On wave energy extraction of oscillating water column device

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Abstract

Oscillating water column (OWC) wave energy converters (WECs) have a well-proven feasibility, reliability and survivability when compared to many other wave energy converters. A good example for this is the LIMPET OWC plant, which has generated electricity to the grid for more than 60,000 hours in a period of 10 years. OWCs are quite successful when compare to other types of wave energy converters, including their simplicity and reliability in structure, their reliability and survivability in power take-off and conversion, and their adaptability in installation on shoreline, shallow water or deep water regions, but so far the wave power generation is still quite expensive. To reduce the cost of OWC wave power generation, one important aspect is how to design an efficient OWC device from the aspects of hydrodynamics and primary energy conversion.

This paper presents an investigation to the relation between wave energy conversion efficiency of OWC devices and the water column, including the column sectional area (column size) and water column length (column length). An analytical analysis/deduction has shown that in order to convert wave energy efficiently and with a high conversion efficiency, the column size and column length must be designed appropriately. Generally, a larger column size may be helpful in capturing more wave energy based on the mathematical equation and the relevant experimental validation. For an OWC device, a larger column size may also mean a higher conversion efficiency.

Keywords: oscillating water column, wave energy conversion, wave energy conversion efficiency

1 Introduction

OWC wave energy converters have been advanced a great deal since the earliest OWC devices have been studied in 1940s (Falcao [1]), and now some practical OWC plants have been built and generated electricity to the grid, for example, LIMPET in Scotland [2] and PICO in Portugal [3]. Though the foundation types of OWC WECs are successful, for purpose of massive energy production, floating types of OWC WECs (due to the economic and structural requirements) are more likely deployed in "deeper" waters of more available wave energy. WaveGen [4] has compared three different floating OWC WECs for wave energy generation from the technical and economic feasibilities. These OWC devices are the spar, sloped and backward bent duct buoy (BBDB) OWC devices, respectively. Because the devices are needed to be tuned to the wave conditions, they tend to have long water columns, a long vertical water column for the spar OWC, a long sloped water column for the sloped OWC, and a long horizontal water column for a BBDB OWC device. A long water column can generally produce a long resonance period of the interior water surface motions so to match the sea states (the sea modal periods).

Generally, OWC WECs have some advantages over many other wave energy converters in terms of (i) a confirmed concept; several practical bottom fixed OWC plants have been built and generated electricity to the grids for many years, for example, LIMPET OWC plant [2]; (ii) a wave energy device with a relatively high wave-to-wire efficiency, including a high primary converting efficiency, "wave-to-pneumatic power" and a high and reliable mechanical power converting efficiency, if the OWC is designed appropriately; (iii) no moving component in sea water; (iv) a lower force and a higher speed for a certain power take-off, such that the reliability of the power take-off system can be accounted. A good example is the LIMPET OWC plant has generated electricity to the grid for more than 60,000 hours over a period of about 10 years (Heath [5]) .

Theoretical work on the hydrodynamic performance of OWCs has been progressed a lot in the past decades. It has been theoretically shown that OWC devices could have a maximal primary wave energy conversion efficiency of 100% (Evans [6] and Evans and Porter [7]). In the theoretical studies, the optimal wave energy conversion efficiency is only dependent on the optimal damping coefficient, but it is not clear how the optimal damping coefficient is related to the actual power take-off system. In the experimental studies on the bottom-fixed or floating OWCs, it is shown that the wave energy conversion efficiency of an OWC device very much depends on the damping coefficient of the flow passing through the power take-off system and the size of the water column (water column area and length). Practically, an OWC device may be optimized to have a good capture capacity over a wider range of wave frequencies, rather than on a single frequency (the resonance frequency). Toyota et al. [8] have shown that both the size of the air chamber and the length of the horizontal duct length of a BBDB device have significant effects on the primary power take-off of the OWC wave energy converters. Imai et al.[9] have also studied the influence of the horizontal duct length to the wave energy capture capacity in a BBDB device, and shown that a longer horizontal duct has increased the maximum IWS response at a longer resonance period. As a result of this, a longer horizontal duct may be desirable for tuning the BBDB to the wave states with a longer wave period.

Morris-Thomas et al. [10] has experimentally studied the hydrodynamic efficiency on a fixed OWC with different front shapes. From the comparison, it can be seen that the front shapes have some but no significant effects on the wave energy conversion efficiencies. For all the four different front shapes, the wave energy capture efficiencies are very similar, and the maximum wave energy conversion efficiency is about 70%.

