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Original Articles

사파중 진동수주형 파력발전장치의 성능평가

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Performance of Oscillating Water Column type Wave Energy Converter in Oblique Waves

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요 약

진동수주형 파력발전시스템의 성능은 OWC챔버의 형상 뿐만 아니라 입사파의 각도와 터빈의 효과로 인한 압력강하등과 같은 작동환경의 영향도 받는다. 기존의 대부분 연구들은 파랑에너지 흡수효율에 초점을 맞췄기 때문에 입사파 방향이 OWC챔버 입구면과 직각을 이룬다는 가정 하에 수행되었다. 하지만 실해역에서는 입사파가 해양환경에 따라 사파의 형태로 입사하게 될 것이고, 고정식 구조물인 경우에는 그 영향이 더욱 지배적이다. 본 논문은 실험및 수치해석적인 방법으로 사파중 OWC챔버의 성능에 대하여 고찰하였다. 실험은 3차원 조파수조를 이용하여 다양한 입사파 각도조건에서 수행하였다. 터빈의 영향을 고려하기 위하여 오리피스를 적용하여 챔버내 진동수주의 수위변동을 계측하였다. VOF모델을 기반으로 한 수치조파수조를 구축하여 실험과 동일한 조건으로 계산을 수행하여 실험결과와 비교분석하여 공기실과 그 인근의 유동변화를 고찰하였다.

Abstract – In an oscillating water column (OWC)-type wave energy conversion system, the performance of the OWC chamber depends on the chamber shape, as well as the incident wave direction and pressure drop produced by the turbine. Although the previous studies on OWC chambers have focused on wave absorbing performance in ideal operating conditions, incident waves do not always arrive normally to the OWC chamber in real sea conditions, especially in fixed devices. The present study deals with experiments and numerical calculations to investigate the effects of wave direction on the performance of the OWC chamber. The experiments were carried out in a three-dimensional wave basin for five different wave directions, including the effect of turbine using the corresponding orifice. The wave elevation inside the chamber was measured at the center point under various incident wave conditions. The numerical study was conducted by using a numerical wave tank-based volume-of-fluid model to compare the results with experimental data and to reveal the detailed flows around the chamber.

Keywords: Wave Energy(파도에너지), Wave Direction(파향), Numerical Wave Tank(수치조파수조), OWC (진동수주), Wave Basin(조파수조), Turbine Effect(터빈영향)

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1. INTRODUCTION

Wave energy is one of the most promising ocean renewable resources. The oscillating water column (OWC) device has been widely employed in wave energy conversion. An OWC wave energy converting system includes three energy converting stages: 1) the OWC inside a chamber forces air alternately into and out of the atmosphere through the duct. 2) a turbine with symmetric blades transforms the bi-directional air flow energy into a torque. 3) an electricity generator linked to the turbine transforms the torque into electrical power. This third stage is not considered in the present study.

There have been several researches on the efficiency and operating performance of OWC wave energy conversion systems. A number of efforts have been put into the research of wave energy converting efficiency and operating performance of the oscillating water column system. Wang *et al*. [2002] constructed and tested physical models with different bottom slopes in a wave tank under regular wave conditions. Hong *et al*. [2007] performed an experiment focusing on the effects of several shape parameters of the OWC chamber on wave energy absorbing capability. Marjani *et al*. [2008] presented a numerical model to predict the flow characteristics in the components of an OWC system used for wave energy capture.

In terms of the turbine system, Setoguchi *et al*. [2001] carried out experimental and numerical investigations on impulse turbines for wave energy conversion with different shape parameters and compared with Wells turbines. Takao *et al*. [2007] studied the performance of a Wells turbine with end plates by conducting a modeling test. Thakker and Abdulhadi [2008] investigated the performance of the Wells turbine under unsteady conditions of bi-directional airflow. They also carried out a comparative analysis of experiments and numerical simulations. Jayashankar *et al*. [2009] designed and studied the twin unidirectional impulse turbine topology for OWC based wave energy plants through a field test in India.

