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Wave Power Absorption Capability of a Multi-Resonant Double Chamber Oscillating Water Column Device

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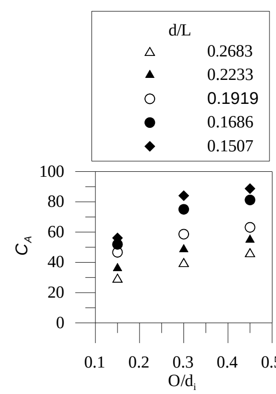
Graphical abstract



Effect of relative bottom opening on wave power absorption efficiency

Abstract

The reduction of the greenhouse gas emission generated through the usage of fossil fuel has become quite vital forcing us to look for alternative renewable energy sources. Among the renewable energy sources, ocean wave energy looks promising leading to worldwide involvement of researchers in the refinements of a number of the concepts. The conversion of energy available in ocean waves requires an interface device to interact with the kinetic and kinematic phenomena under the waves. These devices are known as wave energy converters (WECS). Among the available WECS oscillating water column (OWC) stands out as one of most promising concept. Though the OWC concept has emerged from laboratory model type to prototype plant, the high cost of production makes it less attractive in commercialism. This necessitates further refinement in the configuration of OWC concept to make it more attractive leading to economically competent. This can be achieved either by improving the efficiency or by integrating it with coastal protective breakwaters, viz., offshore detached breakwaters. The double chamber oscillating water is an innovative concept which can bring forth both efficiency and additional stability once it becomes an integral part of coastal breakwater. This system captures the high magnitude of dynamic pressure as the excitation force for the oscillation inside the OWC. The trajectory of flow pattern can provide additional vertical load which will enhance the stability factor of the breakwater. In this paper the wave power absorption capacity of a 1:20 scale physical model under varying regular wave characteristics is reported. In this insightful study the objective assessment over the hydrodynamic performance reveals the parametric influence over wave power absorption capacity of the device.

Keywords: Renewable energy; wave energy; owc; double chamber; breakwater; power absorption; wave amplification

1.0 INTRODUCTION

Energy transport by ocean waves has occupied the scientific thinking even before industrial revolution started. The first patent on July 27, 1799 ever recorded in the history clearly illustrates the attempts to convert wave energy to the clean energy need of the society[1]. The technological developments in both electricity generation and the power grid system have made it possible to transport mechanical energy from one place to another in the form of electrical energy. Over the recent years, there has been a tremendous shift towards sustainable development in technological activities. Subsequently, the interests in renewable energy grew rapidly. The renewable energy sources belong to principally solar energy and its derivatives in the form of bio-energy, hydroelectricity, wind and wave power. Among the renewable energy sources, ocean surface waves possess the highest energy intensity in the combined form of potential energy and kinetic energy. So the proper technological development over energy extraction from ocean waves can address the sustainability problems by providing clean energy. Relatively high cost of production appears as one detrimental factor in its acceptance as a viable technology for power production. The possible technical solution to counteract the above negative effect is to integrate the power absorption unit with coastal protection structures so that the shared cost effect can bring down the cost of power production from WECS. Since OWC has got the adaptability with coastal protection structures, there exists enormous scope for further research in OWC concept to make it more efficient in its performance. In view of the above mentioned factors, double chamber oscillating column requires further research to establish its relevance and to bring forth optimization in its geometrical parameters.

2.0 REVIEW OF LITERATURE

Issues related to technological inventions in ocean wave energy conversion has assumed significance due to the oil crisis in 70's. The continual research has produced a variety of devices with the electricity generating capacity varying from a few watts to mega