Weber et al.[11] presented an investigation to the importance of the air chamber design, and it is shown in one example that 15% relative improvement has been attained for an optimization of the OWC design. A further analysis on the nonlinear aero-thermodynamic effects during small scale physical modelling of OWC WECs has been explored, and a suggestion has been made for how to reproduce the compressibility of the air in the scale model (Weber [12]). In an experimental measurement, Ram et al [13] studied the flow characteristics in a fixed OWC device, and has shown that the contraction design before turbine has well guided the flow to the turbine blades.

In this paper, the primary energy conversion of OWC wave energy converters are examined with regard to two main factors of water column design: the water column size (sectional area) and length (draught). Based on the responses of interior water surface motion, it is possible to derive the power conversion by the OWC device mathematically. It has been shown that a proper design of the OWC water column including an appropriate selection of column size and draught will help to improve the wave energy extraction. More importantly, a larger size of water column may have a larger primary wave energy conversion efficiency.

2 Studies on OWC WECs

2.1 Numerical approach

Though some theoretical analyses have been conducted for some specific OWC devices, such as two-dimensional OWC devices, or some three-dimensional OWCs with very simple structures (Evans and Porter [7], Martins-rivas et al [14]), based on the potential flow theory, a more popular case is the numerical analysis of the OWC wave energy devices, because it is readily available for almost any geometries of the OWC wave energy converters. Based on the assumption of the potential flow, the velocity potential of the flow around the floating structure satisfies the Laplace equation:

$$\nabla^2 \varphi = 0 \tag{1}$$

where φ is the velocity potential of the flow around the floating structure in frequency domain (the corresponding time-dependent velocity potential can be expressed as $\Phi = \varphi e^{i\omega t}$).

A coordinate system can be defined for investigating the behaviour of the floating structure, with the x-y plane on the calm water surface and z-axis positive up vertically. In the coordinate, the free surface conditions can be expressed in frequency domain as (see Lee et al. [15])

$$\frac{\partial \varphi}{\partial z} - \frac{\omega^2}{g}\varphi = \begin{cases} 0, & (on\ S_f) \\ -\dfrac{i\omega}{\rho g} p, & (on\ S_i) \end{cases} \tag{2}$$

where ω is the wave frequency, z the coordinate in z-axis direction, ρ the density of water, g the acceleration of gravity, p the pressure acting on the interior water surface, S_i the interior water surface in the water column, and S_f is the free surface but excludes the interior water surface.

To include the boundary condition of the interior water surface in the conventional BEM code WAMIT[16], Lee et al.[17] introduced so-called generalized modes for the interior water surface motions, such as the piston and sloshing modes of the interior water motions. Similarly, Hong et al.[18, 19] have introduced a linear power take-off (a linear duct) into the potential flow problem, and an extra mode is therefore added for the motion of the interior water surface (IWS).

Figure 1 shows a generic cylindrical OWC model tested in a wave tank. The cylindrical OWC has been fixed on a frame which is also fixed on the tank floor. The model is arranged in such a way that it is supposed that there is no significant influence on the interior water surface motion from the ambient environment, but the OWC device itself. It must be noted that the model is allowed to have a small amplitude horizontal motion, such as surge, sway and yaw, but the vertical motions have been limited, especially the heave motion, which could take an important factor in influencing the interior water surface motions, thus the power capture capacity.

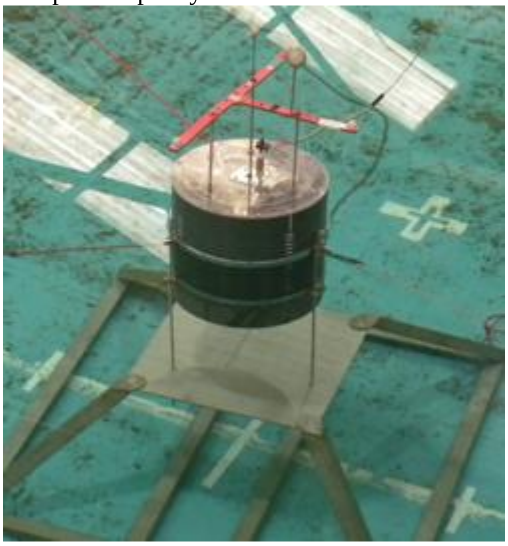

Figure 1 Fixed cylindrical OWC tested in HMRC ocean wave tank

The OWC has a water column of a diameter of 0.104m and draught of 0.3m. The fixed OWC has also a wall of thickness of 0.106m. The setup of this fixed OWC has been taken the same as that of the floating cylindrical OWC device. Figure 2 shows the IWS response of a bottom-fixed generic cylindrical OWC from a numerical simulation (WAMIT), with an IWS resonance period of T=1.15s.

