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Asymmetry Effect on Hydrodynamic Characteristics of Double Chamber Oscillating Water Column Device

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ABSTRACT

Awakening of renewable energy in the latter half of the twentieth century has identified wave energy as a potential source of clean energy due to its high intensity of energy flux compared with other renewable sources of energy. Subsequent research found out that Oscillating Water Column (OWC) concept is an easier and simple technology to harness energy from the Ocean waves. This had lead to a rapid progress in research pertaining to tuning of the system for optimum efficiency. The Double Chamber Oscillating Water Column (DCOWC) concept is a modified form of OWC. The present study is an extension of previous studies for understanding its hydrodynamics with respect to its two geometric parameters; bottom opening and front duct width. The experimental works carried out on a scaled down model for identifying the effective combination between them is explained. The hydrodynamic principles governing the maximum harness of wave energy is detailed here. The discussions related to wave energy absorption, wave energy conversion, phase angle difference between pressure excitation and air pressure and wave amplification which govern the efficiency of the DCOWC are included for a better understanding on the effect between geometry and wave characteristics. It is expected that the findings of this study enhance knowledge on the hydrodynamic aspects of the concept of a DCOWC.

KEY WORDS: *Wave Energy; Dynamic Pressure; Asymmetry; Phase Angle, Wave Amplification.*

NOMENCLATURE

b/B	Relative front duct width
C_A	Wave Power Absorption Efficiency
d/L	Relative water depth
E_{in}	Incident wave energy flux
λ	Energy conversion efficiency
η	Water surface elevation
Ψ	Cross correlation
β	Wave amplification
ϕ_d	Phase difference
ε_η	Spectral width parameter of the incident wave
ε_{p_f}	Spectral width of front wall pressure
ε_{p_r}	Spectral width of rear wall pressure
ε_{p_a}	Spectral width of air pressure
$[(m_0)_r]_{front}$	Dimensionless zeroth spectral moment of front wall pressure
$[(m_0)_r]_{rear}$	Dimensionless zeroth spectral moment of rear wall pressure
$[(m_0)_r]_{air}$	Dimensionless zeroth spectral moment of air pressure
$\frac{p_{f_{max}}}{\rho g H}$	Dimensionless front wall pressure
$\frac{p_{r_{max}}}{\rho g H}$	Dimensionless rear wall pressure
$\frac{p_{a_{max}}}{\rho g H}$	Dimensionless air pressure

1.0 INTRODUCTION

The ocean waves generated by the wind in the deep ocean propagate towards the coast and the energy being transmitted in its direction of propagation. The wave heights in the near shore that dictates the wave power potential may increase or decrease depending on the phenomena like shoaling, refraction, diffraction and their combined effects. The possibility of transporting mechanical energy available at one place in the form of electricity to other places made the energy extraction from ocean waves as a reality. Wave energy is an abundant, indigenous, renewable, clean and sustainable resource. Compared to other renewable energy sources, wave power has got energy density manifolds greater than that is present in wind and sunlight. Hence, there has been a significant and rapid increase in the research and developments in the field of extraction of energy from Ocean waves. Several concepts of the wave energy devices varying in shape and size have been tried through numerical, physical modeling as well as trial pilot plants in the open Ocean. In wave energy conversion process, initially the kinetic and potential energy forms of waves have to be converted into mechanical energy for rotating the turbines in order to generate electricity by means of an interface device. These devices are referred to as Wave Energy Converters (WECs). Wave energy research in a formal way has started with oil crisis of 1970's. Periods of research developed a variety of concepts for energy extraction and the details are given by Hagerman [1]. They are broadly classified into three categories; overtopping devices, wave activated bodies and Oscillating Water Columns (OWC). Among these, OWC has got the unique distinction of having turbine as the only moving component above the water surface. Hence operation and maintenance are easier in OWC device and thus, making it more attractive. Sundar et al.[2] have presented detailed view on socio-economic benefits achievable by integrating OWC with breakwaters. This can facilitate the sharing of costs involved in erecting a wave energy convertor as part of investment could be to protect an eroding coast which normally is exposed to converging of waves.

In its physical form an OWC device consists of a caisson having an opening towards the seaside. The dynamic pressure available at the interface between the structure and the water surface oscillates the water column inside the caisson to develop pneumatic power inside the air chamber. The heaving of water inside the caisson causes the cyclic air flow through a duct provided over the air chamber. By placing a biaxial turbine across the air flow, the bi-directional air flow is converted in to unidirectional rotation of the turbine for electricity generation. This concept was invented by Masuda of Japan [3] and initially it was applied in navigational buoys. To gain operational experience in converting low frequency wave system to match with the high frequency power grid, Masuda [4] conducted sea trial tests with a prototype floating OWC device. Later, the trend turned towards bottom mounted OWC devices, and with researchers focussing on methods of optimising the efficiency of the device and looking at economic viability in wave energy converters, that lead to integrating it with break waters as one of the options.

There have been continual studies of both experimental and theoretical to bring forth optimisation on energy conversion capacity of OWC devices. Ambili et al. [5] in physical model study found that a range of wave periods can cause oscillation inside the air chamber and introduced the Multi-resonant Oscillating Water Column (MOWC) concept. It was observed that provision of projecting side walls in front of the mouth opening improves the energy conversion capacity of the device. Count and Evans [6] studied the effect of projecting side wall by boundary integral method. Malmo and Reitan [7] numerically studied the effect of geometry, wave frequency and direction on energy conversion capacity of OWC devices set in reflecting walls. McIver and Evans [8] adopted the method of matched asymptotic expansion for solving the hydrodynamics of OWC devices. Zheng [9] conducted physical model studies for parametric optimisation and reported that flared harbour walls are more effective for energy conversion rather than rectangular ones. Evans and Porter [10] studied the effect of chamber width, perpendicular to the wave crest, effect of lip wall submergence on energy conversion capacity of the device through theoretical investigations. It was observed that as the depth of submergence increased, the energy conversion from low period waves decreased significantly. It shows that an increase in the submergence depth increases the natural period of the device. Ma [11] through laboratory models formulated analytical expression for natural period of the OWC devices. It was found out that the natural period is inversely proportional to the bottom opening depth. Thus, it is made clear that OWC principle is analogous to forced vibration problem, wherein, the response is determined by both the magnitude and frequency of exciting force. Larger opening of OWC as the bottom is found to be more effective in absorbing higher frequency waves, whereas, lesser opening is found to be more effective in absorbing low frequency waves. To solve the problem of frequency effect between device and the excitation force, studies have been conducted to tune the natural frequency of the device by adjusting the damping level to the hydrodynamic efficiency with respect to frequency. Korde [12] concluded that reactive control of wave energy devices works well for absorbing energy from longer period waves.

Boccotti [13] proposed a modified concept of OWC by incorporating a duct in front of the bottom opening. The intension is to capture the maximum intensity of dynamic pressure for oscillation inside the air chamber. Through analytical studies, it was found that the power absorption capacity of the device at the mouth can reach up to 100%. Later through a field study, Boccotti et al. [14] confirmed the theoretical predictions agree with the experimental observations. It was also observed, that the front duct increases the natural period of the device which can absorb energy from long waves. In its physical form, this device consists of two chambers for the water flow in energy conversion process, hence it is called as the Double Chamber Oscillating Water Column (DCOWC). Since DCOWC device operates like a dynamic system and is under the influence of radiation damping and added mass in wave structure interaction, it is very essential to know the influence of front duct on its hydrodynamic performance. In the present work, this aspect has been studied by changing the front duct width relative to width of energy conversion chamber.

