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ORIGINAL ARTICLE

Comparison of the performance of oscillating water column devices based on arrangements of water columns

Jahirwan Ut Jasron[1,2], Sudjito Soeparmani[2], Lilis Yuliati[2] and Djarot B.Darmadi[2]

[1] Mechanical Engineering, Faculty of Science and Engineering, Universitas Nusa Cendana Kupang, Indonesia
[2] Mechanical Engineering, Faculty of Engineering, Universitas Brawijaya Malang, Indonesia

ABSTRACT – The hydrodynamic performance of oscillating water column (OWC) depends on the depth of the water, the size of the water column and its arrangement, which affects the oscillation of the water surface in the column. An experimental method was conducted by testing 4 water depths with wave periods of 1-3 s. All data recorded by the sensor is then processed and presented in graphical form. The research focused on analyzing the difference in wave power absorption capabilities of the three geometric types of OWC based on arrangements of water columns. The OWC devices designed as single water column, the double water column in a series arrangement which was perpendicular to the direction of wave propagation, and double water column in which the arrangement of columns was parallel to the direction of wave propagation. This paper discussed several factors affecting the amount of power absorbed by the device. The factors are the ratio of water depth in its relation to wavelength (kh) and the inlet openings ratio (c/h) of the devices. The test results show that if the water depth increases in the range of kh 0.7 to 0.9, then the performance of the double chamber oscillating water column (DCOWC) device is better than the single chamber oscillating water column (SCOWC) device with maximum efficiency for the parallel arrangement 22,4%, series arrangement 20.8% and single column 20.7%. However, when referring to c/h, the maximum energy absorption efficiency for a single column is 27.7%, double column series arrangement is 23.2%, and double column parallel arrangement is 29.5%. Based on the results of the analysis, DCOWC devices in parallel arrangement showed the ability to absorb better wave power in a broader range of wave frequencies. The best wave of power absorption in the three testing models occurred in the wave period T = 1.3 seconds.

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INTRODUCTION

Due to global warming and air pollution, meeting energy needs in the present civilization challenges us to find new and renewable energy sources that are environmentally friendly. Therefore, research on renewable energy needs serious attention. One of the promising sources of renewable electric energy is an ocean wave. On the other hand, damage to the coast due to sedimentation is also ongoing, so it is necessary to protect it used twin pontoons of floating breakwater (TPFB) [1,2]. To harvest ocean wave energy, the various wave energy converters (WECs) have been developed and classified in three major systems, namely, Oscillating Water Column (OWC), Overtopping (OT), and Wave Activated Body (WAB) [3].

The oscillating water column is a type of device that widely used in ocean wave energy conversion. The conventional form of oscillating water column consists of a water column, an air column, and an air exhaust duct. Among studies of OWC devices, studies of how to improve the performance of OWC devices are one of the most conducted studies for device commercialization. In this case, some studies concentrated on using various control devices, such as wave characteristics, shape parameters of the device, and exhaust duct system, on increasing the efficiency of OWC [4,5].

The study of device shape parameters as determinants of hydrodynamic performance has resulted in several important conclusions, including the relationship between column width and length of the front wall which submerged to water depth [6], the effect of inlet valve area on the effectiveness of wave energy absorption [7], the effect of the basic form of the column on the hydrodynamic characteristics [5,8] and the effect of column shape on pressure fluctuations [9].

In considering the geometry of the shape of the device, wave characteristics are the main factors considered so that the OWC device can maximally convert the power contained in the wave. Sundar et al. in his study of wave force on the OWC device explained maximum absorption of wave energy occurs when the ratio of water depth to wavelength is around 0.131, it also found in these conditions the horizontal force is greater than the vertical force [10]. At the same time Ashlin et al. stated that the horizontal force acting on a structure is 2.5 to 3 times greater than the vertical force, where the wave force increases with increasing wave steepness [11].

Studies of the forms of OWC devices have made a breakthrough that resulted in a new design. The studies proposed the use of two columns, or even multi-columns, aiming to increase the efficiency and effectiveness of ocean wave energy conversion. Wilbert et al., who analyzed the width of the front duct with the energy conversion chamber, concluded that

*CORRESPONDING AUTHOR | Jahirwan Ut Jasron | jahirwan.jasron@staf.undana.ac.id

the width/depth ratio of the inlet valve regarding wave characteristics of DCOWC devices affects the effectiveness of energy conversion. [12]. According to Hsieh et al., who analyzed the use of two columns using the Savonius turbine, have stated that overall, there is an increase in output power [13]. Also, multi-column devices show better energy conversion effectiveness [14].

Ning et al. who investigated the wave energy conversion of the DCOWC series arrangement, found that the column area ratio had less effect when the total column area was constant, while a small barrier wall draft was more advantageous in terms of energy conversion efficiency. Comparisons between a dual-chamber OWC device and an equivalent typical single-chamber one show that the dual-chamber OWC is favourable with increases in both the peak efficiency and the effective frequency bandwidth. The increases happened because the coexistence of the two sub-chambers affect the resonance mechanics of the system [15].