According to the simple formula (Evan et al.[7]), the resonance period of the IWS is given by,

$$T_1 = 2\pi\sqrt{\frac{D}{g}} \tag{3}$$

where D is the draught of the water column. Therefore, T_1=1.10s

However, if the oscillating water column is large, the size of the water column (sectional area) may have a large effect on the IWS resonance period. As a result of the effect, the resonance period has been modified by Veer et al [20], as

$$T_2 = 2\pi\sqrt{\frac{D+0.41S^{1/2}}{g}} \tag{4}$$

where S is the sectional area of the water column. So, T_2=1.17s.

The theoretical calculations of the resonance period of the interior water surface are calculated well, and both are close to the numerical result. But the modified IWS resonance period given by Eq. 4 is better.

It must be noted that, however, the numerical analysis of the IWS motion is conducted only including the hydrodynamic damping, so that the numerical prediction of the IWS response tends to be overpredicted. It is understandable, because, in reality, the viscous damping, or other forms of the damping may exist and be important. These extra dampings will reduce the IWS response, even the OWC device is not damped via a power take-off system. If the air flow is damped by a power take-off (PTO), for instance, an air-turbine or orifice, the response of the IWS will be further reduced. This is why, in many practical cases, only moderate maximum-resonance-responses of the IWS can be obtained (see [8, 9, 21]).

In the following analysis in this paper, the IWS responses are assumed to be appropriately produced. Then what are the important factors for improving wave energy conversion?

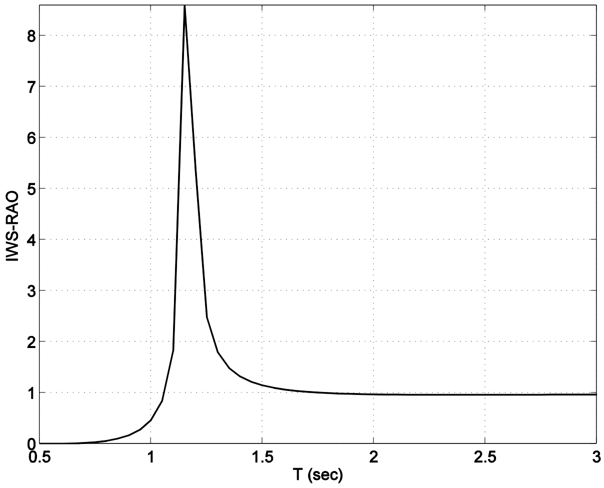

Figure 2 IWS response of a fixed generic OWC device in regular waves

2.2 Experimental investigations

For conventional OWC devices, the air passing through the PTO system is reciprocating during a wave period, and it is possible to use different design strategies for power take-off. However, the self-rectified air turbines, including the Wells or impulse turbines, are more popular in practical applications.

It is well known that the Wells turbine is assumed to have a linear damping relation between the pressure drop across the PTO and the flowrate, and their relation can be expressed as

$$p = k_1 q_p \tag{5a}$$

where p is the pressure difference between the air chamber and atmosphere, and q_p the airflow through the power take-off system, k_1 the damping coefficient. For impulse turbines, the nonlinear relation between the pressure across the PTO and the flowrate can be approximated by the following expression,

$$p = \begin{cases} k_2 q_p^2, & exhalation \\ -k_2 q_p^2, & inhalation \end{cases} \tag{5b}$$

where k_2 is the nonlinear damping coefficient.

For scale OWC model tests, it is always hoped that the PTO system (air turbine) can be scaled for testing according to the relevant similitude laws. However, it is practically difficult to manufacture a scaled air turbine which has the scaled characteristics, due to the mainly frictions in the scaled power take-off system (Payne[22]). Alternatively, it is more practical to model the relation of pressure and flowrate than a practical PTO device. The linear relation of the PTO system can be modeled by porous membrane (see Lewis et al.[23] and Forestier et al.[24]), while the nonlinear relation has been widely modelled by orifice plates ([8-10, 21, 25]). From the relevant model tests, it is shown that the orifice ratio (defined as the orifice area divided by water column area) is mainly between 0.5%-2.0%, for which damping level in the scaled models gives the OWC device an optimal power conversion efficiency.