In this paper, the effects of wave directions on the performance of an OWC chamber have been investigated. Two type of OWC chambers-one without a cover and the other with a duct and an orifice were employed in the experimental study. The experiment was carried out in a three-dimensional (3-D) wave basin located at the Ocean University of China. The wave elevation inside the chamber was measured at center point under various incident wave conditions and wave directions. A Computational Fluid Dynamics (CFD) study using a numerical wave tank (NWT)-based two-phase volume-of-Fluid (VOF) model was also conducted to compare the results with the experimental data and to reveal the detailed flows around the chamber.

2. EFFECTS OF WAVE DIRECTIONS ON OWC WITHOUT COVER

2.1 Experimental Study

A schematic of the OWC air chamber is shown in Fig. 1, where L_f denotes the chamber width, D_s is the draft of the chamber skirt, W is the width of chamber, and D_u is the still water depth. The width length ratio of the chamber is 1.6. The dimensions of the chamber are summarized in Table 1, at both the model and full scales. The incident wave conditions employed in the experiment are summarized in Table 2. H_m denotes the incident wave height of model and full scale, H_p is for full scale. T_m, T_p is the incident wave period at model and full scale respectively.

The experiment was conducted in the 3-D wave basin of the Ocean University of China. The water depth during the exper-

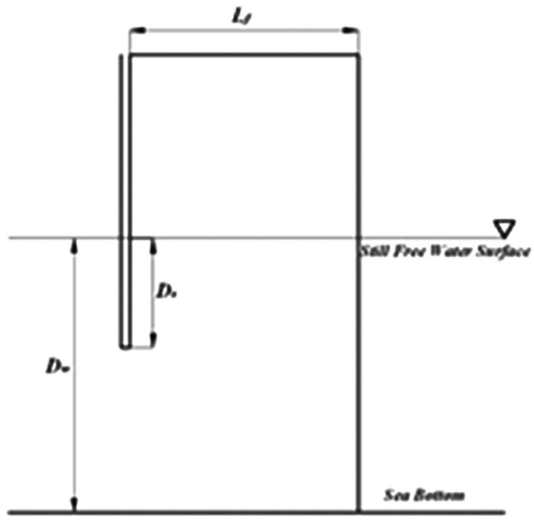


Fig. 1. Schematics of OWC chamber.

Table 1. Dimensions of chamber

	L_f	D_s	W	D_w	W/L
Full Scale	8.0 m	3.84 m	12.8 m	9.6 m	1.6
Model Scale	0.5 m	0.24 m	0.8 m	0.6 m	1.6

Table 2. Summary of incident wave conditions

(a) Incident wave height			
Model, H_m	0.125 m	0.0625 m	0.03125 m
Full Scale, H_p	2.0 m	1.0 m	0.5 m
(b) Incident wave period			
Model, T_m	1.0s	1.5s	2s
Full Scale, T_p	4.0s	6.0s	8.0s

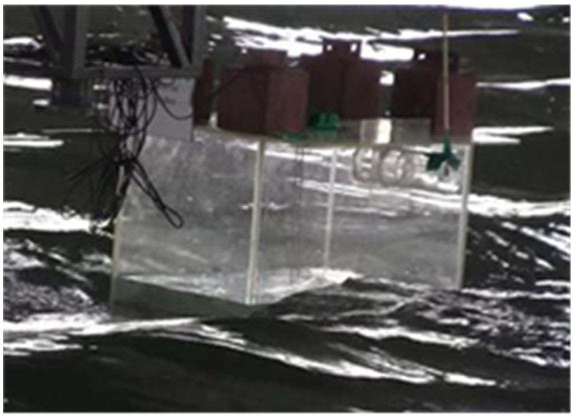


Fig. 2. Experimental set up.

iment was 0.6 m. A piston type wave maker system was installed at one end of the wave basin and a wave absorber was installed at the opposite end.

The OWC chamber model shown in Fig. 2 was fixed at a 40 m distance from the wave maker which is the position of 2/3 according to length of wave basin. The model is made of poly methyl methacrylate (PMMA) acrylic. The scale ratio of the OWC model for the basin test to the prototype was 1/16 and the water depth for the prototype was 9.6 m. The wave height inside the chamber denoted by H_0, was measured at the center of the chamber using a wire-type capacitance wave gauge. The sampling time step was 0.002s, and the number of wave crests was 10-12.