Watts. Bahaj has provided an overview on various technological solutions available for energy extraction from ocean waves[2]. A brief account given on commercial projects being undertaken by different agencies across the globe highlights practical possibility being felt in wave energy conversion. Sundar *et al.* has focused on the art and science in integrating WECS with coastal defense structures[3]. The concept of multi resonating OWC (MOWC) was put forward by Ambli *et al.* was claimed to be more efficient in wave energy absorption[4]. Brendmo *et al.* has represented the mathematical model for the dynamical state of OWC in the form of single degree of freedom mass-spring equivalent[5]. The viscous loss has been taken in to consideration by introducing mechanical loss resistance in to rigid body description. Lovas *et al.* has used the eigenfunction expansion for studying the diffraction and radiation problems of a circular OWC installed at the tip of a coastal corner[6]. The effects of column radius and height, the size of the submerged opening and the angle of incidence on power absorption efficiency were studied. Zheng reported the results of experimental observations made for the parametric optimization of a prototype OWC device[7]. It was found out that flared walls had significant effect on power absorption capacity. Evans & Porter represented the OWC device as a system consisting of a thin vertical surface piercing next to a vertical wall in finite depth water[8]. The important hydrodynamic properties were expressed in terms of integral quantities of functions proportional to the fluid velocity under the barrier. Galerkin method was used for the solution of functions. Koola *et al.* has reported the results observed on a 1:100 model scale conducted for optimizing a prototype OWC[9]. Jayakumar through experimental observations found that under closed condition of orifice in MOWC the dynamic air pressure inside chamber had a six fold increase in magnitude[10]. This shows the dynamic amplification occurring over the incoming wave inside the OWC device. Takahashi gives an account of the caisson breakwater having wave energy absorber working on OWC principle implemented along the Japanese coast[11]. This demonstrated the feasibility of the integration of wave energy devices with coastal defense structures, like breakwaters. Thiruvenkatasamy and Neelamani presented the laboratory observations carried out for the optimisation of WECS in array[12]. Empirical relationship connecting the spacing between adjacent units and the width of the OWC device has been established for maximum performance. Whittake and Stewart through experimental observations established that across fully reflecting coast, OWC in an array had a better efficiency[13]. On comparing with an isolated OWC, it was found that the efficiency increases by a factor two when they are in an array. Graw has discussed the additional benefits derivable in terms of cost sharing and safety factor enhancement while WECS are integrated with coastal defense structures[14]. Boccotti has modified the existing OWC concept by incorporating an additional duct in its front[15]. The duct captures the high magnitude of dynamic force excitation and discharge excitation under the propagating wave for causing dynamic oscillations inside the OWC. The small scale field experiments reported clearly substantiate the above mentioned physics in this conceptual design. Since this concept includes two ducts in its geometrical configuration it is called as the double chamber oscillating water column (DCOWC).

3.0 DESCRIPTION OF MODEL

As the gravity and inertia forces influence the hydrodynamic behaviour, it was decided to conduct a physical model test in agreement with the Froude's similitude criteria. The model scale was selected based on the capacity of the wave maker to generate waves of required characteristics in time period (T) and height (H). Based on the physics occurring over wave structure interaction Kaldenhoff recommended model scale within the range of1:20 to1:60 or larger if laboratory facility permits[16]. In line with the above requirement, a model scale of 1:20 in water depth of 1m was considered. The prototype design parameters are water depth, d=20m, T=5.5s to 10s and H=0.90m to 2m.The corresponding model parameters are T=1.2s to 2.4s, H= 0.045m to 0.10m and d=1m. From Figure 1, one can understand the number of structural configuration parameters that would dictate the efficiency of the device. Hence, four oscillating water columns of which three of same size of 0.30 m x 0.60 m x 1.45 m and the fourth of size 1.0 m x 0.60 m x 1.45 m were considered for simultaneous testing. To avoid the wave interference effect between adjacent units plywood partitioning were used for a length of 11m. To investigate the influence of structural parameters, three depths of duct opening (O) at the bottom of the oscillating column of 0.15 m, 0.30 m and 0.45 m were employed, with the dimensions of other parameters as indicated in the above figure. The mouth clearance, h of all the ducts was maintained constant to 0.30 m from the free surface. To simulate the viscous air damping being introduced by air turbine in prototype structure, the air hole of an area of cross section 0.65% of plan area of the OWC was provided at the top of the air chambers. Thus, the air hole of diameter 0.04 m was provided over the smaller units, whereas, a diameter of 0.071 m was adopted for the bigger unit. The material of construction was fiber reinforced plastics and steel stiffeners were used at suitable spacing for rigidity and strength of model. All the care has been taken to have well rounded corners and edges instead sharp edges to eliminate the vortex shedding and its subsequent energy loss in the system. In the figure AH shows the air hole positions and PF, PR and PA show the pressure transducer positions. The depth of the water column in the outer chamber (DI) is considered to be same as the water depth in front of the DCOWC. To have more clarity on the configuration of different units, the photographic view of the model is included in Figure 2.

