Experimental Study on the Efficiency of an OWC under Different Incident Wave Conditions

Yaw-Huei Lee[1], Duy-Tong Nguyen[2], Yi-Chih Chow[3]

[#] *Department of Systems Engineering and Naval Architecture, National Taiwan Ocean University*
Keelung, Taiwan

[1]lyh@email.ntou.edu.tw

[2]*10551033@mail.ntou.edu.tw*

[3]ycchow@email.ntou.edu.tw

***Abstract*—The Oscillating Water Column (OWC), one type of the wave energy converter (WEC), has been the focus of many researches of marine energy because of its simplicity. The efficiency of an OWC is apparently affected by the incident wave conditions. This paper studies the effect of the incident wave conditions on the efficiency of an OWC using experiments with a model whose geometry is similar to that of the LIMPET. Under different incident wave conditions, we perform experiments with an outlet orifice of two diameters to simulate different pneumatic damping levels of the air turbine. Time-series images of the water level inside the OWC are first obtained by high-speed imaging, and then processed and analysed with a procedure to find the position and velocity of the water level. The capture factor of the OWC is related to the water level's kinematic characteristics using a simple hydrodynamic theory. The results indicate that the OWC's efficiency is strongly related to the incident wave conditions as well as the pneumatic damping levels.**

***Keywords*—Oscillating Water Column (OWC), incident wave conditions, pneumatic damping, high-speed imaging, capture factor**

I. Introduction

Renewable energy has become a global focus in recent years because of the needs of environmental protection and energy conservation. The potential of a form of renewable energy consists in its energy density. According to [1, 2], the energy densities for solar energy, wind energy and ocean energy are respectively 0.1~0.3 kW/m^2, 0.4~0.6 kW/m^2 and 2~3 kW/m^2, indicating that the potential of marine energy is significantly higher than that of other renewable energies. Therefore, the exploitation and conversion of marine energy needs to be seriously considered.

Among different forms of marine energy, wave energy has the largest potential and inspires the highest number of patents published globally in developing its harvesting device: wave energy converter (WEC). These WECs, whether they have been materialized or are still a concept, can be categorized into eight types according to the EMEC (European Marine Energy Centre: attenuator, point absorber, overtopping, pressure differential, Oscillating Wave Surge Converter (OWSC), bulge wave, rotating mass and Oscillating Water Column (OWC). The OWC has drawn many attentions because of its simplicity: the water level in the OWC's chamber goes up to push the air out and down to draw the air in owing to the incident waves, driving the air turbine inside the channel to generate electricity, i.e. there is no mechanical part moving in the water. As a result, the present paper also chooses the OWC as the research target and studies its performance characteristics.

A big advantage of the OWC type of WEC is that it can be integrated with breakwaters to achieve both purposes of structure protection and energy extraction. So the OWC can be used to replace the armour blocks as reported in [3]. Encouragingly, 16 integration modules of OWCs and breakwater entities have been constructed in Spain, and it was reported [4] that these modules generated averaged electricity of 600MWh annually. The OWC can also be integrated with floating platforms on the sea surface, like that of wind turbines [5] to form a hybrid device of renewable energy.

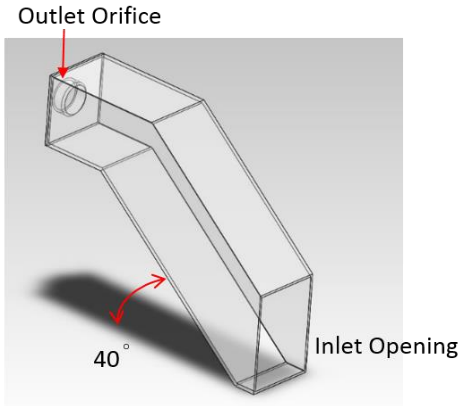
One of the large-scale OWC models still in operation is the LIMPET (Land Installed Marine Power Energy Transmitter, [6]), whose construction was completed at the Isle of Islay, Scotland, in 2000. LIMPET has well demonstrated its long-term robustness with the fact that it has been operating for about 18 years and it keeps operating now. Nevertheless, the overall efficiency of LIMPET has not reached its design goal in this long period of operations. Based on the background review above, the OWC type of WEC has obvious merits of simplicity, multi-purposes of structure protection, energy extraction and forming hybrid energy device, and long-term robustness. Once again, the OWC has shown its worthiness of study and exploration.