Airflow motion and wave energy absorption are related to the oscillation of water column in a chamber. Therefore, it is important to investigate the response of free-surface to demonstrate the effects of the corresponding wave directions on power conversion. To investigate the effects of wave directions on the performance of the OWC chamber, a very simple model was employed where the top of the chamber was open along the entire length. Considering the capacity of wave basin, three incident waves with periods varying from 4 to 8 seconds were chosen when the wave height was 2.0 m in full scale. Five wave directions varying from 0º to 90º were selected to demonstrate the effects of wave direction.

Fig. 3 shows results for the effects of wave direction at an incident wave height of 2.0 m in full scale. The dimensionless relative wave heights were compared in each wave period, where H_P is the incident wave height, H_0 is the oscillating height of the water column in the chamber, and the wave direction was varied from 0º to 90º. It is noted that, at 90º of wave angle, the incident wave approaches normal to the OWC chamber.

In the case without cover, the results show that the wave

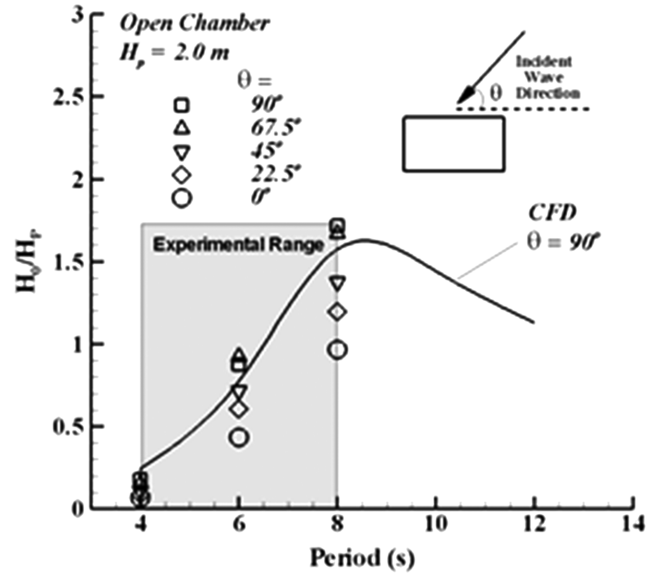


Fig. 3. Experimental results on the wave amplification in a chamber for five different wave directions.

height in a chamber varies as a function of the incident wave periods. The effect of wave direction was not so prominent at the wave angles higher than 67.5º. As the wave angle became smaller, the relative wave height decreased at every incident wave conditions. The numerical result at the wave angle of 90º was also shown in Fig. 3 to figure out the general feature of the performance of simple OWC chamber. It can be seen that the peak wave height inside chamber occurred around the period of 8~9 seconds. Unfortunately, the experiment at the incident wave period longer than 8 seconds could not be performed due to the load limitation of experimental set-up. It is however worth noting for the present OWC chamber model that the present experiments well demonstrate the effects of incident wave angle in general sense. More detailed analysis can be seen in the next section.

2.2 Numerical Study

For the converting stage, in which wave energy is converted into bi-directional air flow energy, the NWT-based tow-phase VOF model (Fluent) established by Liu *et al*. [2007] was used for incident wave generation and propagation. The OWC system was placed at the end opposite to the wave maker. The VOF model has been demonstrated to simulate the complex free surface interaction, predicting not only the wave motion but also the pressure distribution and air flow motion. It has been successfully employed in the investigation of both the OWC and overtopping wave energy converting facilities by Liu *et al*. [2007, 2008].

The effects of wave direction were investigated using the

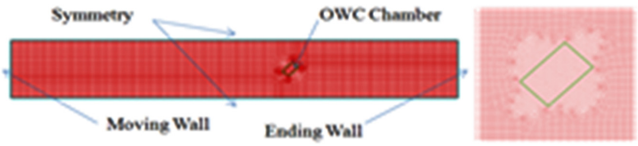


Fig. 4. Schematics of grid structure.