4.0 EXPERIMENTAL INVESTIGATIONS

4.1 Test Facility

The present model tests were conducted in a 72.5 m long, 2 m wide and 2.7 m deep wave flume in Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai, India. A wave maker is provided at one end of the flume and the other end of the flume is provided with an absorber which is a combination of a parabolic perforated sheet and rubble mound below it to effectively absorb the deep water waves and shallow water waves

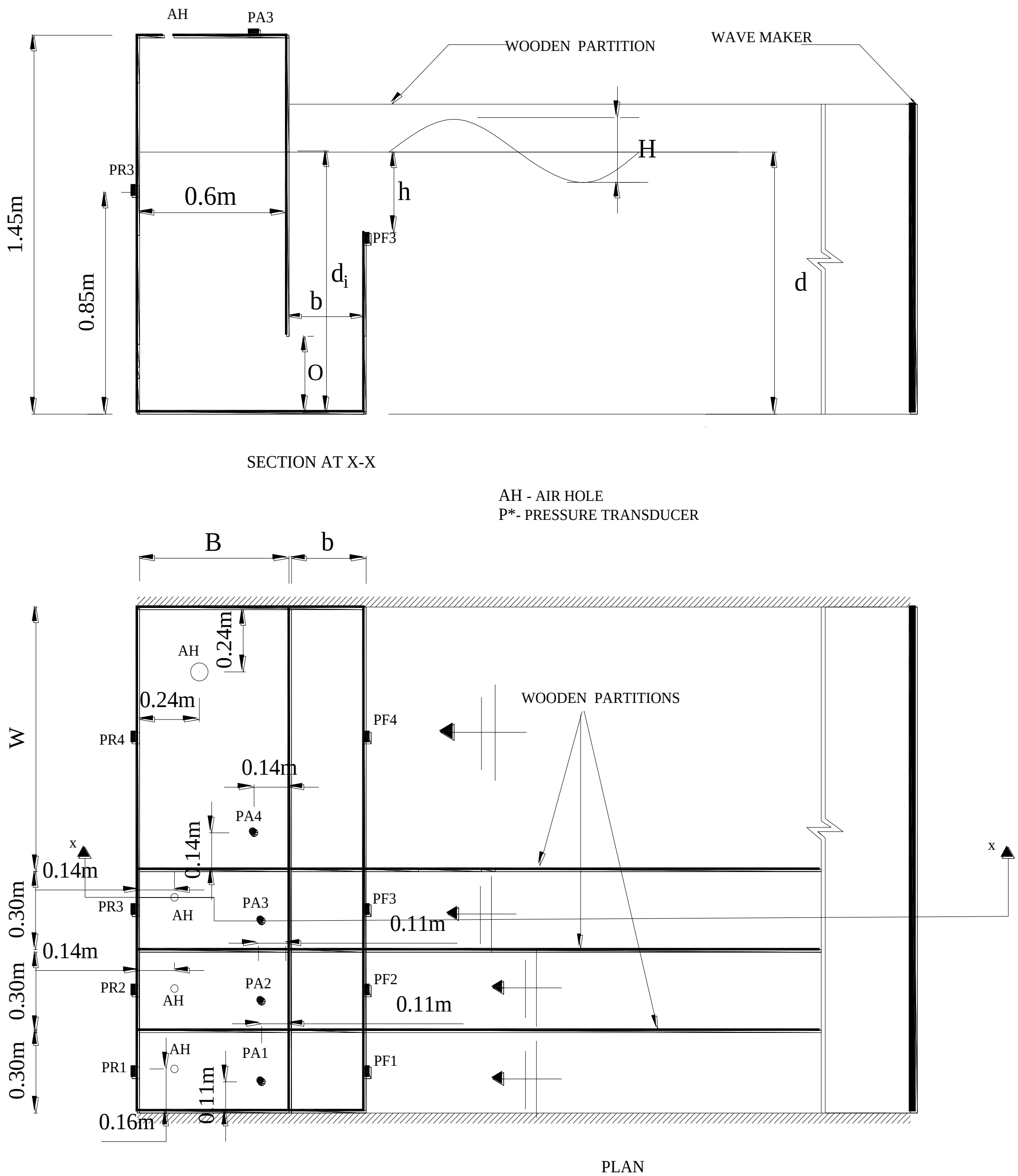


Figure 1 Plan and section of the DCOWC models in four compartments inside the wave flume