The following comments will be given to the orifice PTO modeling of the nonlinear impulse turbines because the following analysis will be focused on such a nonlinear PTO system. As it is shown by many researchers, the impulse turbines have a better wave energy conversion capacity than the Wells turbines [26] when used in OWC wave energy converters. It can be envisaged that in future impulse turbines may be more likely installed in OWC WECs.

In addition, as shown by Forestier et al [24], the linear porous membrane and the nonlinear orifice PTO takeoff modelling give very close power extrcation in a 1:15 device (see Figure 3).

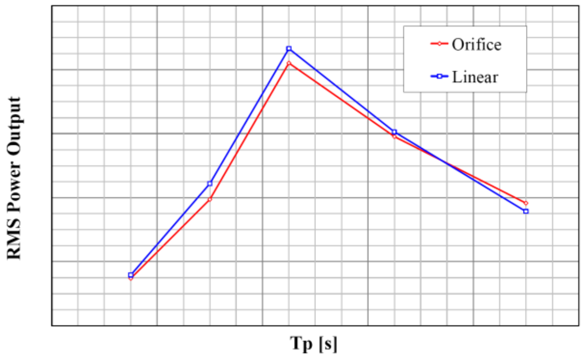

Figure 3 Power output from porous membrane and orifice PTO for a 1:15 scale model (Forestier et al.[24])

3 Methodologies

3.1 Primary conversion efficiency of an OWC device

Theoretical analysis has shown the maximum primary conversion efficiency of OWC device can be 100% (Evans and Porter [7]) under the optimal damping condition. However, in reality, for an actual wave energy converter, its wave energy conversion efficiency is normally lower (or even much lower) than that. Table 1 lists the maximum wave energy conversion efficiencies for some OWC model tested in wave tanks/flumes. It can be seen that the OWC devices have very different wave energy conversion efficiencies. A generic OWC in [21] has a very low wave energy conversion efficiency of 7.5%. Later on in this paper, it will be shown why the primary wave energy conversion efficiencies can be so different in these different cases.

Table 1 Primary conversion efficiency of OWC devices from model tests in regular waves

	OWC type	AC area (m^2)	Orifice ratio, ε	η_{max} (%)	Period T (s)	Ref.
1	BBDB	0.116	0.5%	35	1.67	[25]
2	BBDB	0.164	0.77%	70	1.43	[8]
3	BBDB	0.156	0.81%	65	1.48	[9]
4	Fixed	0.96	0.78%	70	1.69	[10]
5	Cylinder	0.0085	1.7%	7.5	1.25	[21]

Note: AC area means the sectional area of air chamber

3.2 Interior water surface response

To understand why the OWCs have such different wave energy conversion efficiencies shown in Table 1, the interior water surface responses is examined first. Experiments have shown the maximum IWS RAOs are about 1.5 and 1.0 in Sheng et al [27] and Imai et al [9], respectively. Though it is hoped that the IWS responses are very large so that more wave power can be extracted, in reality, the IWS responses can only be moderate, especially when the air flow is damped (by air turbines or orifices), as shown in the following figures, where the numerical simulation gives the maximum IWS response about 10 (the simulation has been conducted by including the hydrodynamic damping only, see Figure 4). Obviously, the numerical prediction has much overpredicted the IWS response. If an extra damping is applied, as shown by Sheng et al.[28] , then the numerical simulation is much close to the experimental data (Figure 5).

In reality, for an OWC device, either of floating type or of bottom fixed, it is possible to get appropriate IWS responses around 1.0. Large responses of IWS can be easily damped due to the air flow damping. For example, for an OWC device (Figure 6), the experiment has shown the IWS responses in an umdamped and damped case. It can be seen that the undamped IWS response can reach a maximum value of 5.3, and the corresponding value in the damped OWC is only 1.5 (see Figure 7). Hence, practically it is very difficult to have a very large IWS response for the purpose of power take-off. A question may arise as this: how to maximize the primary power conversion (and its conversion efficiency) in an OWC device when the IWS response can only be practically produced?

In the following sections, the IWS response is assumed to be appropriately produced. It must be noted that the appropriate IWS response may be obtained by adjusting the water column length/draught. For example, if the appropriate IWS response is expected in long waves, the water column draught needs to be large, otherwise, a short water column may be needed.