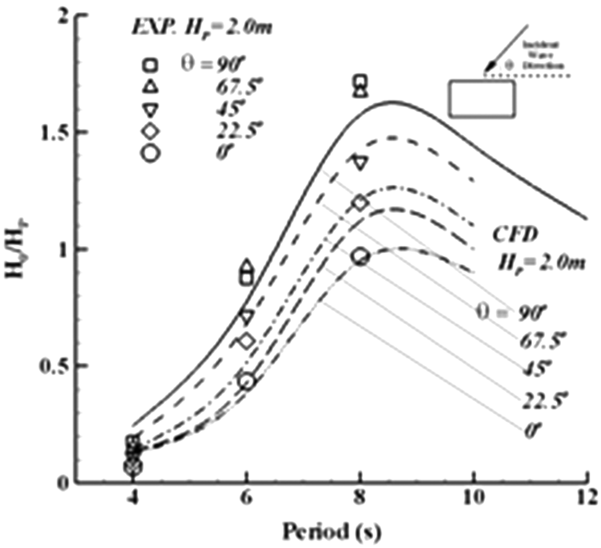


Fig. 5. Comparison with experimental results at 5 different wave directions.

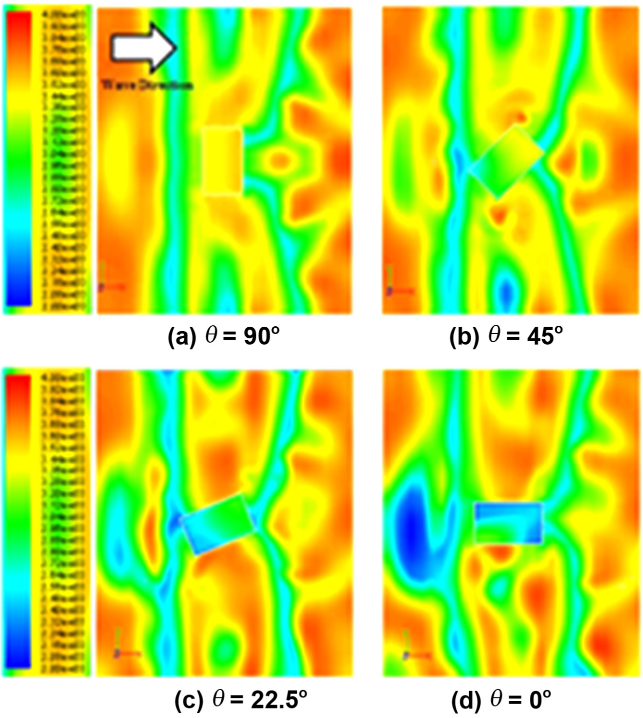


Fig. 6. Calculated pressure contours near free surface (H_p=2.0 m, T_p=6.0 s).

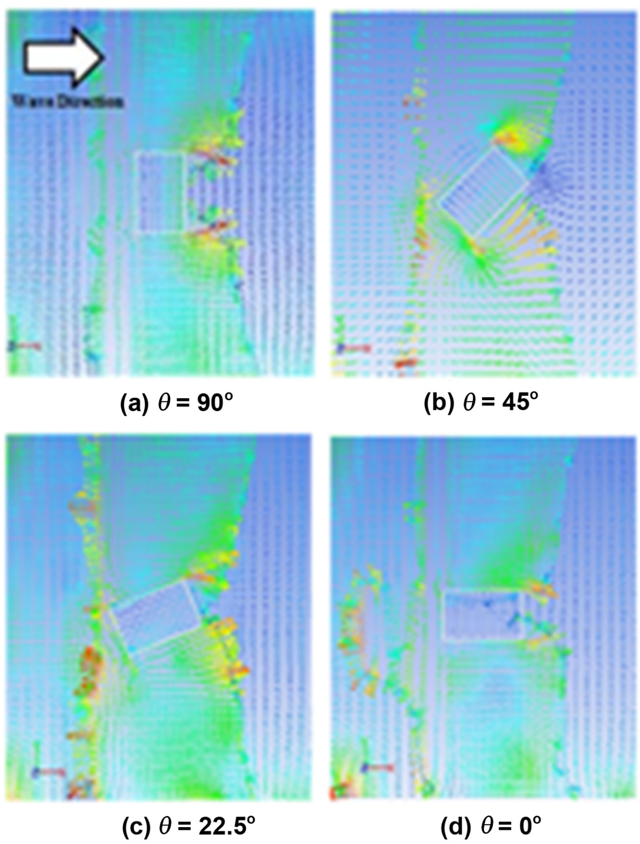


Fig. 7. Calculated velocity vectors near free surface (H_p=2.0 m, T_p= 6.0 s).