Figure 2 The top view of the model units

4.2 Experinental Set Up

For the present study, the model was placed 46 m away from the wave maker and one wave gauge was placed at 9 m in front of the wave paddle, To study the two dimensional effect of wave structure interaction with the model, plywood partitions for a length of 11 m were used. The plywood partition prevented the interference effect of waves between the individual units.

4.3 Instrumentation

The water surface elevation was measured by wave gauge which works on principle of varying conductivity as the depth of immersion varies. The pressure transducers used were strain gauge type and of make KISTLER RTC 28 having maximum range of 0.5 bar. In proportion to the magnitude of external pressure, the transducers produced voltages and the same were converted to pressures after multiplying it with calibration coefficients. Each module of the OWC model had two pressure transducers, one on the top of the air chamber to measure the pneumatic air pressure and another one on leeward side of the model at a height of 0.85 m, to measure the water surface level variation within it. Over the mouth of each OWC module pressure transducers to measure the dynamic pressure and wave gauge to measure the wave amplification were used.

5.0 METHODOLOGY

Since the hydrodynamic pressure excitation at the mouth causes flow, Boccotti determined the average rate of work done by the pressure as the wave power absorbed by the device[15]. The wave power absorption capacity of the device is defined by the term energy absorption coefficient (C_A) as

$$C_A = \frac{\frac{1}{T}\int_t^{t+T} p_f A_{in} V_{in}\, dt}{P_{in}} \times 100 \qquad (1)$$

where, p_f, A_{in}, V_{in} and P_{in} are the dynamic pressure excitation measured at the absorption chamber, plan area of the absorption chamber, velocity of flow and the incident wave energy flux. The incident wave power (P_{in}) across the width 'W' normal to the wave crest for a wave of height 'H' and celerity 'C' in a water depth of 'd' by linear wave theory is

$$P_{in} = \frac{\rho g H^2}{8} . \frac{C}{2}\left(\frac{2kd}{\sinh 2kd} + 1\right) W \qquad (2)$$

where k=2π/L, L is the wave length.

6.0 RESULTS AND DISCUSSIONS

Typical time series of incident wave, front wall pressure, rear wall water pressure and the air pressure developed for the given incident wave (H=.095 m & T= 2.2 s) for a geometric parameter O/d_i=0.45, b/B=0.50 and h/d_i=0.30 are shown in Figure 3a, 3b, 3c and 3d respectively. The measurements were carried out such that at least three steady state cycles in the pneumatic pressure variation could be captured during a particular test. The velocity of water surface oscillation inside the energy conversion module is obtained by the numerical differentiation of the difference between rear wall pressure and air pressure. The water flow velocity at the mouth is obtained by applying conservation of mass between the air chamber and mouth.