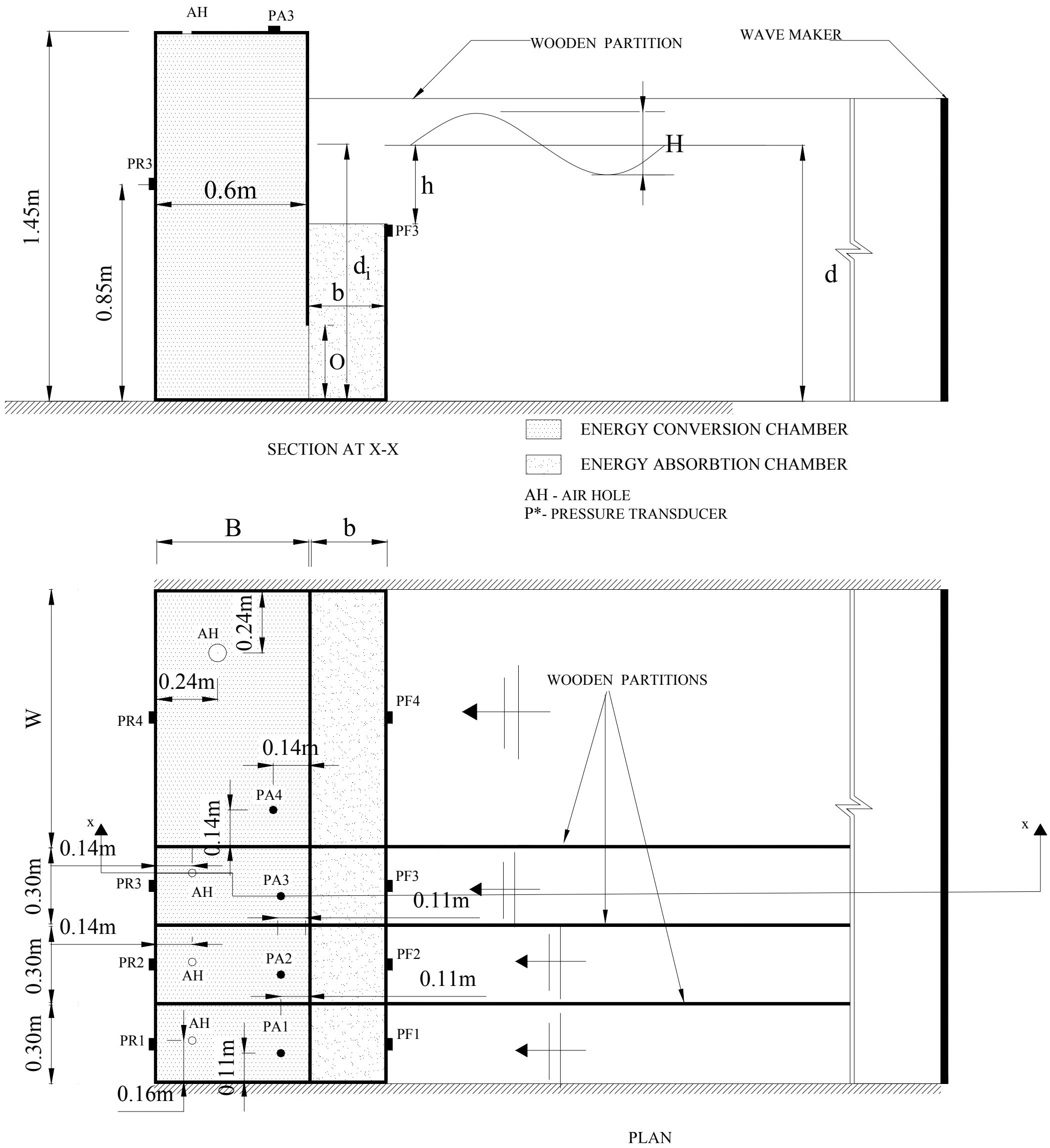

Figure 1: Plan and section of the model.

2.0 EXPERIMENTAL SET UP

The experiments were carried out in the wave flume of 72.5m long, 2m wide and 2.7m deep at the Department of Ocean Engineering, Indian Institute of Technology, IIT Madras, India. The physical model consists of four DCOWC model units integrated together. This facilitated simultaneous testing of models of different system parameters to particular wave characteristics. Considering the dominance of gravity force in wave structure interaction problem, Froude similitude criteria is adopted and a model scale of 1:20 was assigned in accordance with the guide lines of Sarmento and Thomas [15]. Each device has two parts namely the front chamber, the energy absorption chamber and the rear chamber, the energy conversion chamber. Among the four DCOWC units, three are smaller of same size having energy conversion chamber of 0.30mx0.6mx1.45m and the fourth is of 1.00mx0.60mx1.45m. The energy absorption units of fiber reinforced plastic covered over steel frame had a depth of 0.70m and the width(W) parallel to the wave crest was kept same as the width of the respective energy conversion unit and the width (b) perpendicular to the wave crest varied as 0.15m, 0.30mand 0.45m. To change the width, provisions were made in the frame work to fix the vertical plate at the respective locations. The top of the energy conversion chambers were covered with 12mm thick perpex sheets to view the nature of water oscillations inside the air chamber. To achieve water and air tightness at joints silica gel was used. For simulating the turbine effect on energy conversion chambers, circular air holes having 0.65% of its plan area were provided. Wang et al. [16] have reported OWC experimental works carried out with similar provisions for damping. Thiruvenkatasamy and Neelamani [17] have reported a decrease in the efficiency for air hole area beyond 0.85%. Rapaka [18] through model studies concluded that the energy conversion processes is optimum for the air hole area within a range of 0.45% to 0.68% of water plane area.

The plan and sectional view of the model adopted for the present study is shown in Fig.1 The model parameters that are likely to govern the efficiency of the device considered are bottom opening depth (O), width (W) parallel to the wave crest, width (B) perpendicular to the wave crest and the width (b) of the energy absorption chamber. The depth (h) for mouth opening was set to 0.30m and maintained constant throughout the tests. The bottom opening depth, for the smaller units were 0.15m, 0.30m and 0.45m, whereas, for the larger unit, it was 0.30m. The depth (d) of water in the flume was kept at 1.0m. The depth (d_i) water inside the model was same as d. The width of the energy conversion chamber of the caisson, 'B' for the energy conversion unit was 0.60m, whereas, for energy absorption unit 'b' was varied in terms of 0.15m, 0.30m and 0.45m . The width 'W' for the bigger and smaller units was 1.0m and 0.30m respectively. To avoid any possible interference effect, the adjacent units were separated by plywood partitioning for a length of 11m along the flume. Wave gauges of conductivity type measured the time histories of water surface elevation and the pressure sensors having maximum range of 0.2bar and 0.5bar were used for measuring the air and water pressures respectively. The locations of these measurements are indicated in the above figure. The photographic view of the model with the accessories is shown in Fig.2. The model units were exposed to the action of both regular waves of periods, T ranging between 1.2s and 2.4s at an interval of 0.1s. and random waves. For each period, wave heights of 0.045m, 0.055m, 0.065 and 0.045m were employed. In addition, tests with random waves following Pierson-Moskowitz (PM) spectrum were also considered for the tests, in which case, the peak period, T_P was varied from 1.2s to 2s at an interval of 0.2s. For each T_P three significant wave heights, H_S of 0.055m, 0.065m and 0.095m were adopted for the tests.

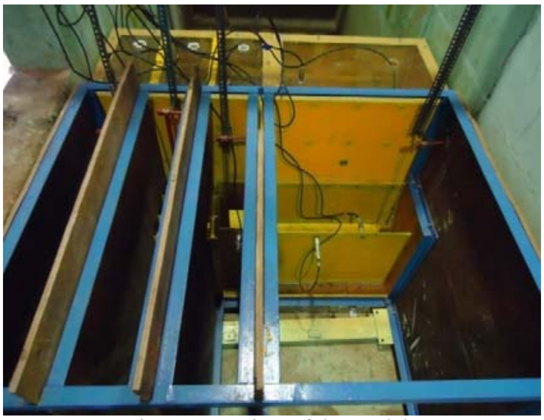

Figure 2: A view of the model.

For studying the effect of asymmetry between the energy absorption chamber and the energy conversion chamber, three test cases for b/B = 0.25, 0.50 and 0.75 were taken up. Considering the system parameters combination and wave characteristics, a total number of 201 test runs were executed for data collection.

3.0 RESULTS AND DISCUSSION

Typical time series of measured quantities, wave elevation, η, pressure on the front wall, p_f, pressure on the rear wall, p_r and air pressure, p_a, for a wave of H= 0.095m and T=2.3s for the model with b/B=0.25 and O/d_i=0.45 are shown in Fig.3 The velocity of water oscillation inside the energy conversion chamber is obtained through numerical differentiation of rear wall pressure and air pressure. Central difference scheme was adopted to reduce the order of error in the computation. While, analysing data the under regular waves, three successive steady cycles after the transient state were considered. To study the effect of water plane area on pneumatic damping, energy conversion efficiencies, results for two W/B of 0.5 and 1.67 were considered. Since the efficiency values for the two units were nearly same, the results of smaller units are reported herein.

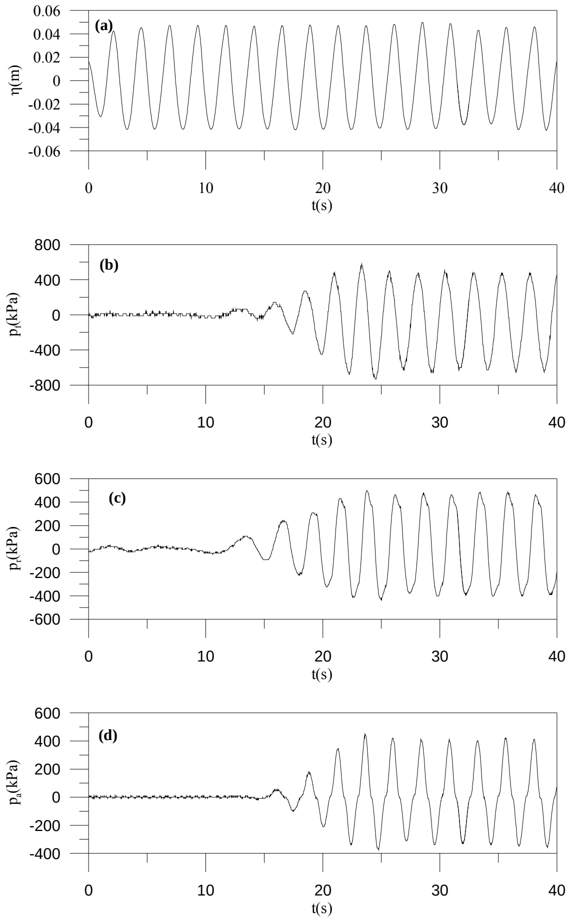

Figure 3: Time history of (a) incident wave surface elevation, (b) front wall pressure, (c) rear wall pressure and (d) air pressure.

3.1 Wave power absorption

For a DCOWC exposed to the waves, the dynamic pressure beneath the wave induces the necessary driving force at its mouth that is responsible for the water surface oscillation inside the energy conversion chamber. This causes water flow over the mouth in the vertical direction. Boccotti [13] computed the wave power absorption efficiency (C_A) at the mouth in terms of the velocity of flow(v_m), the dynamic pressure (p_f) , plan area (A_m) of mouth, width (W) and the incident wave energy flux (E_{in}) as detailed in Eqn. (1).

$$C_A = \frac{\frac{1}{T}\int_t^{t+T} p_m v_m A_m dt}{E_{in}} \qquad (1)$$

The energy flux (E_{in}) across the width (W) associated with the given wave height (H), period (T) propagating with celerity (C) in water depth (d) across the width (W) is computed following linear wave theory and is as per Eqn. (2).