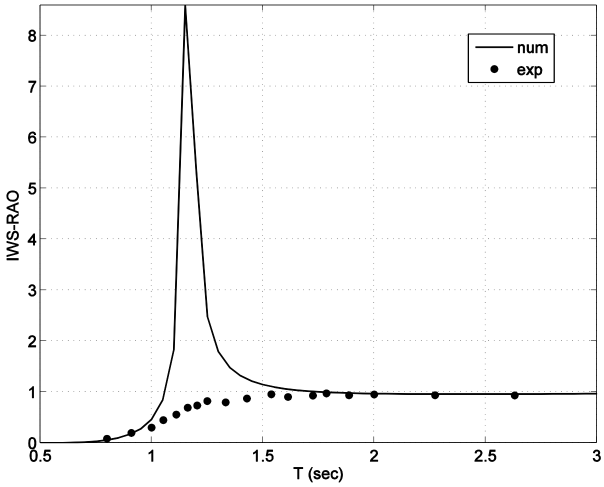

Figure 4 Fixed OWC interior water surface motion response (φ=12mm, numerical response is undamped)

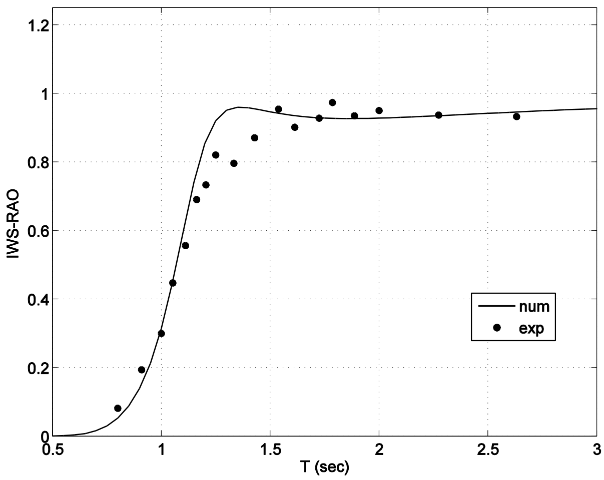

Figure 5 Fixed OWC interior water surface motion response (φ=12mm, numerical response is damped)

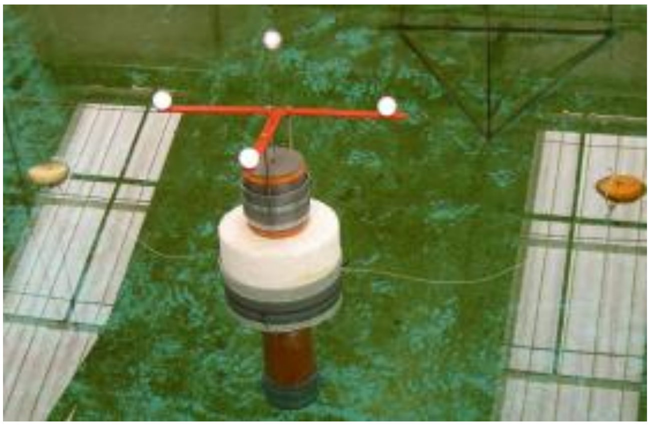

Figure 6 Spar OWC model in a wave tank

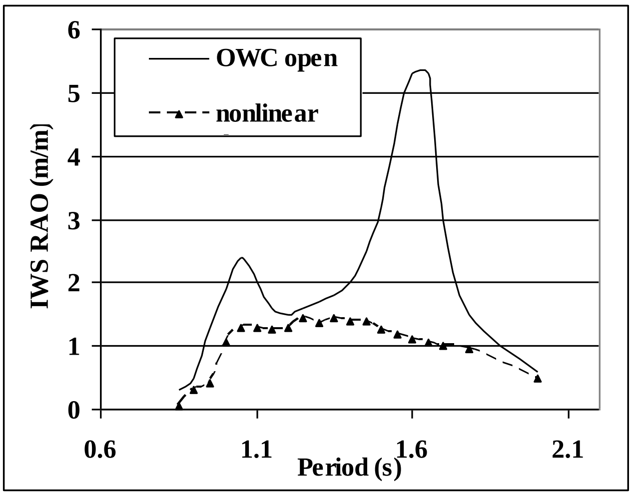

Figure 7 Experimental data for IWS responses for the undamped and damped air flow for the device in Figure 6

3.3 Primary wave energy conversion and efficiency

In the primary wave energy conversion of an OWC device, the response of the interior water surface (IWS) is assumed to be known. An orifice is used for power take-off for modeling the nonlinear impulse turbine. Following Sheng et al.[27], if the IWS response is ξ_7, its motion, X_7, and velocity, V_7, can be expressed as

$$\begin{cases} X_7(t) = \dfrac{H}{2}\xi_7 \sin \omega t \\ V_7(t) = \dfrac{H}{2}\omega\xi_7 \cos \omega t \end{cases} \tag{6}$$

where H is the wave height, ω the wave frequency.