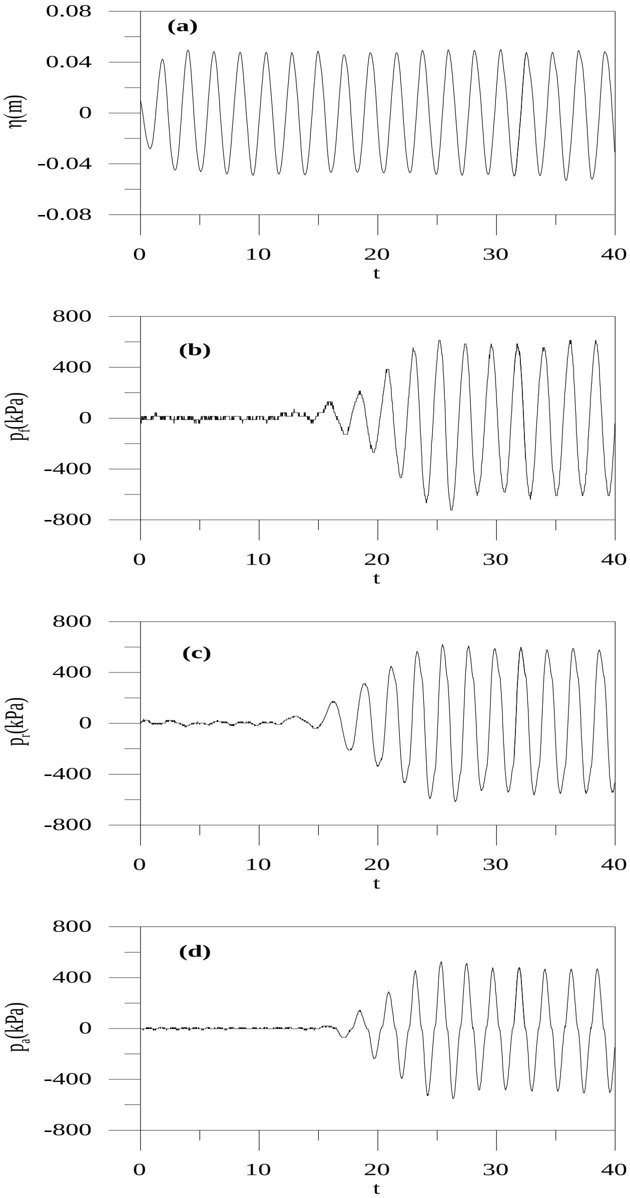


Figure 3 Time history of (a) incident wave surface elevation (b) front wall pressure (c) rear wall pressure and (d) air pressure

6.1 Effect of Relative Volume (W/B)

The main cause behind the energy conversion in OWC is the vertical oscillation of water mass within the device due to the waves entering into it. It is understood that the damping is one of the main factors that determines the efficiency of the system. In the energy conversion unit, since, the air flow is being constrained by provision of an air hole of small cross-sectional area, it causes the development of an additional pneumatic damping, in addition, to the viscous damping present in the system. In order to examine the effect of water plane area, the variation of the energy absorption efficiency of the system, C_A as a function of d/L for the two aspect ratios is presented for h/d_i =0.30 (maintaining the others dimensionless parameters, O/di and b/B constant) in Figure 4. The effect of water plane area on the variation of C_A is insignificant. This suggests that bigger units do not possess any preferential advantage in the energy conversion compared to smaller units. Hence this is an added advantage as construction and installation of smaller units are easier, economical and relatively safer.