The present paper experimentally studies the effect of the incident wave conditions on the efficiency of an OWC, whose model was designed with geometry similar to the LIMPET as mentioned above. Chapter II describes the detailed experimental setup; Chapter III shows the sample result of image processing and analysis for the water level inside the OWC and the application of a simple hydrodynamic theory to estimate the relative capture factor, and discusses the experimental results; Chapter IV concludes the present paper.

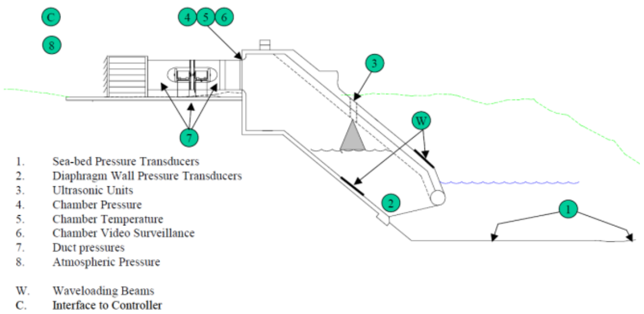
II. Experimental Setup

The experiments were performed in a wave flume of the Hydraulic Laboratory, located at the Department of Harbor & River Engineering of National Taiwan Ocean University. Four incident wave conditions and two pneumatic-damping levels simulated by two different diameters of the outlet orifice were set in eight combinations for the experiments. We used a high-speed camera to shoot images of the water level in time series inside the OWC and developed an image processing and analysis procedure to yield the water level's position and velocity.

A. OWC Model



(a)



(b)

Fig. 1 Schematic plots of (a) the OWC model used and (b) the LIMPET ([6])

The OWC model used in the experiments was made of transparent acrylic as shown in Fig. 1(a), and its geometry was designed to be similar to the LIMPET as shown in Fig. 1(b). The dimensions of the OWC model is 1.3 m long, 0.32 m wide and 1.02 m high. The front channel is inclined at 40 degrees to the horizontal plane.

The two diameters of the outlet orifice at the end of the OWC to simulate different pneumatic-damping levels are 194 mm and 130 mm, corresponding to low and high pneumatic-damping coefficients, respectively.

B. Wave Flume and Incident Wave Conditions

As Fig. 2 shows, the wave flume used in the experiments has dimensions of 16 m long, 2 m wide and 1 m high, and an observation window of about 4 m long on each side wall. The wave maker was designed and manufactured by the Edinburgh Design Ltd., UK. Two wave gauges were set at the longitudinal middle plane of the wave flume with distances of 2 m and 6 m to the wave maker, as shown in Fig. 2.

The incident wave conditions are four combinations of two wave periods of 1.56 sec and 1.90 sec and two wave heights of 7 cm and 10 cm. The water depth in the wave flume in the experiments was kept at 50 cm.

C. High-Speed Imaging

The Phantom v310 CMOS high-speed camera with the maximum resolution of 1280 x 800 pixels at the acquisition rate as high as 3200 fps was used to image the water level inside the front channel of the OWC model. The Micro-Nikkor 105 mm f/2.8 camera lens to zoom in to enlarge the image details of the water level was also used.

III. Analyses and Results

The time-series images of the water level were processed and analysed to yield the water level's position and velocity, which was then related to the capture factor using a simple hydrodynamic theory. The final results were to be used to find the influence of the incident wave conditions on the efficiency of the OWC.