If the air is considered as incompressible, then the continuity equation requires that the flowrate of the air driven by the interior water surface must equal to the flowrate of the air through the orifice, i.e.,

$$Q(t) = C_q A_1 V_1(t) = A_0 V_7(t) \tag{7}$$

where A_1 and A_0 are the areas of the orifice and the water column, respectively. C_q is the flowrate coefficient (flow discharge coefficient) through the orifice, $V_1(t)$ the air velocity through the orifice.

The pressure drop across the orifice is

$$\Delta p(t) = \frac{1}{2}\rho_a V_1^2(t) = \frac{\rho_a}{2C_q^2}\left(\frac{A_0}{A_1}\right)^2 V_7^2(t) \quad (8)$$

where ρ_a is air density (ρ_w is for water density).

The power extracted by the orifice is

$$P(t) = \Delta p(t) \times Q(t) = \frac{\rho_a A_0}{2C_q^2}\left(\frac{A_0}{A_1}\right)^2 \left|V_7^3(t)\right| \quad (9)$$

Hence, the average primary energy conversion is thus

$$\overline{P} = \frac{2\pi^2 \rho_a A_0}{3C_q^2}\left(\frac{A_0}{A_1}\right)^2 \xi_7^3 H^3 / T^3 \quad (10)$$

with T the wave period.

The energy conversion efficiency is

$$\eta = \frac{64\pi^3 \rho_a}{3C_q^2 \rho_w g^2 B}\left(\frac{A_0}{A_1}\right)^2 A_0 \xi_7^3 H / T^4 \quad (11)$$

where B is the width of the OWC device.

The wave power extrcation and the conversion efficiency given by Eqs. 10 and 11 are very important in understanding how to improve an OWC device wave energy conversion efficiency, and can give an explanation to the different wave energy conversion efficiencies in Table 1. It can be seen from the equations, large water column size (sectional area) is very good for improving wave energy conversion capacity, and wave energy conversion efficiency. In contrast, wave energy conversion capacity and efficiency decrease when the wave period increases, hence for long waves (with large period), the wave energy conversion capacity and efficiency will be low. A simple explanation to the case is that the long wave can easily by-pass the device, hence the wave energy can only extract a small portion of the energy.

In the cases 2 and 3 in Table 1, the water column sizes and the resonance periods are very similar, hence similar maximum conversion efficiencies are expected for them (70% and 65% respectively). Case 1 has a smaller water column, and a larger resonance period, hence its maximum efficiency is much lower (about 35%). Case 4 has a very large water column, but its resonance period is also high, so that its overall maximum primary conversion efficiency is close to the cases 2 and 3 at 70%. Though case 5 has a smallest resonance period, its water column is far too small when compared to other cases. As a result of the smallest water column, the OWC has a very low maximum primary conversion efficiency (7.5%).

3.4 Validation with experimental data

To validate the accuracy of eqs. 10 and 11, experimental data have been used. The available experimental data are from the bottom-fixed OWCs [29]. There are four the water columns of two different sectional areas and 2 different draughts. Figure 8 shows two water columns of different diameters, d_1=50mm and d_2=150mm respectively. In the test, two different draughts (D_1=380mm and D_2=170mm) of the water columns have been also conducted. Therefore, the four combinations of the OWCs are: (1) D_1=380mm/d_1=50mm; (2) D_1=380mm/d_2=150mm; (3) D_2=170mm/d_1=50mm; (4) D_2=170mm/d_2=150mm.

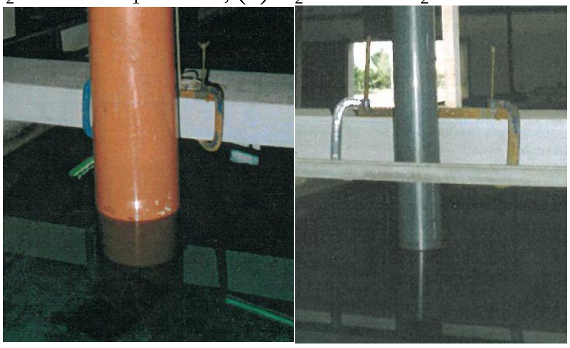

Figure 8 Water columns (diameter d_1=50mm, right and d_2=150mm, left)

3.5 Power capture and water column sizes

Figure 9 shows the measurement of the captured wave power by the four OWC setups. It can be seen that for different draughts, the captured wave powers are quite different. For a small draught (D_2=170mm), the OWCs tend to capture more energy from shorter waves (the dashed lines in Figure 7), because the shorter OWCs have a shorter resonance period of interior water surface motions. For longer OWCs (D_1=380mm), their resonance periods are longer, hence they tend to capture more energy from longer waves. This explains why some OWCs have long water columns so that the OWCs are designed to match the sea states.