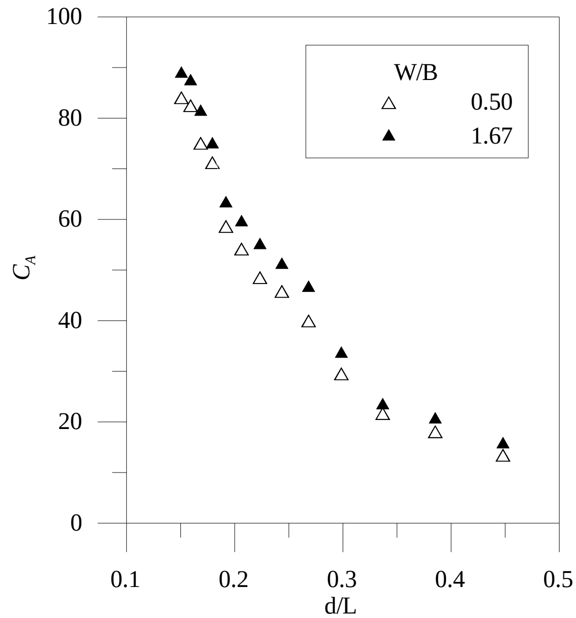


Figure 4 Effect of water plane area on the variation of C_A with d/L

6.2 Effect of Relative Opening Depth (O/d_i)

The fundamental driving force causing the oscillation inside the air chamber of DCOWC is the dynamic pressure under the progressive waves. The geometry of the device should be such that its shape and size are properly designed so that it is capable absorbing maximum amount energy available within the waves with minimum loss. The present study is oriented towards understanding the effect of bottom opening (O) in absorbing the incident wave energy. Here the mouth elevation of front duct (h) and width of front duct (b) were kept to a constant value of 0.30 m. The effect of relative bottom opening (O/d_i) with wave frequency parameter (d/L) on wave power absorption capacity of the device is projected on Figure 5. The variation on C_A with O/d_i for a particular incident wave frequency indicates its effectiveness in bringing tuning effect in the device. The increase in energy absorption with O/d_i is due to the oscillation inside chamber is nearing to resonance condition. The physics behind the enhancement in power absorption can be attributed to the decrease in flow length for flow trajectory and subsequent decrease in natural period of the system. Thus it can be inferred that the provision of front duct rectifies the limitation of conventional OWC. In OWC to increase the natural period of the system one has to decrease the O/d_i. As the bottom opening depth decreases the hydrodynamic pressure causing oscillation inside the air chamber decreases due to its hyperbolic variation with depth. In DCOWC, it is possible to capture the maximum effect of dynamic pressure excitation by adjusting mouth opening depth (h) and the natural period of device can be controlled by changing the bottom opening depth (O). This flexibility to bring resonance condition in DCOWC can be considered as the technological sophistication.