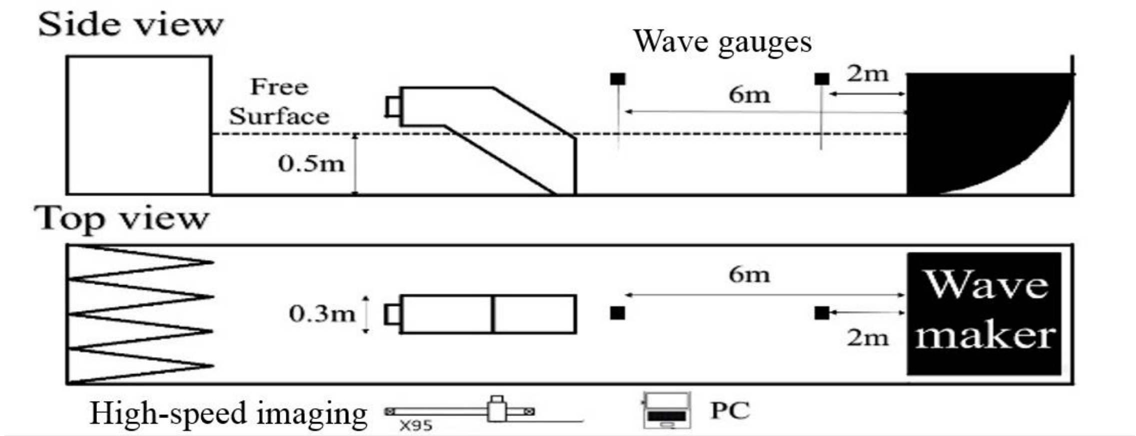


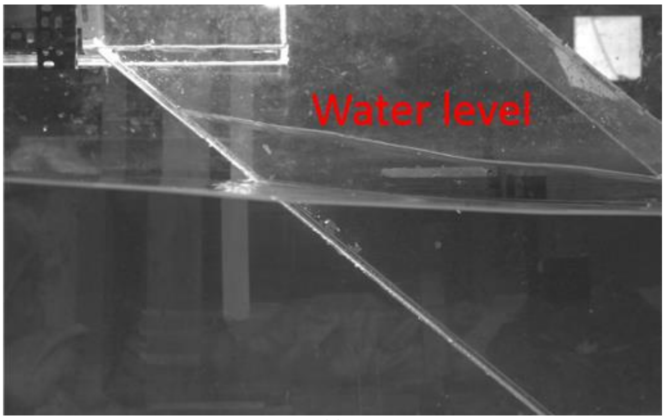
Fig. 2 Schematic plot of the experimental setup

TABLE I
EXPERIMENTAL DATA OF 8 TESTS: MAXIMUM WATER LEVEL DIFFERENCE AND CAPTURE FACTOR RATIO

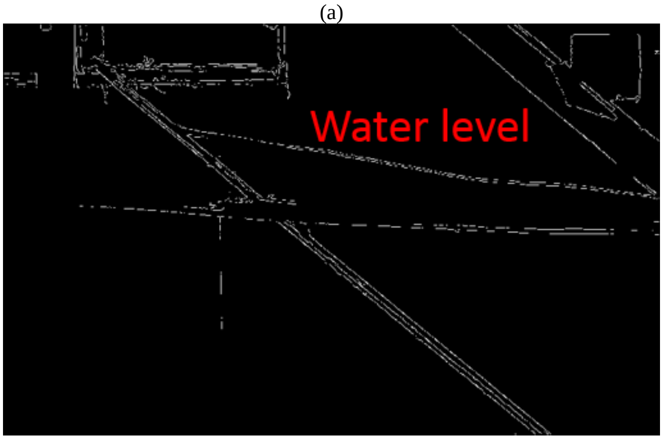
Test No.	1 (ref.)	2	3	4	5	6	7	8
Outlet orifice diameter (mm)	130				194			
Wave period (sec)	1.56		1.90		1.56		1.90	
Wave height (cm)	7	10	7	10	7	10	7	10
Maximum water level difference (cm)	7.57	9.01	20.26	23.18	7.24	9.11	20.55	23.63
CF/CF₁	1	0.89	4.89	3.79	0.84	0.88	4.81	3.77

A. Image Processing and Analysis

As a sample shown in Fig. 3(a), the image of the water level was clearly captured. Then, the algorithm of Canny Edge Detection was applied on the whole image to enhance the edge-like image objects as shown in Fig. 3(b). With using some filtering algorithms, the signal-to-noise ratio was effectively improved for us to clearly identify the water level and then obtain its position and velocity.