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

where, $k = \frac{2\pi}{L}$, L is the wave length

The influence of b/B and O/d_i on the variation of wave power efficiency, C_A against the relative water depth, 'd/L' for a constant wave height of 0.095m for O/d_i=0.15, 0.30 and 0.45 are presented in Figs. 4a-c respectively. The results show that for the three O/d_i , the C_A decreases with an increase in d/L and is found to be a maximum for the longest wave tested and decreases as the waves become shorter. This is probably due to the reflection of longer waves from any obstruction being more leading to amplification of the waves near the opening into the chamber of the device. Further, the C_A is found to increase with an increase in the O/di as larger power is expected to propagate into the energy conversion chamber, which is found to be pronounced for d/L less than 0.25. The results also demonstrate that the wave power efficiency of the DCOWC is higher in relatively shallower waters. The effect of b/B is least for the smallest O/d_i of 0.15 tested. Since the physics of C_A follows linear circuit theory [19] there exists the possibility of entire mouth pressure not being fully utilised for causing flow inside the energy conversion chamber. In wave structure interaction the mouth pressure splits into two components namely active part and reactive part. The active part contributes to the velocity of flow and reactive part contribute to the wave height growth in front of the structure. Hence it is difficult to conclude the hydrodynamic effectiveness of the device under varying b/B based on C_A.

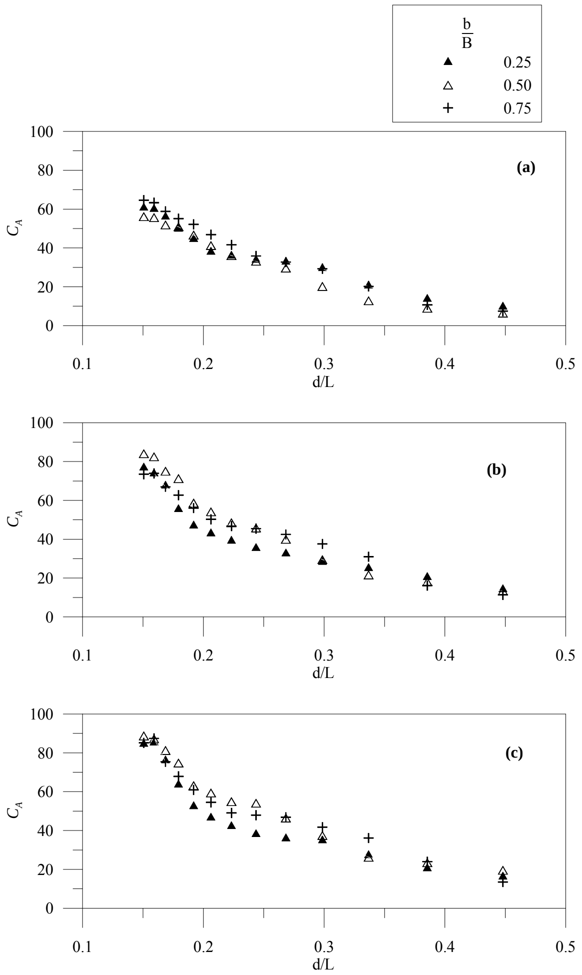

Figure 4: Effect of asymmetry on wave power absorption efficiency at (a) O/d_i=0.15, (b) O/d_i=0.30 and (c) O/d_i=0.45

The effect of wave steepness on C_A, as a function of d/L for the three b/B for the structure with O/d_i=0.45 and h/d_i =0.30 for b/B=0.25, 0.50 and 0.75 are brought out in **Figs. 5a-c** respectively. The effect of H/L is observed to be the least for the least b/B of 0.25 tested, whereas, it is found to be more pronounced for the other two indicating certain degree of nonlinearity either in velocity of flow or on pressure developed at the mouth. The C_A is found to reach 100% for d/L about 0.1 which agrees with the findings of Boccotti et al. (2007).. The trends observed over the wave power efficiency variation necessitate further analysis for ascertaining the best combination of b/B and O/d_i for maximum possible energy.

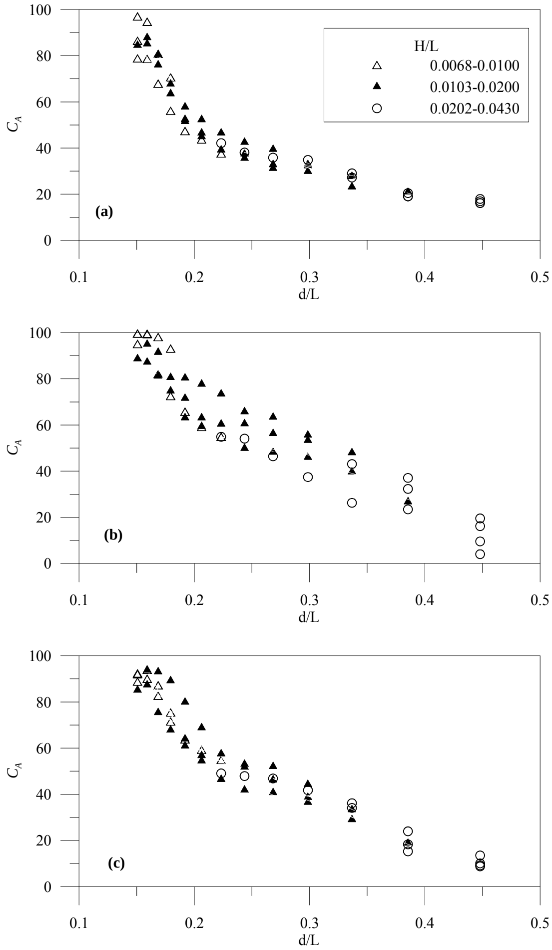

Figure 5: Effect of wave steepness on wave power absorption efficiency at O/d_i=0.45 for asymmetry values of (a) b/B=0.25, (b) b/B=0.50 and (c) b/B=0.75

3.2 Energy conversion efficiency

DCOWC converts wave energy in to pneumatic energy which rotates the turbine for electricity generation. Since pneumatic power calculation is very difficult due to the measurement of both velocity and pressure at the air hole, researchers compute [16, 17, 20, 21] the hydrodynamic power using the velocity of water surface oscillation and air pressure. In agreement with the existing methodology, the energy conversion efficiency (λ) is computed from hydrodynamic power developed and incident wave power as per Eqn. (3)

$$\lambda = \frac{\frac{1}{T}\int_{t}^{t+T} p_a A v \, dt}{E_{in}} \times 100 \qquad (3)$$

where p_a is the air pressure, v is the velocity of water surface oscillation inside the air chamber, A is the plan area of air chamber and E_{in} is the incident wave power computed as per Eqn. (2). The effect of O/d_i on the variation of λ with d/L for the three b/B's for a constant wave height of 0.095m-is brought out in Figs. 6a-c. Herein, h/d_i is mainatained as 0.30. The variation of B/L is also incorporated in the plot.

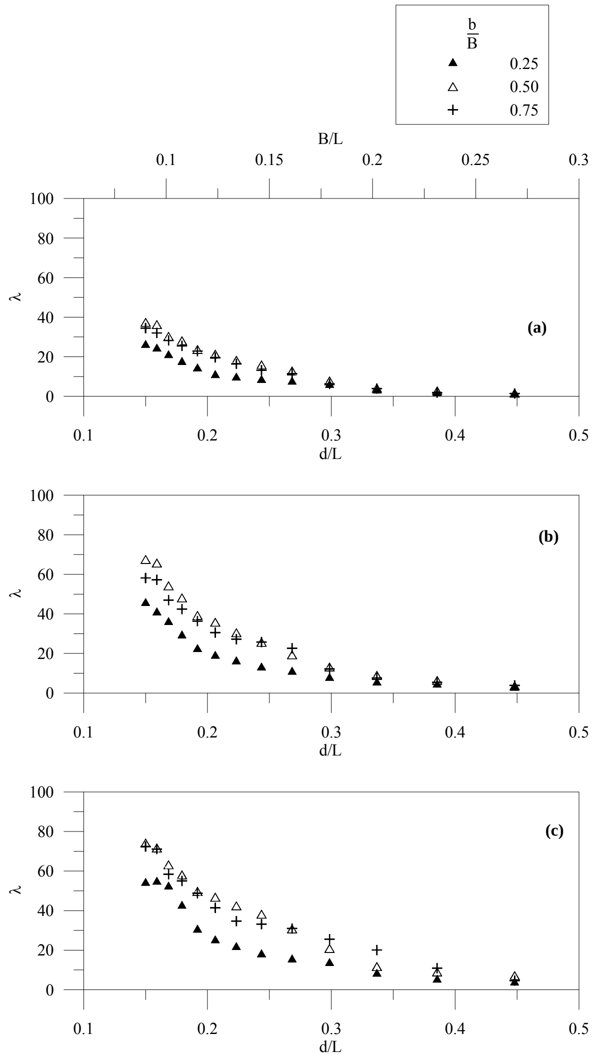

Figure 6: Effect of asymmetry on energy conversion efficiency at (a) O/d_i=0.15, (b) O/d_i=0.30 and (c) O/d_i=0.45

The effect of asymmetry in hydrodynamic performance is explicitly revealed in these figures. The low efficiency associated with the lowest b/B can be considered as the characteristic feature of DCOWC. The slope of the trend line for b/B=0.25 (Fig. 6c) up to d/L of 0.2 indicates the zone closer to the resonance region and the system exhibits an orientation towards energy conversion. However, the steady value of λ for the lowest frequency indicates that wave reflection is dominating at the mouth of the device. This can be explained by considering the higher values for group celerity at lower frequencies. As the wave moves past the vertical wall of front duct, it feels the obstruction like a submerged wall and gets partially reflected. Further, the lower values of λ at b/B =0.25 indicates the predominance of energy reflection rather than energy absorption. In wave structure interaction, the growth of added mass with respect to the geometry of the device may be the reasons for the lower performance in energy conversion. The increase in λ with an increase in O/d_i below d/L=0.20 and B/L=0.125 may be due decrease in the flow length and corresponding changes in the natural period of the systems. The loss due to wall friction is not considered herein. The convexity over the trend line of λ at lower values of d/L for O/d_i=0.45 at b/B=0.25 may be due to the higher wave celerity, the waves moving past the vertical plate of the front duct feels the vertical face of air chamber and gets reflected. The absence of this trend for O/d_i=0.15 and 0.30 can be related to the natural period variation. The comparison of λ for b/B of 0.50 and 0.75 indicates that the variation is marginal. A slight decrease in λ for b/B=0.75 compared to that for b/B=0.50 indicates that for b/B>0.75, the dynamic pressure excitation is likely to undergo modulation. Thus, the comparative analysis conclusively prove that the system performs well with a characteristic asymmetry with b/B=0.50.