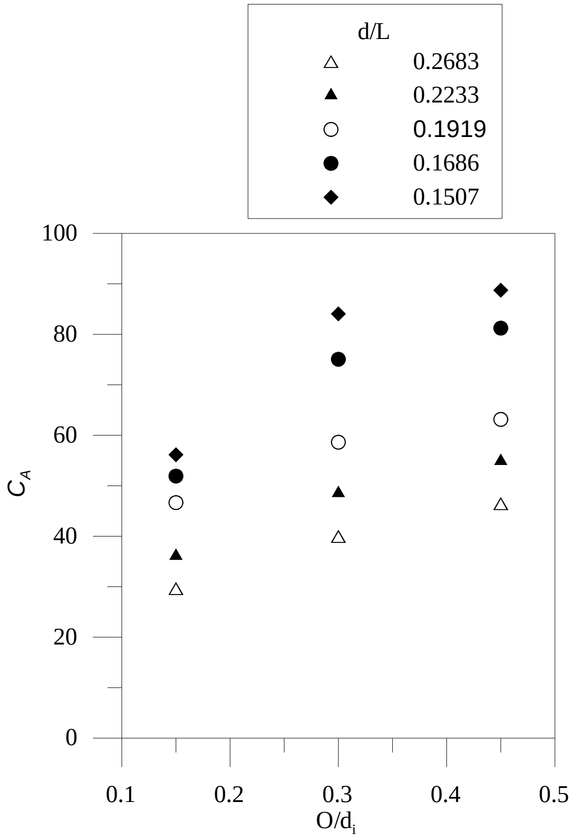


Figure 5 Effect of relative bottom opening on wave power absorption efficiency

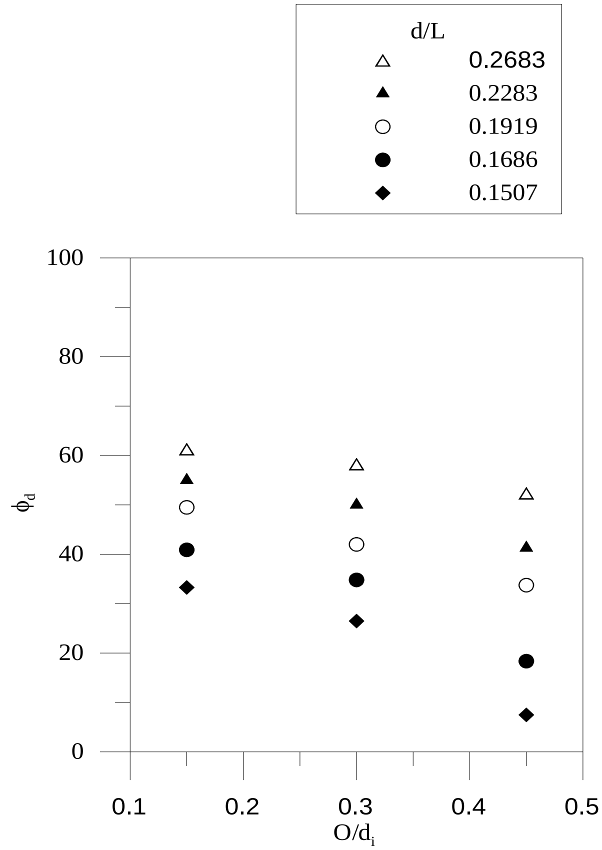


Figure 6 Effect of relative bottom opening on phase angle variation

6.3 Phase Variation

In DCOWC, the primary energy conversion from waves involves the oscillation of water mass inside the air chamber. Thus the energy conversion process becomes a forced vibration problem. So maximum energy conversion is possible at resonance condition. Here the effect of bottom opening on natural period is qualitatively indicated by phase angle (ϕ_d). It is measured as the time lag between excitation pressure at the mouth and the air pressure. ϕ_d values and its dependence on O/d_i and wave frequency are presented in Figure 6. It is clear that at a particular wave frequency, ϕ_d values are getting reduced with increase in O/d_i. This indicates that the system is nearing towards resonance region. This agrees with the earlier discussion on wave power absorption efficiency. To bring more clarity on phase variation, wave amplification (β) as defined by

$$\beta = \frac{Wave\ height\ at\ mouth}{Incident\ Wave\ height} \tag{3}$$

is presented in Figure 7. It is clear that for lesser phase variation, β values are lower. This can be explained by the principle behind the linear circuit theory in electrical engineering. The driving force at the mouth splits in to active part and reactive part. The active part causes flow in the device while the reactive part causes wave amplification near the mouth. By theory it is established that with decrease in phase variation there will be reduction in reactive part. Thus it is inferred that for zero phase variation, the reactive component becomes zero and entire incoming energy will be absorbed by the device, In Figure 7, it is evident that β values reaching nearer to one is the indication of nearness to resonance condition. These results indicate the possibility of bringing resonance condition in DCOWC by suitable combination of geometric parameters in accordance with the incident wave period.

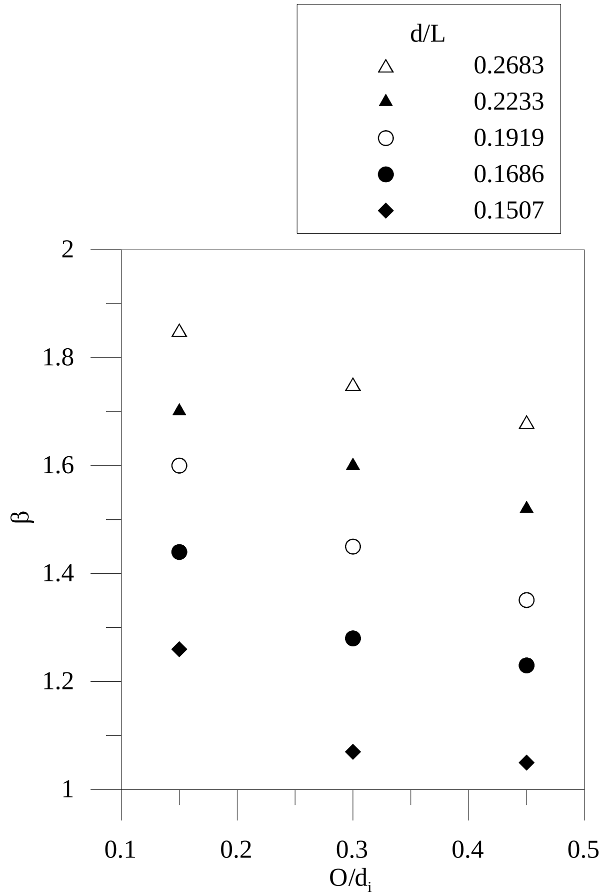


Figure 7 Effect of relative bottom opening on wave amplification

7.0 CONCLUSIONS

Based on a detailed experimental investigation on the power absorption capability of the device, the following conclusions are derived.

- The power absorption capability of the device increases with decrease in phase angle variation.
- For the same value of O/d_i the dynamic oscillations inside the OWC are independent of volume of the device.
- The lower values of power absorption efficiency at O/d_i =0.15 show that the hydrodynamic performance is relatively low at lower values of bottom opening depth.
- The power absorption efficiency values reaching around 100 at higher wave periods indicate the possibility of bringing tuning in the device by suitable combination of system parameters with respect to the incident wave condition.

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