NWT based on the two-phase VOF model. The boundary conditions and the grid structures are given in Fig. 4. Four direction angles of 90°, 67.5°, 45°, and 22.5°, in addition to 0° were employed in the numerical study. Four incident wave periods varying from 4 to 10s were applied, and the incident wave height was 2.0 m.

Comparisons of wave amplification in a chamber between numerical and experimental results are shown in Fig. 5. Obviously the small θ produces the less wave amplification. The numerical calculation shows qualitatively fair agreement with the corresponding experimental data, while experiment gives a little higher amplification factors in quantity. It is likely that the nonlinear wave amplification phenomenon is more prominent in experiment at W/L_f = 1.6.

Fig. 6 shows the instantaneous pressure contours near the free surface at difference wave directions around the chamber. The incident waves arrive from the left. The pressure contours shown in Fig. 6(a) shows the case of 90° of wave angle, where the pressure field inside the chamber was rather uniform. As the angle of the incident waves decreased, an inequitable pressure contour was found, especially at 0°. This may be evident that highly complex motions such as sloshing phenomenon and various wave interactions each other occurred inside a chamber because of the presence of the side walls, dominant reason of high 3-D effects in the range of studies in this paper.

The instantaneous velocity vectors near the free surface at various wave angles are shown in Fig. 7. High velocity gradients are observed at the corners of a chamber. Based on the velocity vectors, it can be seen that complex flows appeared outside the chamber may also influenced the pressure field inside a chamber.

In this study, It is now interested to investigate the effect of the width-length ratio. Fig. 8 shows the wave amplification inside a chamber with varying chamber widths at the wave direction of 45°. Here the width-length ratio of $W/L_f = 1.6$ is the chosen case in this study, while $W/L_f = 10$ is the case of very large chamber width, almost comparable to the wave length. It is shown that the chosen case, $W/L_f = 1.6$, gives the best performance among the cases investigated. This kind of tendency becomes more prominent with the larger width-length ratio. It even shows the 80% reduction of wave at $W/L_f = 10$ compared to $W/L_f = 1.6$ in case of longer wave period. It could be anticipated that the wave interactions inside a chamber are the major reason of the reduction of wave height at the larger chamber width.

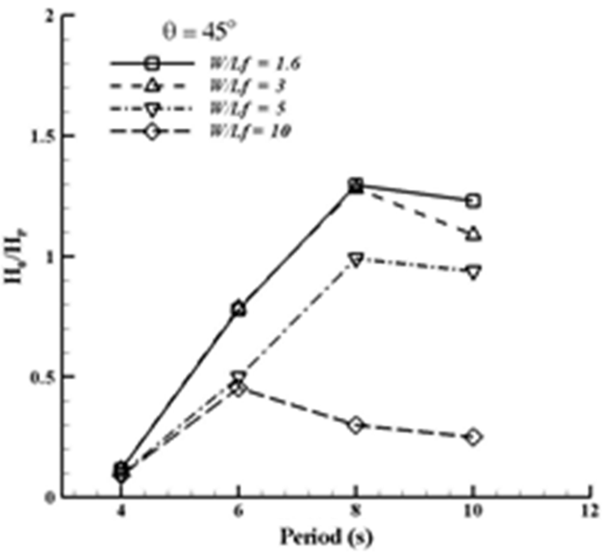


Fig. 8. Effect of chamber width on the wave amplification inside a chamber.

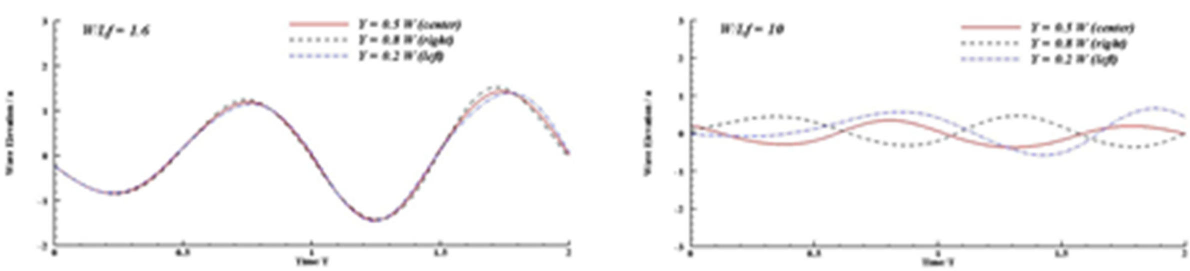
It is well demonstrated in Fig. 9 showing the time series wave profiles at typical locations in a chamber. The three locations along the chamber width are chosen; y/W=0.2, 0.5(center), 0.8, where y is the direction in chamber width. The wave amplification is clearly seen at $W/L_f = 1.6$ without any interaction along the chamber width. The case is quite different in Fig. 9(b) that the wave interactions each other create the cancellation of the overall wave elevation, that is the reduction of total airflow in air chamber. It is concluded that the selection of chamber width plays the critical role in designing OWC, especially at oblique wave conditions.

