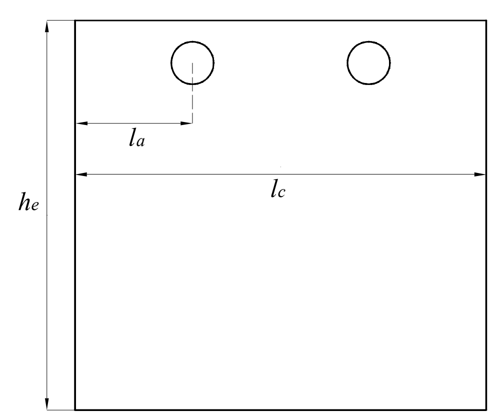

Figure 2. Back view for schematic of OWC chamber within two ducts installed on the side.

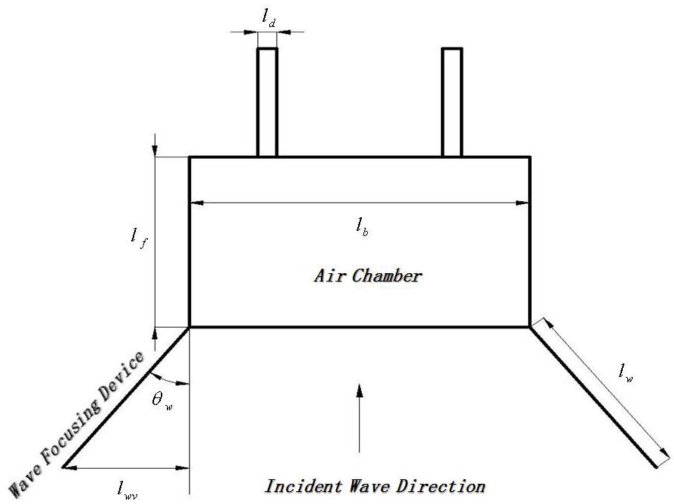

Figure 3. Top view for schematic of OWC chamber within two ducts installed on the side.

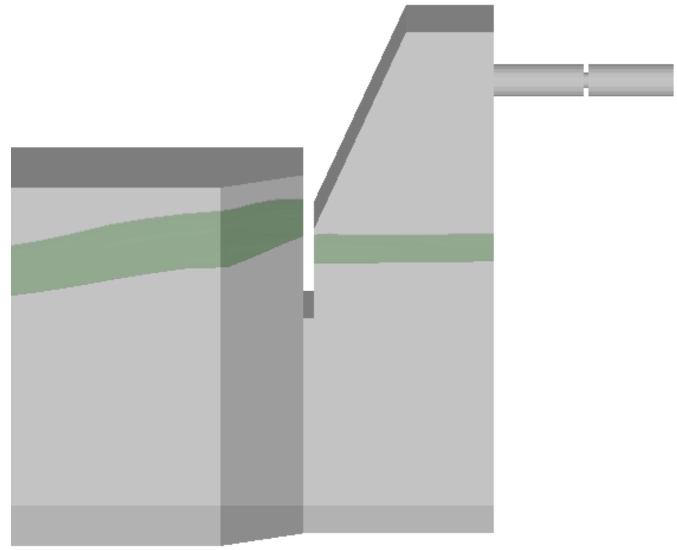

Figure 4. 3D Instantaneous Snapshot of Free Surface for OWC Chamber with WFD Devices.

TABLE I
TEST CONDITIONS FOR WFD DEVICES

Case	l_{wv} (m)	θ_w (°)	d_s(m)	Case	l_{wv} (m)	θ_w (°)	d_s(m)
01	0	0	20	06	0	0	15
02	2.0	45	20	07	8.0	15	15
03	4.0	45	20	08	8.0	30	15
04	8.0	45	20	09	8.0	45	15
05	16.0	45	20				

Nine cases with various test conditions are summarized in Table. I. In all the cases, there are the orifice devices installed in the duct to replace the effects of the turbine on the air pressure loss for OWC chamber. The ratio between the diameters of the orifices and air duct is 0.48. Different still water depths are employed for effects of expanding angles and vertical wall lengths, respectively. The incident waves whose period varies from 3.5s to 8.0s are employed for each case. In the numerical simulation, the OWC chamber is settled at the end of the wave tank, which is opposite to the wave maker plate. 8 to 10 regular waves were simulated and employed after the incident waves arrive the front skirt of the chamber.