Since the energy conversion assumes forced vibration behaviour, as the natural period changes corresponding changes are induced over the phase angle difference between air pressure and dynamic pressure excitation. The fundamental principle behind the energy conversion can be related to the theory of linear circuit where the output power is in direct proportion with the cosine function of phase angle. From the asymmetry effects it is observed that better performance is for the system with b/B=0.50 and O/d_i=0.45. The important aspect in DCOWC is that the dynamic pressure below the wave behaves as the forcing function at the mouth opening of front duct. Herein, as the asymmetry increases there is a possibility for the wave interaction phenomena to become a wave transmission type where the hydrodynamics gets adversely modified. This is revealed in the figure as the λ values at b/B=0.75 takes lower values compared to its counterparts at b/B=0.50. The trend line of λ at b/B=0.75 for d/L> 0.30 coming above the trend line of lower asymmetry values may be due to the discharge effect under the waves.This follows the control effect of harbour wall in Single Chamber Oscillating Water Column (OWC) as observed by Ambili et al.[5]. Thus, for h/d_i=0.30, the asymmetry value b/B=0.50 exhibits a better efficiency in its performance. It is understood that for an efficient performance in pneumatic power conversion, the water surface inside the energy conversion unit has to follow piston mode movement. The recent study of on OWC by Zhang et al. [21] showed that there are possibilities for sloshing mode behaviour in water oscillation depending on device width perpendicular to wave crest. With this as the background, in the present study it is observed that the maximum efficiency to an extent of about 80% occurs for B/L around 0.10. Further analysis is required to also consider the effect of variation with phase angle prior to concluding the magnitude of B/L.

The effect of wave steepness on the variation λ with d/L for O/d_i = 0.45 for the three b/B are plotted on Figs.7a-c.For all the b/B tested, it is seen that λ decreases with an increase in d/L. The insignificant effect of H/L on λ for b/B=0.25, indicates predominance of wave reflection at this asymmetry value. This substantiates the increase in added mass effect, the flow has to negotiate in causing oscillation inside the air chamber.

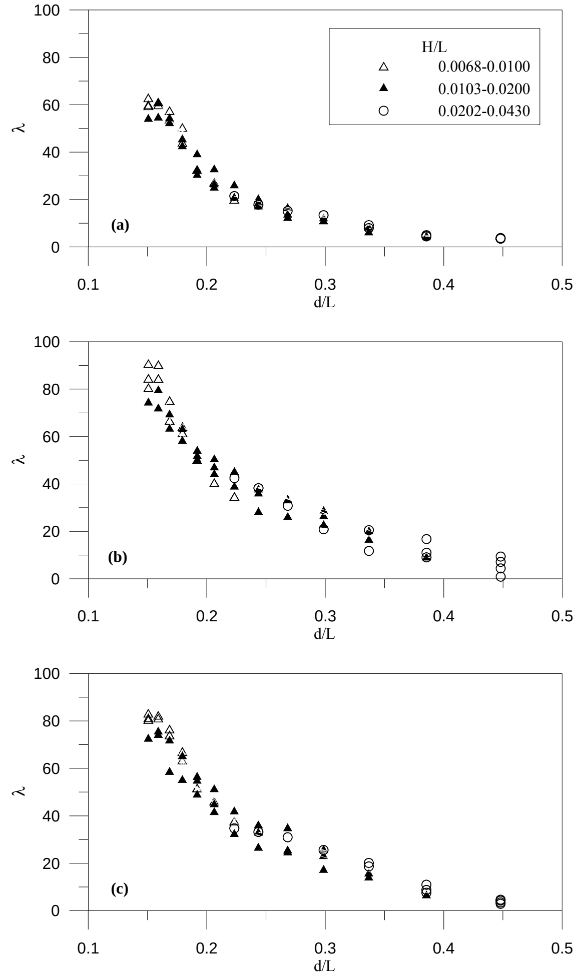

Figure 7: Effect of wave steepness on energy conversion efficiency at O/d_i=0.45 for asymmetry values of (a) b/B=0.25, (b) b/B=0.50 and (c) b/B=0.75.

The effect of H/L (for H/L ranging between 0.0068 and 0.043) for a particular d/L is found to be insignificant. λ is found to decrease with an increase in d/L and for the lowest d/L it attains a maximum of about 60%. It is clear that λ is inversely proportional to the wave frequency. It is further observed for b/B=0.75 that λ for lower d/L is about 70%. For the small wave steepness, an increase in λ up to about 10% is noticed. This indicates that as H/L increases, the energy loss associated with the fluid flow is more.

3.3 Phase angle variation

The basic preposition behind the working of DCOWC is the increase in both natural period of the system and the dynamic pressure available for oscillation. In OWC, the natural period of the system can be increased by decreasing the opening depth which causes a reduction in dynamic pressure available for forcing. As the bottom opening increases, there are possibilities for wave trough clearing the lip wall depth and air enters through the front mouth opening causing stalling for the turbine and power shut down in the system. This limitation of OWC is thus overcome in DCOWC by providing front duct. The variation of phase angle (ϕ_d) as computed

$$\phi_d = 360 \times \frac{T^*}{T} \qquad (4)$$

where, $\Psi(T^*)$ is the lag of the absolute maximum of cross-correlation between wave pressure (p_f) at the mouth and the air pressure (p_a) inside the air chamber.

$$\Psi\left(T^*\right) = \left\langle p_f(t)\, p_a\left(t + T^*\right)\right\rangle \qquad (5)$$

The variation of phase angle between dynamic pressure excitation and air pressure for b/B = 0.25, 0.50 and 0.75 for O/d_i = 0.15, 0.30 and 0.45 are plotted in Figs.8a, b and c respectively.

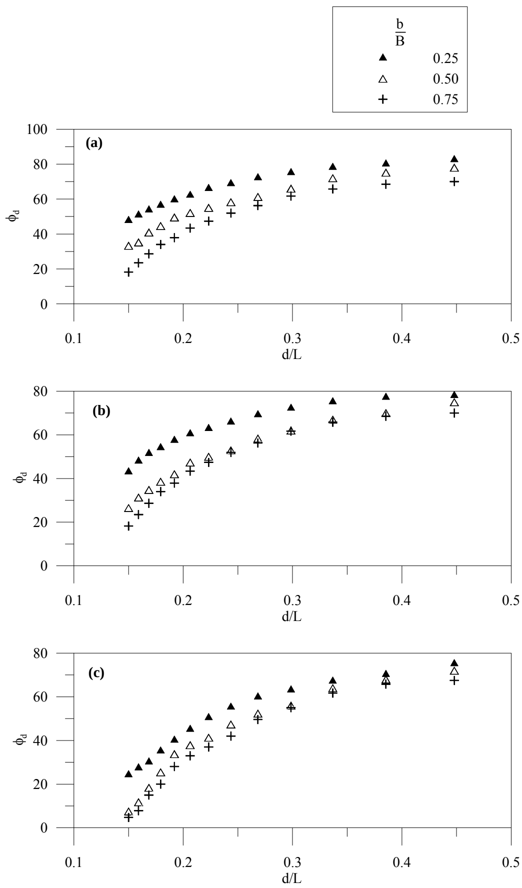

Figure 8: Effect of asymmetry on phase angle variation at (a) O/d_i=0.15, (b) O/d_i=0.30 and (c) O/d_i=0.45

It is observed that ϕ_d for b/B=0.25 is exceptionally high. This is probably due to the longer stream line length in the flow occurring inside the DCOWC. The possible reasons for this phenomenon are the added mass effect and the wave amplification occurring near the mouth of the device. The reason for the regressive performance in energy conversion efficiency for b/B of 0.25 is attributed to larger phase variation. For d/L >0.25, ϕ_d for b/B= 0.50 and 0.75 reaches an asymptotic value indicating an out of phase condition. It is inferred that the DCOWC response to higher frequencies is low. It can be substantiated by observing the corresponding energy efficiency values. A diminishing trend for O/d_i=0.30 and 0.45 are observed (Figs. 8 b and c). Similarly, for d/L < 0.25, there exists slight variation over ϕ_d for O/d_i=0.15. It shows that the added mass effect and the wave amplification are negligible over the above frequency range for these system parameters.

The phase variation due to the asymmetry in the device, thus, indicates that the geometrical system parameters can be tuned by understanding the phase difference. The phase variation and corresponding energy conversion efficiency indicate that phase difference is the central aspect in the design of DCOWC device. For maximum energy conversion, the phase difference between the wave and the fluctuating air column should be close to zero. This can be realized by suitably selecting the system parameters to bring the natural frequency of the system closer to the predominant wave frequency.

3.4 Wave amplification

The assessment of energy conversion process is the primary criteria for the evaluation of the DCOWC concept. A qualitative evaluation of the relationship between different device parameters in regulating the conservation principles is an important aspect to formulate design criteria. The wave height growth in front of the structure is called as the wave amplification (β) and it is computed as

$$\beta = \frac{H_m}{H_{in}} \qquad (6)$$

where, H_m is the wave height in front of the device and H_{in} is the incident wave height..