3. EFFECTS OF WAVE DIRECTIONS ON OWC CHAMBER WITH TURBINE EFFECTS

In this section, the effects of wave direction are studied in an OWC chamber with a duct and a 0.5D orifice which is integrated OWC system. The diameter of duct is 0.1 m, and the orifice is installed in the center of duct. In real operating conditions, the damping pressures in the chamber caused by the turbine effects reduce the wave elevation. Therefore, an investigation of the effects of wave direction considering turbine effects is very important.

In numerical studies, embedding the turbines into the NWT is difficult because of the geometry and mesh complexity of the impulse turbine. Furthermore, the effects of the air turbines on the OWC chamber generate a drop in the pressure. Therefore, to achieve the pressure drop without turbines, a substitute that has simple shape and is also easily installed in the NWT must be found. Liu *et al*. [2009] demonstrated that orifice devices can be utilized successfully as pressure drop substitutes. The validation of the proposed numerical method is presented in Liu *et al*. [2011].

The experimental results on relative wave height at different wave directions and various incident wave heights are presented in Fig. 10. As mentioned previously, a wave direction of 90° indicates an incident wave that arrives normal to the OWC cham-



(a) $W/L_f = 1.6$ (b) $W/L_f = 10$

Fig. 9. Time series wave profiles at typical locations in a chamber.

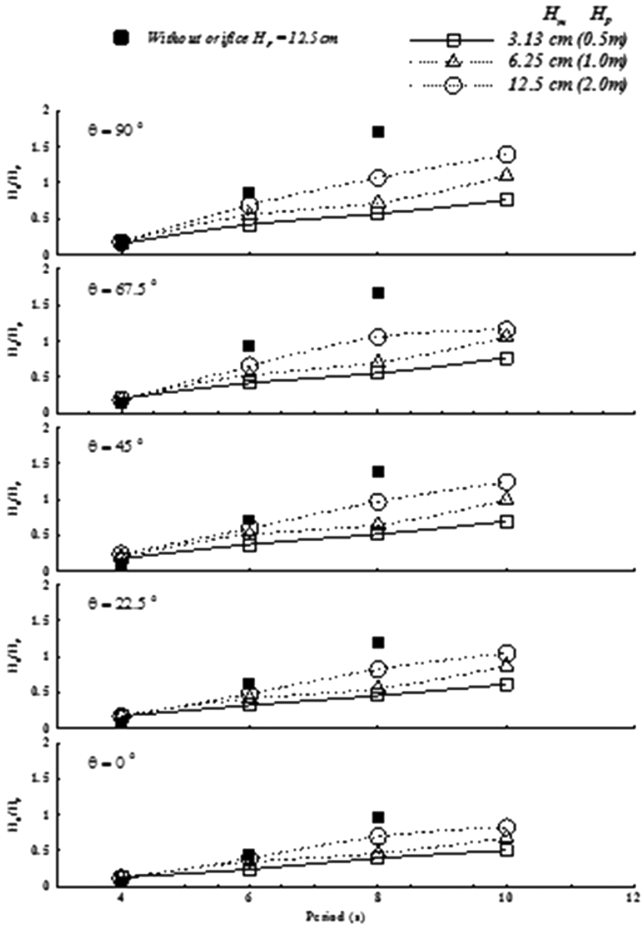


Fig. 10. Experimental results on wave height with various incident wave heights (with 0.5D orifice).

ber. The effect of incident wave height on the relative wave height increases as the incident wave height increase at every wave direction. The effect of wave height at the same incident wave period is actually due to the effect of wave slope. As the wave direction angle decreases, the relative wave height decreases at almost all incident wave conditions.