(a)



(b)

Fig. 3 One sample image of the water level: (a) the original image, and (b) the result after image processing.

Capture factor (CF) is defined as the ratio of the average power transmitted from the water to the air inside the OWC chamber to that of the incident wave. Chen [7] has shown that the CF of the OWC type of WEC is in proportion to the square of the maximum vertical velocity of the water level inside the OWC chamber, $(V_{\max}^{WL})^2$, as

$$CF \propto \frac{(V_{\max}^{WL})^2}{H^2\left(1+2kh/\sinh(2kh)\right)} \quad (1)$$

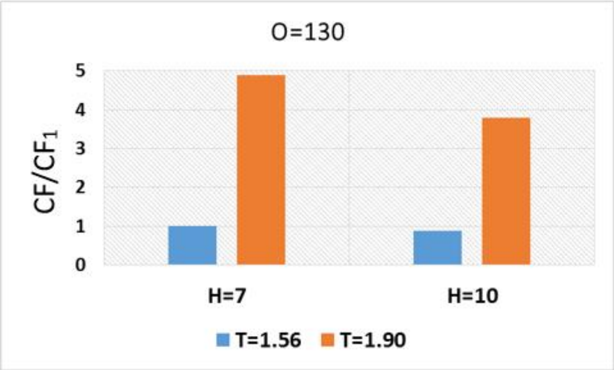
where H is the wave height, k is the wave number, and h is the water depth. Equation (1) shows that once the velocities of the water level are yielded from the image analyses, the relative CF value can be obtained.

B. Results

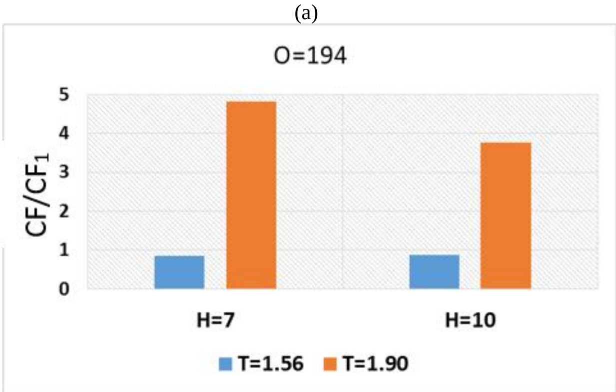
As Eq. (1) can be used to compute the relative values (ratios) of CF for comparisons of cases of different test conditions, we choose the CF of Test No.1, CF_1, as the reference value (denominator of the CF ratio) to form the capture factor ratio (CF/CF_1) as shown in Table 1. If the ratio value is greater than 1, the efficiency of the OWC at that test condition is higher than that of Test No.1. Obviously, the greater the ratio value, the higher the efficiency of the OWC.

Figure 4(a)&(b) clearly shows that the OWC's efficiencies in the operations with the incident wave period of 1.9 sec are much higher than that of the cases of 1.56 sec. Also clearly shown in Fig. 4(a)&(b) is that the cases of the smaller wave height (7 cm) have better efficiencies except Test No. 5. As shown in Fig. 4(c)&(d), the OWC's efficiencies in the operations with the smaller orifice diameter (130 mm), i.e. the higher pneumatic damping level, are a little higher than that with the larger orifice diameter (194 mm), i.e. the lower pneumatic damping level.

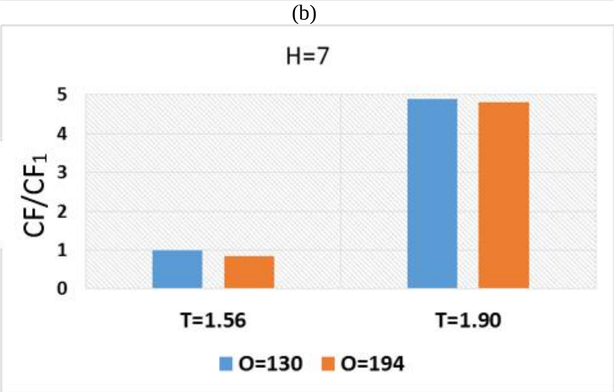
These experimental results are consistent with many reports of previous works. For example, López et al. [8] concluded