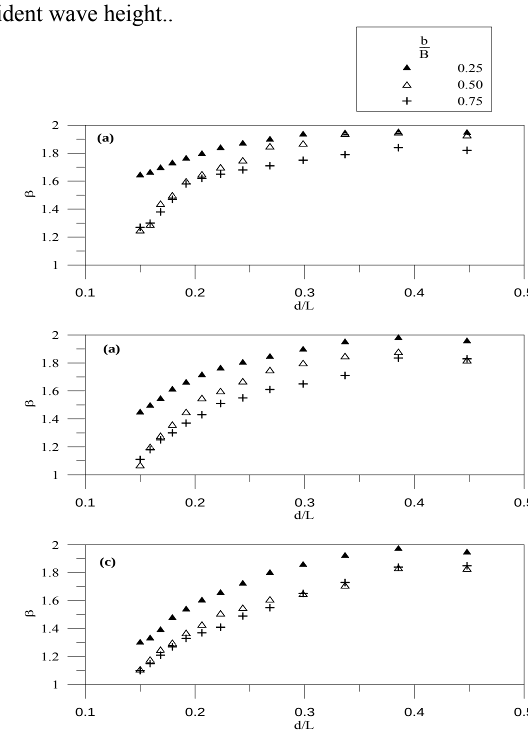

Figure 9: Effect of asymmetry on wave amplification at (a) O/d_i=0.15, (b) O/d_i=0.30 and (c) O/d_i=0.4.

The degree of variation of β for the three asymmetry factors is presented for O/d_i =0.15, 0.30 and 0.45 in Figs.9a, b and c, respectively It is evident that, in general, β increases with d/L. This indicates that the system is tending towards the resonance region with a decrease in the frequency of excitation. The reason for the lesser energy conversion for b/B=0.25 can be inferred from the trend in their variation. It is observed that irrespective of the relative bottom opening O/d_i,, β takes relatively larger values for DCOWC with b/B=0.25. At low asymmetry factor, the waves get amplified near the mouth constraining the flow in to the device. The possible reason for this phenomenon can be related to the added mass effect developing in the present wave structure interaction problem. This agrees with the general concept existing for the added mass that it depends mainly on the structural configuration.

Furthermore, for d/L < 0.20, β takes closer values for b/B=0.50 and 0.75, which shows that the mouth captures the incoming energy and β is higher for the least asymmetry at the lowest frequency indicating the minimum capture of energy at the mouth. For d/L > 0.30 , it is observed that the trend lines of β for O/d_i=0.15 at b/B=0.25 and 0.50 merge, while, the same for b/B=0.75 is less. It is an indication that larger asymmetry factor modulates the wave profile. That is, beyond a critical b/B, the wave interaction can transform into a wave transmission problem making the regime of performance entirely different from what is envisaged as a DCOWC.

3.5 Pressures

To investigate the asymmetry effect in a boarder sense, its effect on the wave induced pressures on the front and rear walls as well as on the air pressures are plotted for a constant wave height of 0.095m in Figs.10, 11 and 12 respectively. The peak pressures are plotted in non dimensional form after normalising it with wave height as a function of d/L. In each of the above figures, the variations of the pressures for the three O/di tested are superposed for b/B=0.25,05 and 0.75. The results show that the pressures on the front wall decreases as d/L decreases and the rate of decrease being more drastic uto d/L of 0.3, beyond which, the effect is not significant. The peak pressure is a maximum at the lowest d/L tested for all the test conditions. The results also show that the wall with the largest O/di of 0.45 experiences least pressure for all d/L and b/B. Furthermore, The model with the least b/B of 0.25 is found to experience more pressures compared to the other two larger b/B of 05 and 0.75. This may be due to multiple reflection between the front wall and the energy conversion chamber, which is likely to reduce as the gap between increases. This indicates that the asymmetry effect beyond a critical limit will modulate wave forcing over the mouth. For a DCOWC, the combination of b/B=0.50 and O/d_i=0.45, rear wall pressure and air pressure at the lowest d/L reaching nearly equal to front wall pressure indicate that the system performance is better at the resonance region.

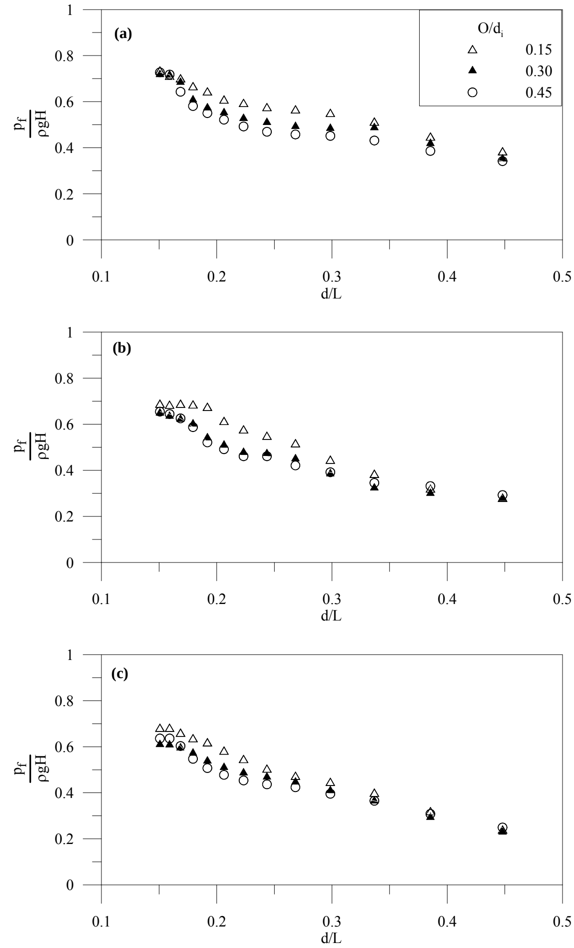

Figure 10: Effect of asymmetry on front wall pressure at (a) b/B=0.25, (b) b/B=0.50 and (c) b/B=0.75

Table 1: Comparison between energy conversion under regular and random waves (b/B=0.75, O/d=0.45).

$(d/L)/(d/L_P)$	Energy conversion Under regular waves	Energy conversion under irregular waves	Percentage change in Energy conversion
0.448	4.61	6.67	+44.69
0.3368	20.11	15.44	-23.22
0.2683	30.96	26.10	-15.70
0.2233	34.70	31.96	-7.90
0.1919	48.80	45.34	-7.09

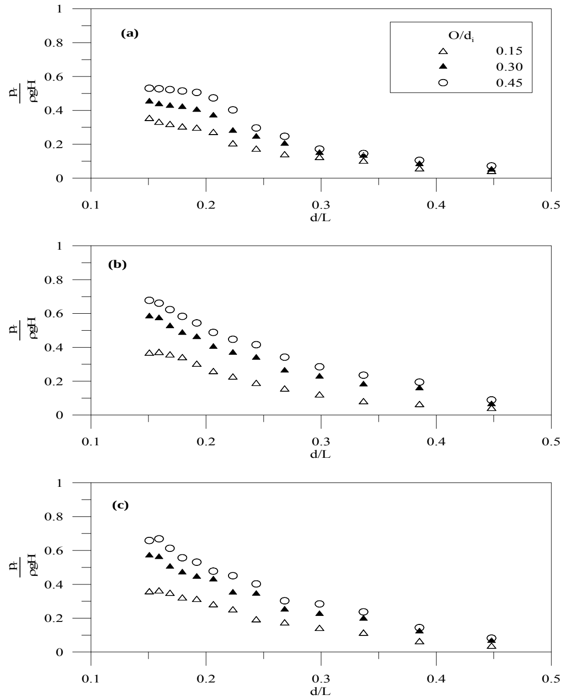

Figure 11: Effect of asymmetry on rear wall at (a) b/B=0.25, (b) b/B=0.50 and (c) b/B=0.75.

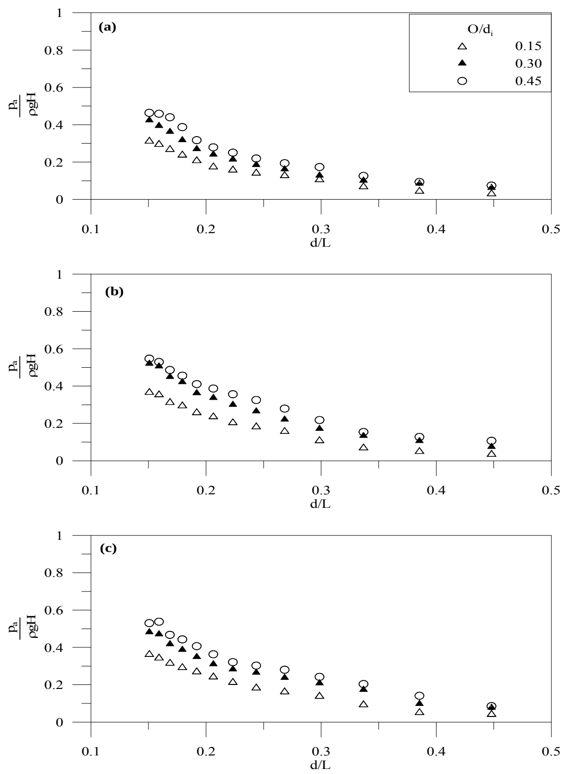

Figure 12: Effect of asymmetry on air pressure at (a) b/B=0.25, (b) b/B=0.50 and (c) b/B=0.75.