B. Effects of WFD on the performance of OWC Chamber

The free water surface elevation in front of the front skirt of OWC air chamber and effects of Wave Focusing Device are illustrated in Fig. 4. It can be seen that the incident waves included in the length of the WFD crest line will be collected by WFD and the free water surface is lifted by the vertical walls, then propagate to the OWC chamber. The elevation of the incident wave can be seen higher than that without WFD facility.

The effects of expanding angles of WFD within the same vertical wall length are shown in Fig. 4-5. The air pressure inside the chamber and air flow rates varying in the duct are employed in the present paper, which is more evident comparing with the water column elevation in the chamber.

Effects of WFD expanding angles on OWC performance are given in Fig. 5 and Fig. 6. l_{wv} represents the projected length of the wall on the direction against incident waves. There are no evident difference for air pressure and flow rate variation, and effects of expanding angles are minor at the short-period domain for $T \leqslant 5.0$s.

Although the pressure difference are significant at long-period domain (T>5.0s), the air flow rates show mild improvements as the expanding angles increase. The enhancement is only about 8.6% quantitatively for the case within 45° expanding angles, which means its effects on OWC operating performance is not as significant as proposed.

When the expanding angle is fixed, effects of WFD wall lengths are studied and shown in Fig. 7 and Fig. 8. The air pressure inside the chamber and flow rates measured in the duct are utilized in this study.

It can be seen that the difference of the air pressure and flow rates for various wall length is minor in the short wave period domain. On the other hand, the evaluating parameters will converge in the long wave period domain and the values will increase as the length of the vertical walls increases.

Generally from the above calculating results, it can be concluded that the Wave Focusing Device has effects even on the chamber-duct systems within effects of air turbines.

Although there are some improvements of operating performance for the chamber-duct system, the expanding angles and wall lengths should be large enough. It means that the construction expense will increase much more than the original structure. The input-output ratio is not suitable and satisfied enough for the wave power station and it should be considered carefully for the final optimal design.

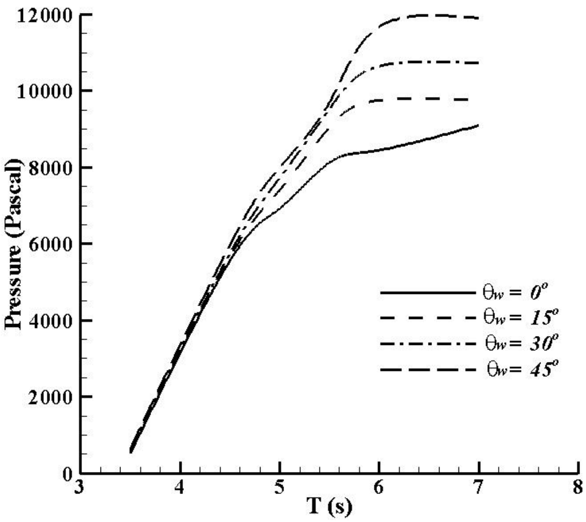

Figure 5. Effects of WFD wall lengths on air pressure variation for OWC chamber, lwv=60°