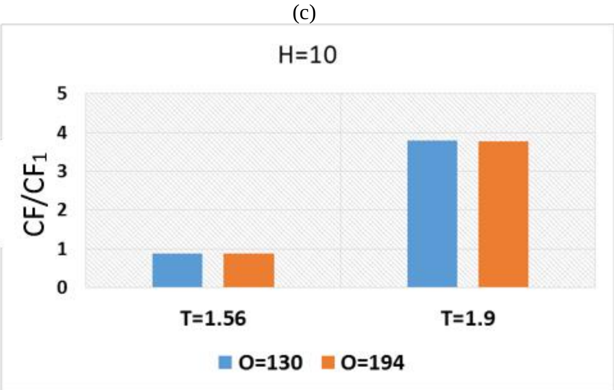
(a)



(b)



(c)



(d)

Fig. 4 Comparisons of capture factor ratios for cases of different outlet orifice diameter (O, 130 mm and 194 mm), wave height (H, 7 cm and 10 cm) and wave period (T, 1.56 sec and 1.9 sec)

that the OWC efficiency is significantly influenced by incident wave conditions, tidal conditions and the pneumatic damping level formed in the OWC's chamber. Therefore, an OWC will perform at its highest efficiency with the optimal combination of these factors.

IV. Conclusions

The present paper reports an experimental study of a fixed OWC with high-speed imaging measurement. Image processing and analysis techniques were used to analyze the motions of the water level in the chamber of the OWC. Combined with a simple hydrodynamic theory, the relative capture factor (capture factor ratio) can be evaluated with the results of the vertical velocity of the water level.

Two incident wave periods, two incident wave heights and two pneumatic damping levels were set as the test conditions for the OWC. The results show that the most influential factor in the performance of the OWC is the incident wave period, and the longer period the higher efficiency (capture factor ratio). Since the experimental work cannot afford large variation and number of parameters, we will resort to numerical simulations in the future for finding the optimal combination of the factors for the OWC's efficiency like the incident wave period and height and the pneumatic damping level.

Acknowledgment

This work was sponsored by the Ministry of Science and Technology of Taiwan with the grant number: MOST 104-ET-E-019-006-ET. The authors would like to thank then master students Yi Chen and Jia-Wei Lin for their assistance.

References

[1] J. Falnes, *A review of wave-energy extraction*, Marine Structures, 20, (2007), 185~201.

[2] I. López, J. Andreu, S. Ceballos, I. M. de Alegría and I. Kortabarria, *Review of wave energy technologies and the necessary power-equipments*, Renewable and Sustainable Energy Reviews, 27, (2013), 413~434.

[3] D. C. Hong, S. Y. Hong, S. W. Hong, *Reduction of hydroelastic responses of a very-long floating structure by a floating oscillating-water-column breakwater system*, Ocean Engineering, 33 (5-6), (2006), 610~634.

[4] Y. Torre-Enciso, I. Ortubia, L. I. López de Aguileta, J. Marqués, *Mutriku Wave Power Plant: From the Thinking out to the Reality*, In Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden, 7–10 September, (2009).

[5] Thomas Kelly, Thomas Dooley, John Campbell, John V. Ringwood, *Comparison of the Experimental and Numerical Results of Modelling a 32-Oscillating Water Column (OWC), V-Shaped Floating Wave Energy Converter*, Energies 6 (8), 4045-4077, 2013.

[6] C. B. Boake, J. T. Whittaker Trevor, M. Folley, *Overview and Initial Operational Experience of the LIMPET Wave Energy Plant*, Proceedings of The Twelfth International Offshore and Polar Engineering Conference, Kitakyushu, Japan, (2002), 26~31.

[7] Y. Chen, *Experimental Investigations on the Performance of OWC Combined with Wave Guide Plates*, Master thesis, National Taiwan Ocean University, (2016).

[8] I. López, B. Pereiras, F. Castro, G. Iglesias, *Performance of OWC wave energy converters: influence of turbine damping and tidal variability*, Int. J. Energy Res. 2014.