3.6 Random wave

The real sea state is random in nature. It is a prerequisite to assess the hydrodynamic characteristics by simulating similar sea state in the laboratory. By studying the interaction with random waves, the asymmetry effect of the device as compared to the same under regular waves can be brought out. The random waves defined by Pierson–Moskowitz (PM) spectrum were adopted for the tests. The characteristic factors of the spectrum are significant wave height (H_s) and peak wave period (T_p). Under the random wave incidence, the air pressure and the velocity of free surface are also of random in nature. Thus, the device has to be designed for average power development. The average power (P_{ave}) is calculated from significant velocity of free water surface oscillation (v_0) and significant air pressure (p_0) following the general methodology as,

$$P_{ave} = \frac{1}{2} p_0 A v_0 \tag{7}$$

wherein, A is the cross sectional area of the oscillation chamber. The incident energy flux (P_{in}) is calculated using significant wave height and group celerity (C_g) corresponding to peak wave period as,

$$P_{in} = \frac{1}{8} \rho g H_S^2 C_g \tag{8}$$

The energy conversion capacity (λ_R) is determined as

$$\lambda_R = \frac{P_{ave}}{P_{in}} \times 100\ \% \tag{9}$$

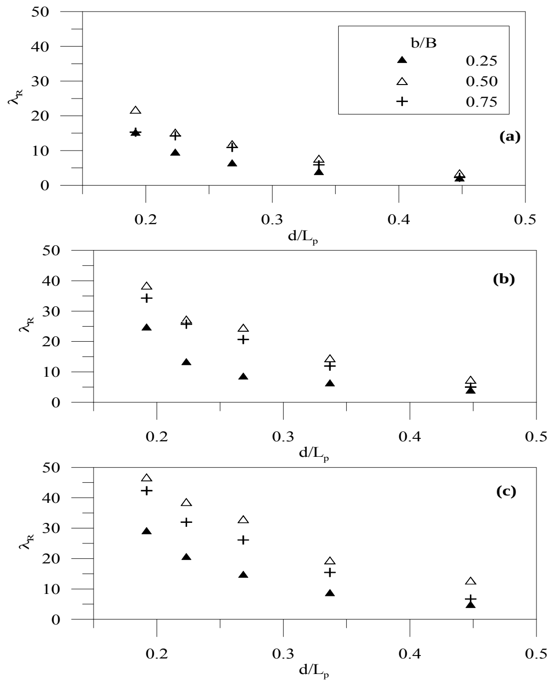

Figure 13: Effect of asymmetry in energy conversion under random waves (a) O/d_i =0.15, O/d_i =0.30 and (c) O/di =0.45.

The variation of energy conversion capacity (λ_R) with the relative water depth (d/L_P) for three b/B's aganist O/d_i=0.15, 0.30 and 0.45 are presented in Figs. 13 a, b and c, respectively. The wave height here is H_S=.095m. λ_R achieves relatively higher values at b/B=0.50 under each O/d_i. The trend observed indicate that energy conversion under random waves depends mainly on device configuration and peak wave period. Table 1 summarises the energy conversion under both regular and random waves. The percentage changes were calculated taking energy conversion under regular wave as the reference value. This table illustrates that the device is towards resonance condition with the increase in peak period of the incident wave.

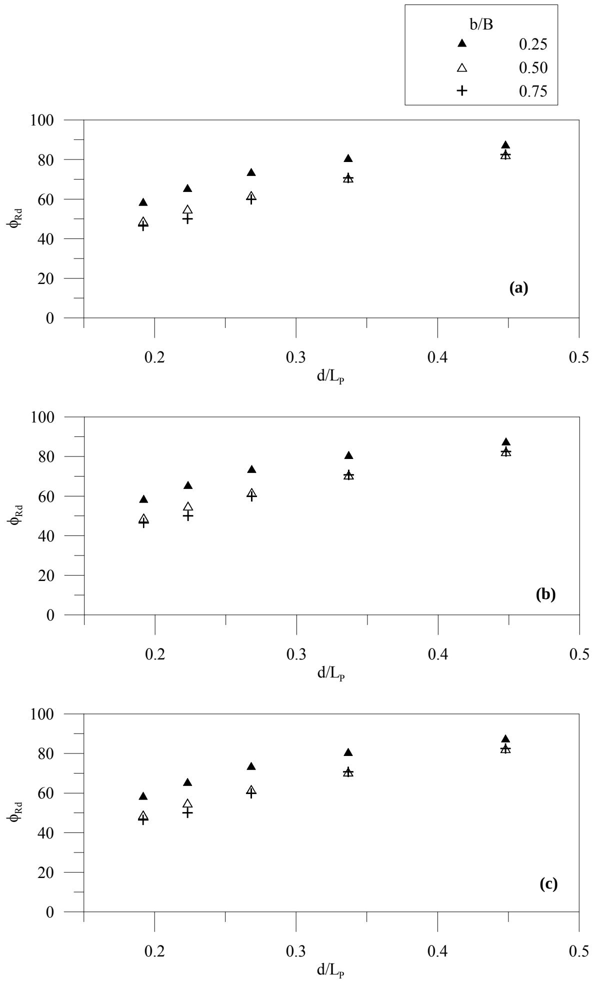

Figure 14: Effect of asymmetry in phase difference under random waves (a) O/d_i =0.15, O/d_i =0.30 and (c) O/di =0.45.

Further analysis over the sensitiveness of device with respect to peak wave period carried out under the phase difference (ϕ_{Rd}) between air pressure and incident dynamic pressure are plotted in Figs.14 a, b and c. The results do demonstrate an increase in natural period for the lower asymmetry at b/B=0.25. The explanation was given in section 3.3 holds true here also. The exact reasoning behind the increase in energy conversion with peak wave period can be inferred from the lower values of phase difference. These results substantiate that tuned system of DCOWC can hydrodynamicaly convert energy from random waves without any limitations. To have clear understanding on random wave structure interaction, the effect asymmetry plays on wave amplification (β_R) over the mouth is investigated. β_R is computed between maximum incident wave height (H_{maxi}) and maximum wave height at mouth (H_{maxm}) as per

$$\beta_R = \frac{H_{\max m}}{H_{\max i}} \tag{10}$$

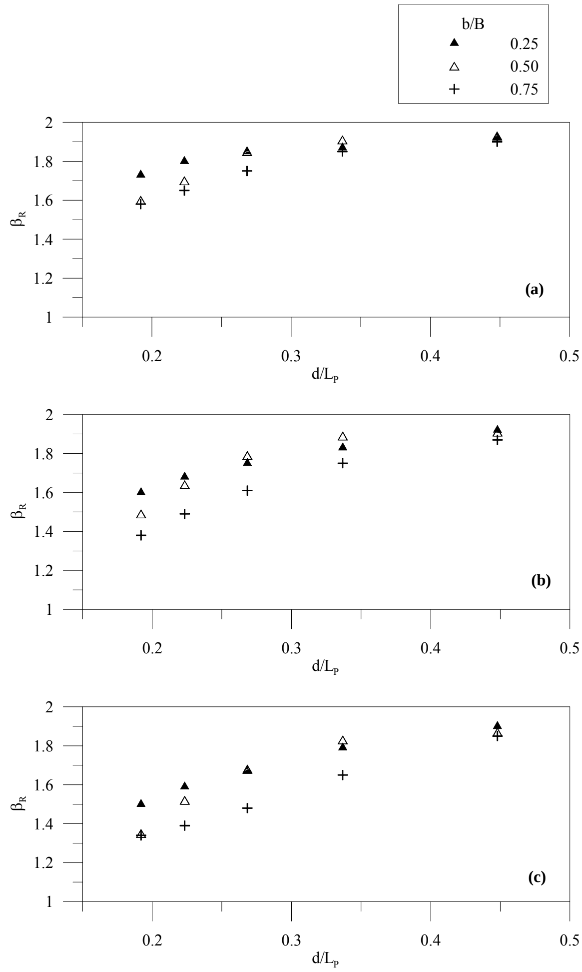

Figure 15: Effect of asymmetry in wave amplification under random waves (a) O/d_i =0.15, O/d_i =0.30 and (c) O/di =0.45.

β_R plotted for the three asymmetry values against the frequency parameter d/L_P are presented in Figs.15a-c. The trend follows the similar pattern observed under regular waves for the same. This shows that for tuned system, the maximum wave height present under random waves does not contribute to wave height growth near the device. To describe the asymmetry effect adequately tests carried out under the regime of random wave conditions are analysed in the subsequent sections.

3.7. Spectral width

In section 3.3 it was observed that asymmetry along with relative bottom opening produces phase control effect on energy absorption. Hence, studies on the effect of phase control over the spectral width of front wall, rear wall and air pressures are required for identifying the optimum combination of system parameters. The spectral width of the incident wave elevation, ε_η used at asymmetry values 0.25, 0.50 and 0.75 are presented in Figs.16a, b and c respectively. The figure indicates that all the waves used in the study had spectral width around 0.50. The effect of asymmetry over front wall pressures is plotted in Figs 17a-c. It is evident that at O/d_i=0.15, the spectral width ‘ ε_{p_f} ’ for front wall remains around 0.40 irrespective of b/B. This may be due to the effect of more reflection from the device. The spectral width value reaching more than 0.5 for higher values of d/L_p at b/B=0.25 and O/d_i=0.30 indicates that incoming wave splits in to higher order components after hitting front wall of energy conversion chamber. The lack of spread and change in the trend line for the spectral width at b/B=0.50 indicates that this asymmetry does not modulate the incoming wave. The trend line change for b/B=0.75 at O/d_i’s 0.30 and 0.45 show the asymmetry effect interference with the incoming wave.

The effect of b/B’s and O/d_i’s combination on rear wall pressure under the varying wave conditions are plotted in Figs. 18a-c. These figures illustrate the phase control effect in a clear manner. The rear pressure represents the water oscillation characteristics inside the energy conversion units. It is to be seen that larger spectral widths are indication of poor performance while smaller spectral widths are for the energy concentration around the peak period. For the better performance the latter aspect is a desirable thing in the design. The larger values of ε_{p_a} at b/B=0.25 indicate the underperformance of the device at this asymmetry value. From this, it can be inferred that the stabilised value for ε_{p_r} reaches around 0.40 at b/B=0.50 and O/d_i=0.45. This is agreeable with respect to the incident wave having spectral width of 0.50. The spectral width parameter reaching to the above value for the least favourable system parameters combination (b/B=0.25 and O/d_i=0.30 and 0.45) at the highest d/L_P tested indicates that by suitable combination of system parameters with respect to the incident wave characteristics, tuning effect can be produced in the device for maximum energy conversion.