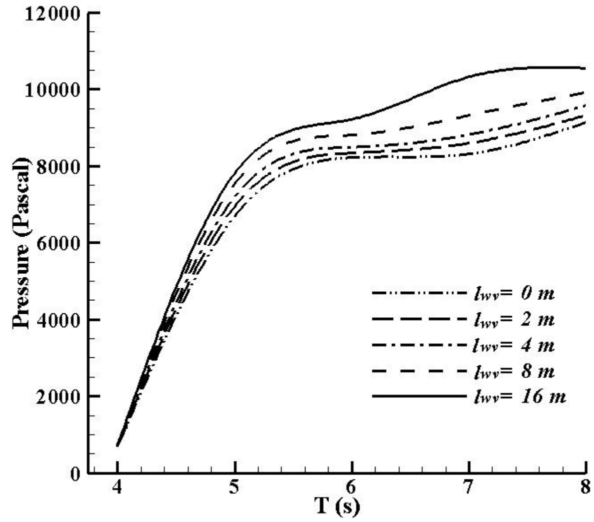

Figure 7. 3D Instantaneous Snapshot of Free Surface for OWC Chamber with WFD Devices.

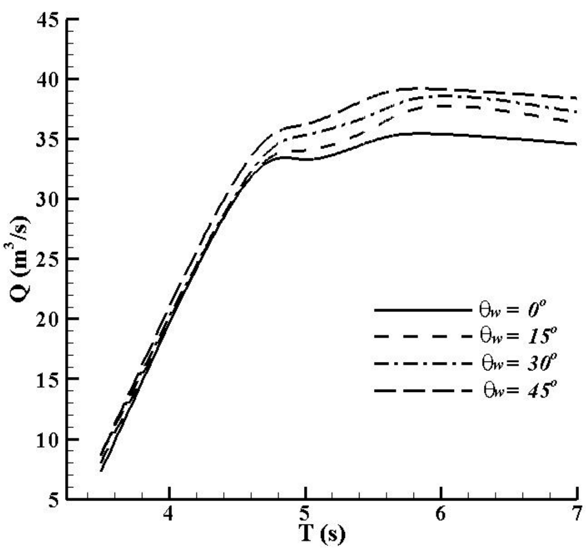

Figure 6. 3D Instantaneous Snapshot of Free Surface for OWC Chamber with WFD Devices.

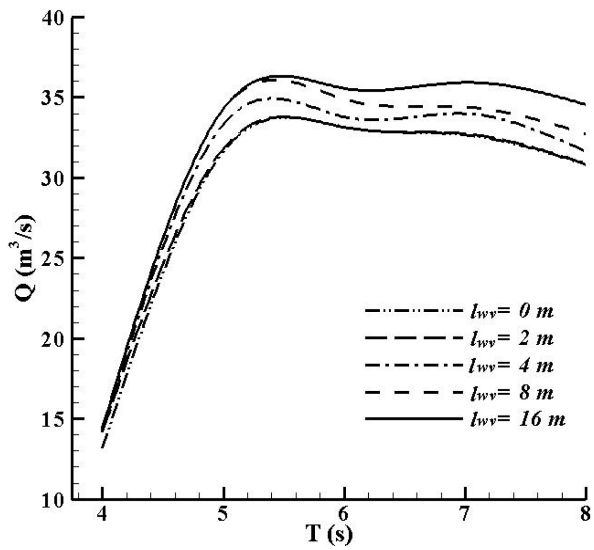

Figure 8. 3D Instantaneous Snapshot of Free Surface for OWC Chamber with WFD Devices.

IV. Conclusions

A 3D numerical wave tank based on the commercial CFD software Fluent 6.2.16 using VOF model has been developed to simulate the wave propagation in this paper. The RANS equations, standard turbulence model and dynamic mesh technique were employed in the present model.

The Wave Focusing Devices within bell-mouthed shaped vertical walls are employed to improve the wave energy converting efficiency of OWC air chamber. The numerical results indicate that the Wave Focusing Devices has minor effects on the performance of OWC chamber in the short wave period and some effects on the wave energy absorbing. The air pressure variation inside the chamber and air flow rates variation in the duct also will increase as the length of vertical walls and expending angles. The investigation here indicates that the Wave Focusing Device is a useful facility to improve the wave energy converting ratio of OWC chamber, but the construction expenses will be much higher than the original wave power plants and it still need more effort to be studied in the future.

Acknowledgment

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