Another important trend is that the larger OWCs (with larger diameters) capture much higher power than those of small column sizes. As shown in eq.10, the power captured by the OWC is proportional to the sectional area of the water column. If the captured power of the small water columns (d_1=50mm) is multiplied by the ratio of the column sectional areas of 9, then the comparison is very different, shown in Figure 10. It can be seen that, for a same water draught, the “captured” powers are quite close: the cases with larger draught of 380mm are the solid lines; the cases of shorter draughts are shown in dashed lines. There are some discrepancies, however, if the possible errors in experiments is considered, especially in the cases of very small power measured (small diameter OWCs). This example confirms that the responses of the interior water surface motions in the different column size are the same if the column length is the same, hence the generality of Eq. 10 is proved.

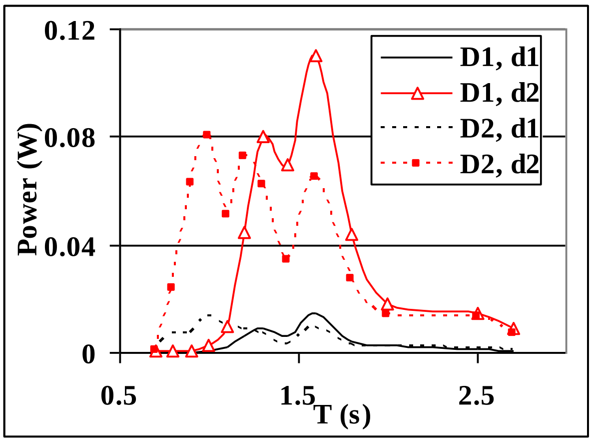

Figure 9 Measured power for different water column (data source [29])

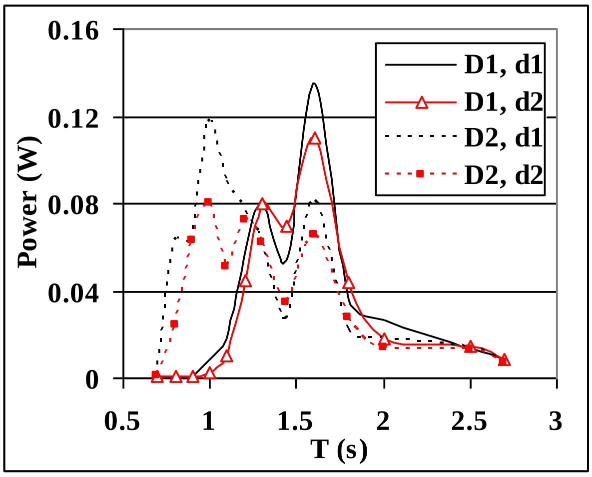

Figure 10 Measured power data (black lines have been adjusted by the square of water column diameters (150/50))

4 Figures Analysis

4.1 Higher energy capture efficiency in short waves

It has been shown in Eq. 11 that the wave energy conversion efficiency of an OWC is inversely proportional to the biquadratic of the wave period. Hence, it can be understood that the device may have a significantly higher efficiency in short waves if the IWS response can be appropriately produced.

Generally, to obtain a good IWS response of an OWC device in short waves, it draught should be small based on the IWS resonance period formulas (Eqs. 3 and 4).

If the IWS response can be produced appropriately, the wave energy capture efficiency in short waves can be higher, even the capture power is moderate. Hence, a high wave power capture efficiency for very short waves may not mean that a high wave power can be extracted. In addition, for short waves, they contain less energy than longer waves. More importantly, corresponding to the sea states, there may not have much energy in short waves. In this regard, a high energy conversion efficiency at short waves may be meaningless.

Similar to most other types of wave energy converters, the energy in short waves can be more easily extracted by WECs.