The air pressure spectral width ‘ ε_{p_a} ’ variation against d/L_p for the system parameters b/B and O/d_i are plotted in Figs.19a-c. The spectral width varies within a range of 1.0-0.50 with increase in d/L_p. The larger values at b/B=0.25 for O/d_i’s 0.15, 0.30 and 0.45 are due to the greater phase variation within the device for the system parameters combination. In general it is observed that there is decrease in spectral width with increase in peak period. Among the configurations tested, the best system parameters identified are b/B’s 0.50 and 0.75 at O/d_i’s 0.30 and 0.45.

3.7 Spectral energy ratio

To study the device response under different system parameters and wave characteristics, ratio between spectral energies of front wall pressure, rear wall pressure and air pressure to the corresponding incident wave energy represented as $[(m_0)_r]$front, $[(m_0)_r]$rear and $[(m_0)_r]$air are shown in Figs.20,21 and 22 respectively. In Fig.20, observed that at a particular b/B, the energy ratios are getting relatively higher values with decrease in O/d_i. The high values around 1.2 are reached at O/d_i=0.15. The same for the largest asymmetry b/B=0.75 reaches around one. This indicates that energy reflection is more at O/d_i=0.15. In the same manner it is observed that energy absorption is more at O/d_i=0.45.

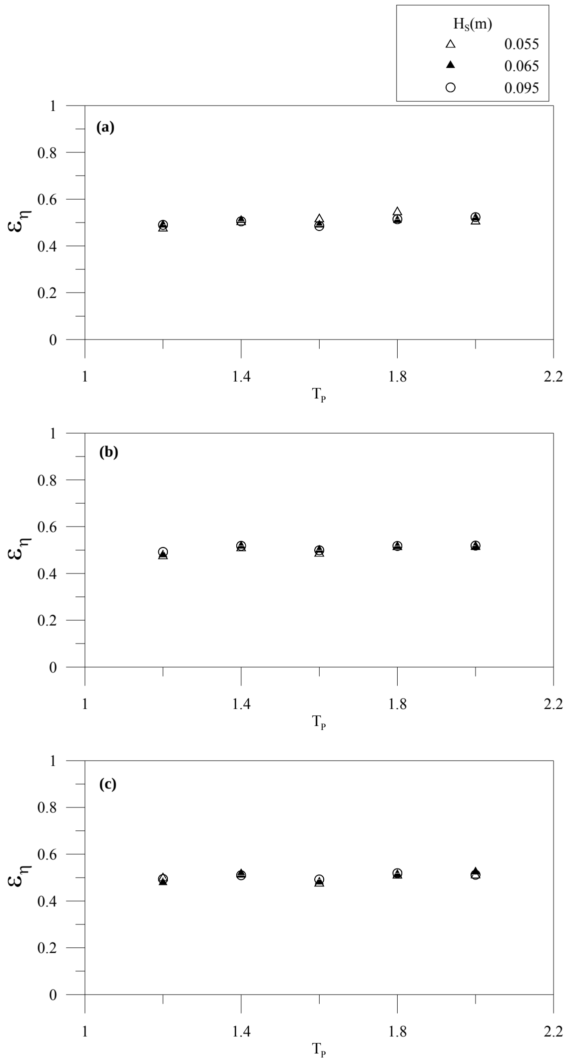

Figure 16: Spectral width of the incident wave at (a) b/B=0.25, (b) b/B=0.50 and (c) b/B=0.75.

The spectral energy ratio for rear wall pressure is plotted in Figs.21a-c brings out the effect of asymmetry and relative opening depth. Here the trend appears in inverse proportion to the one observed for front wall pressure. It is apparent that b/B=0.50 and O/d_i=0.45 produces favourable phase control effect in energy conversion. In the same manner, the energy ratios for air pressures are plotted in Figs.22a-c. This figure also supports the claims made over b/B and O/d_i in the foregoing sections.

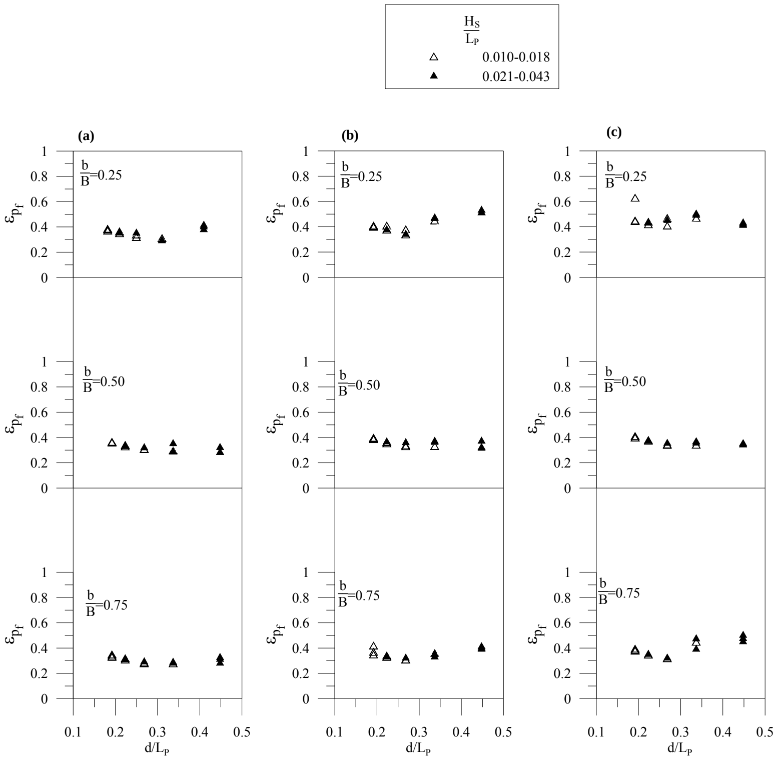

Figure 17: Effect of asymmetry on spectral width of the front wall pressure at (a) O/d_i=0.15, (b) O/d_i=0.30 and (c) O/d_i=0.45

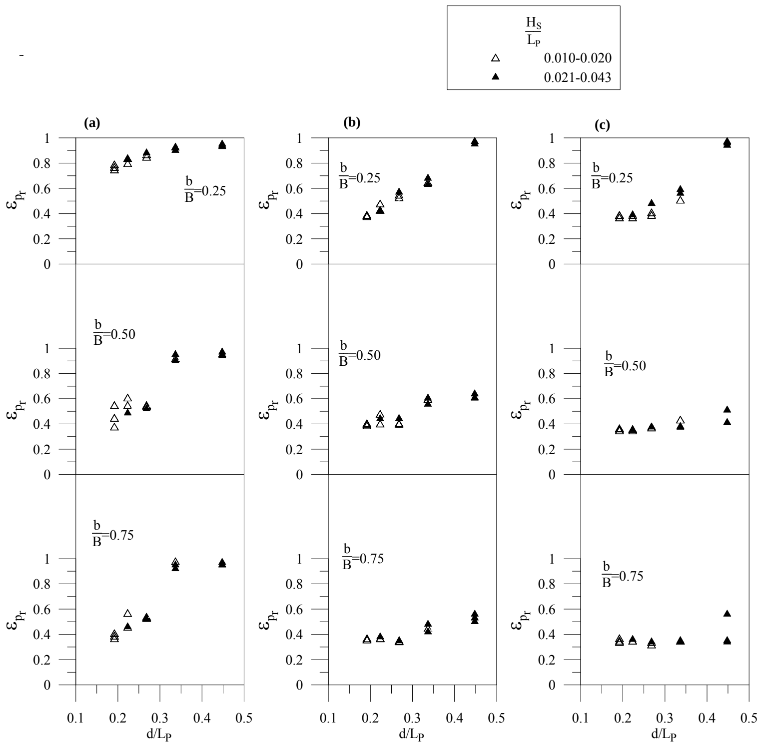

Figure 18: Effect of asymmetry on spectral width of the rear wall pressure at (a) O/d_i=0.15, (b) O/d_i=0.30 and (c) O/d_i=0.45