The numerical results shown in Fig. 11 are compared to the corresponding experimental results. The viscous CFD method based on the two-phase VOF model shows the good agreement with the experimental results. This suggests that the present model could be a useful tool to investigate the effects of wave direction for an integrated OWC system considering the turbine effects. In OWC system, the water column in the chamber produces the bi-directional air flow through the air turbine in the duct, and consequently the driving force of turbine in operation.

The calculated positive amplitude distributions of the air flow rates in the duct at various incident wave periods are shown in Fig. 12. Similar to the wave height in a chamber, the effect of wave direction on performance of air flow rate is decreased as

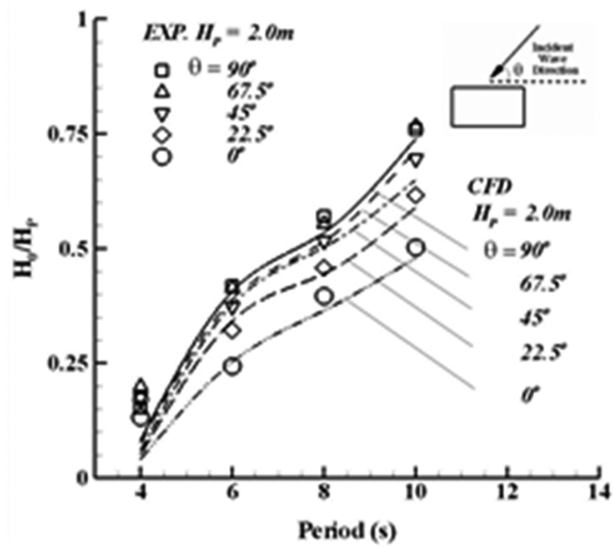


Fig. 11. Comparisons between numerical results and measurements with turbine effect.

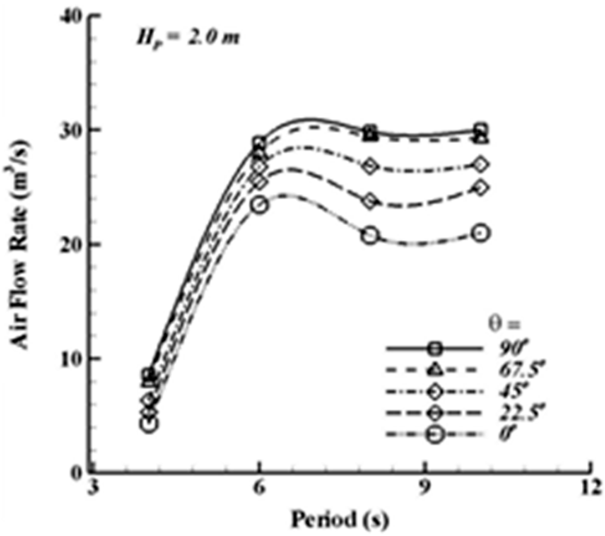


Fig. 12. Calculated air flow rates inside duct with turbine effect.

the wave angle decreases. Compared to the range of long wave periods, the reduced air flow rates were not obvious in the range of short wave period. The results show that the maximum air flow rate occurred in this device was 30 m^3/s. The maximum reduction in the air flow rate ratio is about 27% compared to the normal incident wave direction of 90°.

4. CONCLUSIONS

This paper deals with the effects of wave direction on the performance of a fixed OWC-type wave energy converter. Experimental and numerical investigations were carried out on wave energy absorption at various wave directions. The experimental results show that the relative wave height inside the chamber is decreasing as the direction of incident wave decreases. The decrements in relative wave heights inside chamber reached a maximum of 40% owing to wave diffraction.

The viscous numerical method shows good agreement with the corresponding experimental data on the relative wave heights. Similar to the experimental results, the effect of wave direction on the relative wave height is small at a large direction angle and the operating performance of the integrated OWC system is reduced as the direction angle decreases at a certain rate. The numerical results also demonstrate that 3-D effects promote the wave elevation inside the chamber.

Since the present model can predict the operating performance of the integrated OWC system at various wave directions, a look-up table of OWC - NWT can be established with the inclusion of the effect of wave direction. Using the modules above, more convenient software can provide engineers with more realistic performance data under real sea conditions.

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