4.2 Large device for long waves

Suppose the OWC device is scaled up by Froude similitude.
Rewrite Eq.11as

$$\eta = C_1 \frac{A_0 H}{BT^4} \tag{12}$$

where $C_1 = \dfrac{64\pi^3 \rho_a}{3C_q^2 \rho_w g^2}\left(\dfrac{A_0}{A_1}\right)^2 \xi_7^3$, a non-dimensional constant according to the Froude similarity. For example, when the model is scaled, the orifice ratio (A_1/A_0) is kept same (a constant). The non-dimensional IWS response is also a constant.
If the device is scaled up via a scale factor, ε ($\varepsilon = \dfrac{L_L}{L_s}$, with the subscript: *L* means large device, *s* small device), then the Froude similarity gives following relations:

$$\begin{cases} (A_0)_L = \varepsilon^2 (A_0)_s \\ (H)_L = \varepsilon (H)_s \\ (B)_L = \varepsilon (B)_s \\ (T)_L = \varepsilon^{\frac{1}{2}} (T)_s \end{cases} \tag{13}$$

Hence the efficiency scale ratio, ε_η is

$$\varepsilon_\eta = \frac{(\eta)_L}{(\eta)_S} \tag{14}$$

Substitute (13) into (12) and (14), it is

$$\varepsilon_\eta = \frac{\left(C_1 \dfrac{A_0 H}{BT^4}\right)_L}{\left(C_1 \dfrac{A_0 H}{BT^4}\right)_S} = \frac{(A_0)_L}{(A_1)_s}\frac{(H)_L}{(H)_s}\frac{(B)_s}{(B)_L}\frac{(T^4)_s}{(T^4)_L} = 1 \tag{15}$$

From Eq.(15), it can be seen that if the device is scaled up to a larger device, and the wave period and height are also scaled up for a longer and larger wave, then the wave capture efficiency can be maintained. In other word, to obtain a high energy conversion efficiency, a larger device must be used.

4.3 Larger water column for more energy extraction

From Eq. 10 and 11, it can also be seen that the capture power and the energy conversion efficiency are both proportional to the area of the water column and inversely proportional to the width of the water column

(*B* has been taken as the width of the water column). Hence, it is possible to increase the wave energy conversion by using a larger water column. However, it must be noted that it is only true when the uniform interior water surface motion and an appropriate IWS response can be produced.

4.4 Limitations of large wave energy devices

It has been shown that a larger wave energy device is good for both a high wave energy conversion efficiency and a larger captured power from waves. However, there are some practical limitations in utilizing a larger device:

- Structural problem. It is well known when the device is large,
- There is a limitation in the horizontal size of the device. In wave direction, the length of the device must be well smaller than the wave length. In addition, due to the nature of waves in seas, the waves are short-crested. This will also limit the dimension of the device with regard to the crest length of the waves. The reason is same as that of the wave length.
- Large draught is used for better extracting wave energy from long waves. However, there are many practical problems for the devices with large draughts. For example, the devices with large draughts can not be deployed in shallow waters, and there may be problems in manufacturing, installation and transportation.

5 Concluding Remarks

In designing an oscillating water column wave energy converter, the sizes of the device (both in draught and sectional area of the water column) are very important for an appropriate wave energy extraction of the device. To design an efficient OWC wave energy converter, the following factors must be considered:

- The resonance period of the interior water surface is largely decided by the draught of the water column. For a bottom fixed OWC, it is expected that the IWS response will be close to unit when the wave period is larger than the IWS resonance period. For a floating OWC, the relative IWS motion in the water column must be coupled to the motions of the floating OWC. For example, the spar OWC utilizes the heave motion for improving wave energy capture ([4]).
- The maximum efficiency and the captured wave power are more likely decided by the water column sectional area, i.e., if more energy is extracted from a larger wave (with high wave height and longer wave length), then a large device is desirable, as shown in this research. Simple explanation could be that long waves may by-pass the small wave energy device easily, hence, it power capture capacity will be very limited.

It must be emphasized that the size of the OWC device may also be decided by some practical limitations:

- Structural problem. Generally, the larger of the device, the more problems in structural design. Structural requirements would limit the size of wave energy converters.
- The wave length may limit the size of the OWC. For example, the horizontal length of the OWC in wave direction may not exceed the 1/4-1/5 wave length. Otherwise, the interior water surface may have more sloshing motion rather than the piston motion. Sloshing motion in water column does not produce useful energy for the power take-off system (i.e., air turbine).
- In reality, the sea waves are 3 dimensional. Hence the horizontal length of the OWC device perpendicular to the wave direction may also be limited. The reason is similar, due to the short-crested waves, the transverse length of the device (related to wave direction) can not be larger than the crest length of the waves.

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