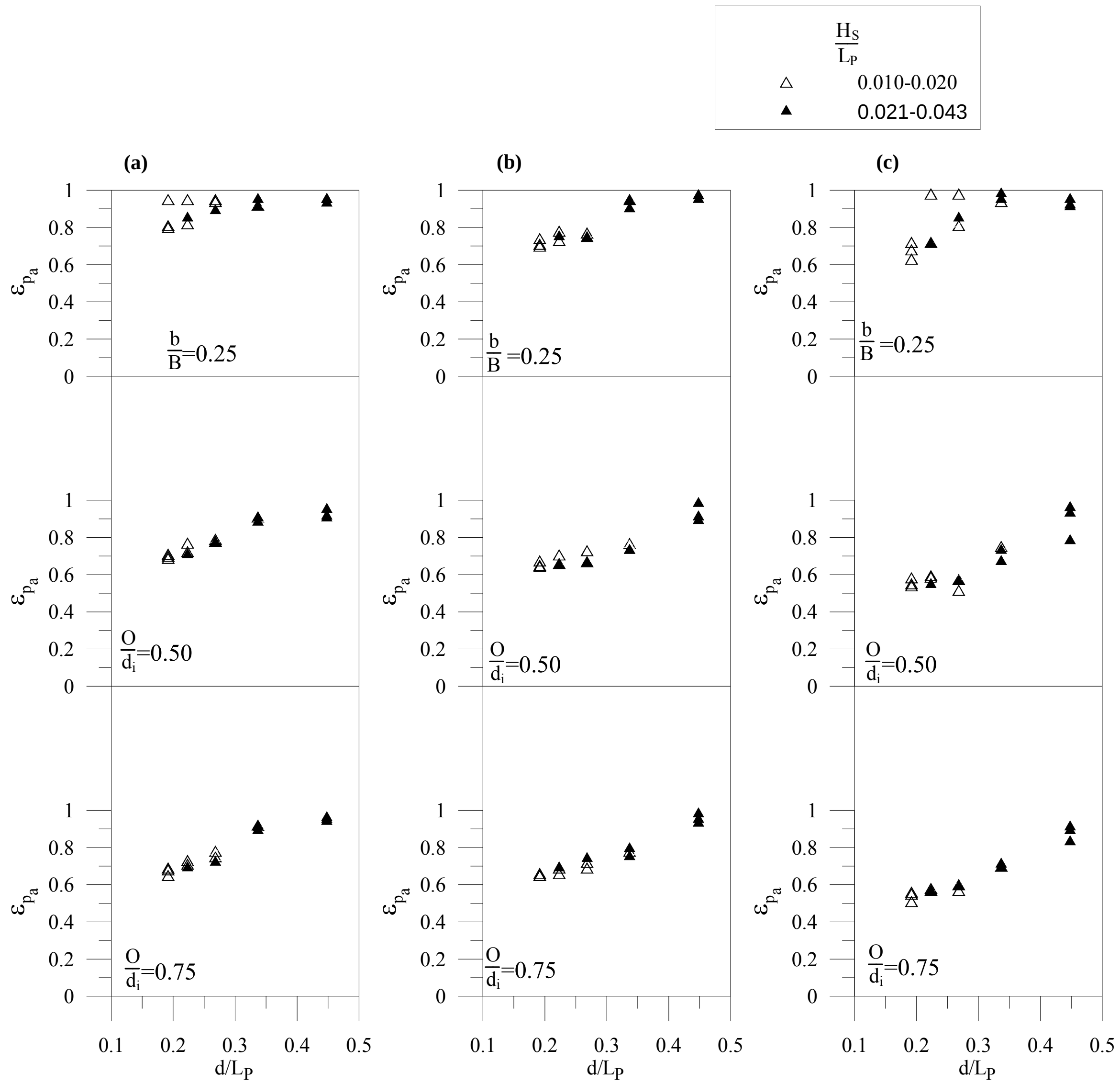

Figure 19 Effect of asymmetry on spectral width of the air pressure at (a) O/d_i=0.15, (b) O/d_i=0.30 and (c) O/d_i=0.45

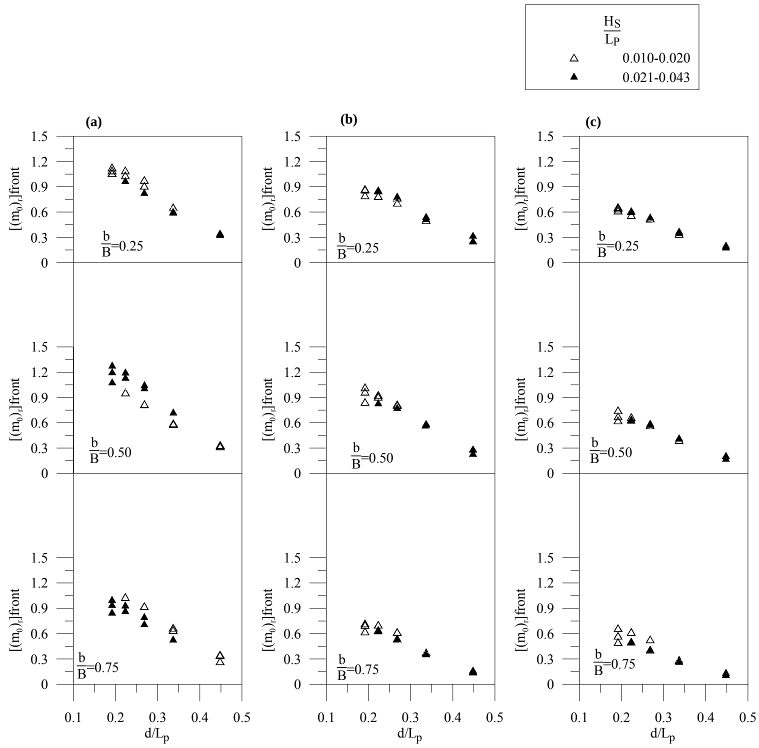

Figure 20: Effect of asymmetry on spectral energy of front wall pressure at (a) O/d_i=0.15, (b) O/d_i=0.30 and (c) O/d_i=0.45.

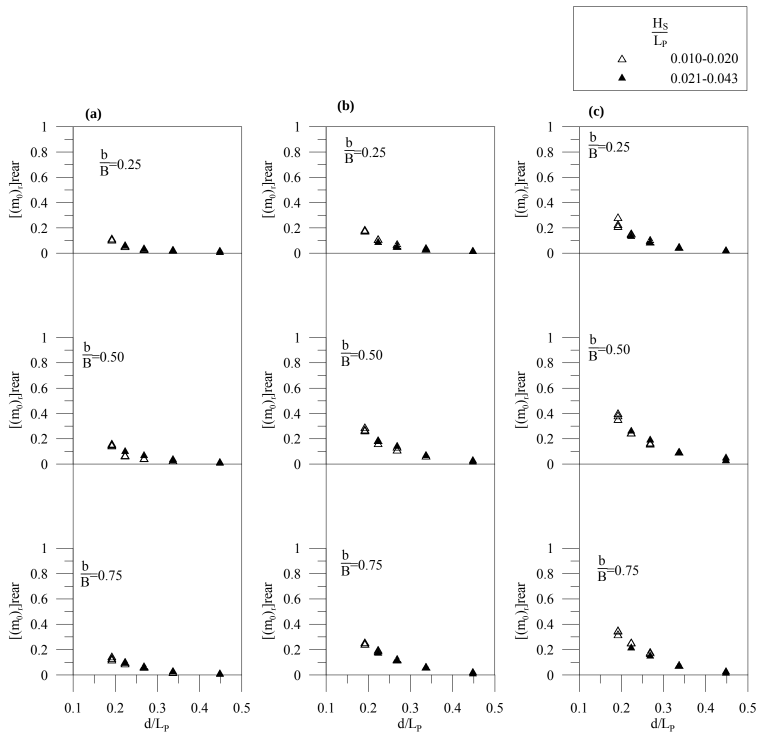

Figure 21: Effect of asymmetry on spectral energy of rear wall pressure at (a) O/d_i=0.15, (b) O/d_i=0.30 and (c) O/d_i=0.45.

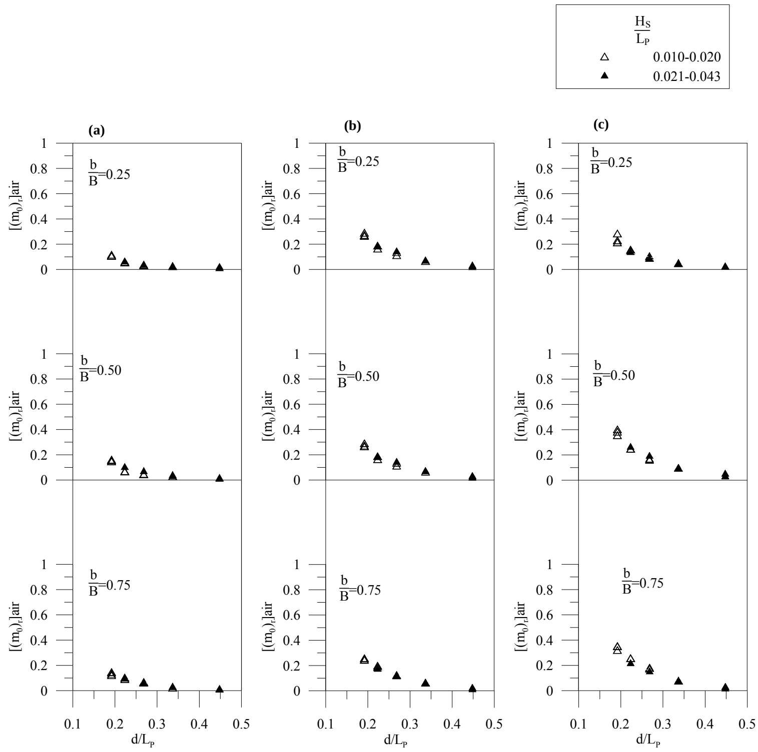

Figure 22: Effect of asymmetry on spectral energy of air pressure at (a) O/d_i=0.15, (b) O/d_i=0.30 and (c) O/d_i=0.45.

4. CONCLUSIONS

DCOWC is the new concept to achieve efficiency and effectiveness in energy conversion from waves. Though its principle of operation has been studied extensively by Boccotti [13,14], proportioning of geometric details remains unaddressed. The present study considers the influence two parameters namely; bottom opening depth and width of the front duct normal to the wave crest. Wave conditions of both regular and random were considered. It was observed that relative opening depth along with asymmetry value is having strong effect on hydrodynamic energy conversion capacity of the device. The important findings of the study are

- The piston movement of water surface inside the energy conversion chamber can be obtained by maintaining B/L=0.10, where B is the width normal to wave crest and L is the wave length.
- The energy conversion reaches optimum level for the asymmetry b/B=0.50, for lower values wave reflection predominates and for higher values attenuation over wave forcing is about to occur.
- The energy conversion reaches around 80% of the incident wave energy nearer the resonance condition.
- Resonance condition can be obtained by suitable combination of geometric parameters so that natural frequency of the device becomes equal to the wave frequency.

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