In previous research conducted, it was found that the use of DCOWC is more profitable than the SCOWC, but nothing compares the DCOWC performance for series and parallel arrangement with SCOWC using the same geometric parameters (i.e., chamber breadth and barrier wall draft). This research is needed to get the certainty of the benefits of each parameter tested.

This study focuses on the velocity changes of air outflow in the air exhaust duct as a parameter for efficiency in single-column oscillating water column (SCOWC) device and double chamber oscillating water column (DCOWC) devices arranged in series and parallel. Another focus is the comparison of the absorption capacity of each wave power device. The analysis involves the wave characteristics parameters and the inlet openings ratio of the device. The results show the difference in wave power absorption capability of each device in the same testing condition and can use as a consideration for the next OWC device design.

METHODS AND MATERIALS

Tests conducted at the Fluid Mechanic and Machinery Laboratory, Department of Mechanical Engineering, Faculty of Engineering, Brawijaya University, using open canal which was 9 m long, 0.5 m wide, and 0.6 m high. The canal made of acrylic material with a thickness of 9 mm. A wavemaker was placed at one end while at the other end was placed a wave absorber. The OWC testing models consisted of a single chamber oscillating water column (SCOWC), and double chamber oscillating water column (DCOWC) arranged in series and parallel column. The testing models were placed 4 meters in front of the wavemaker, as can be seen in Figure 1. The testing models made of acrylic material with a thickness of 5 mm and a dimension of 25 x 25 x 52 mm, as shown in Figure 2.

Figure 1. Photos of laboratory wave flume

The wave generator used in the tests was a piston-type wave maker. The changes in the free surface of the water in the canal due to waves and water surface fluctuations in the water column measured using the HC-SR04 ultrasonic sensor with range detection between 2 cm to 400 cm. The BMP180 barometric pressure sensor was placed at the top of the air column to measure barometric pressure changes that occurred in the air column. Whereas, air velocity through air exhaust duct was measured using the CEM DT-8880 hot wire anemometer, which has air velocity reading range 0.1 - 25 m/s. All signals read by the sensors were converted into digital data by a data logger and stored in the CPU of the computer unit, as shown in Figure 3. For further details in data collection, in Figure 4, a flow chart is displayed for the treatment given by the OWC device.

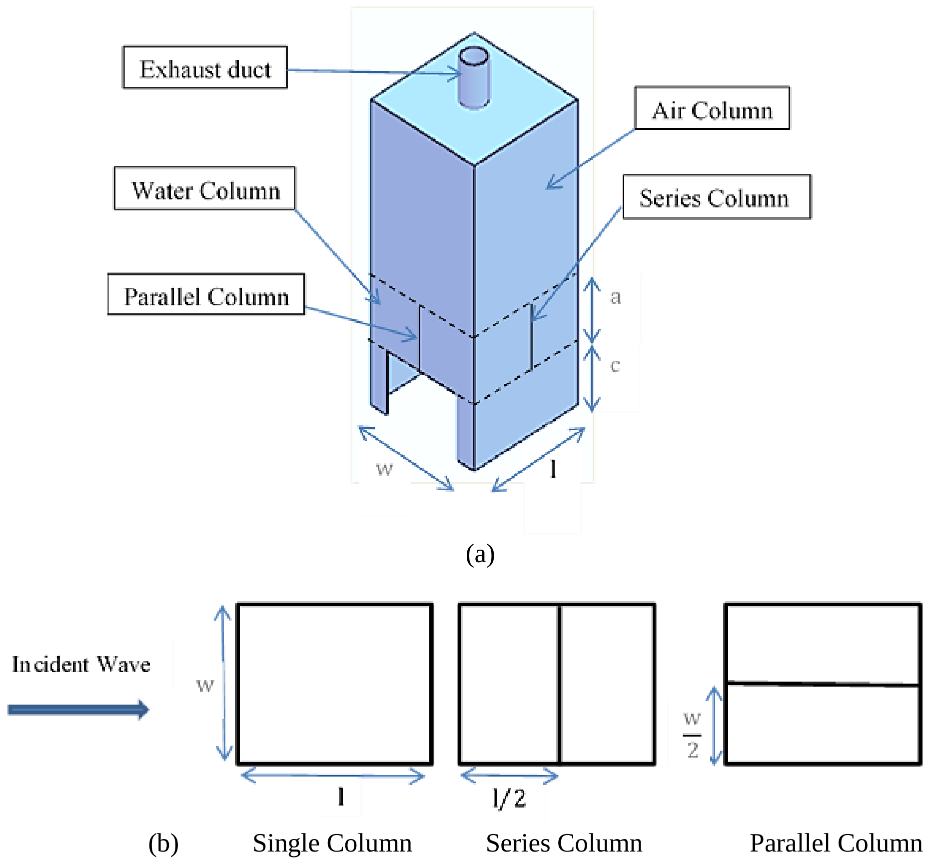


Figure 2. (a) OWC device and (b) Cross section of the water column SCOWC and DCOWC

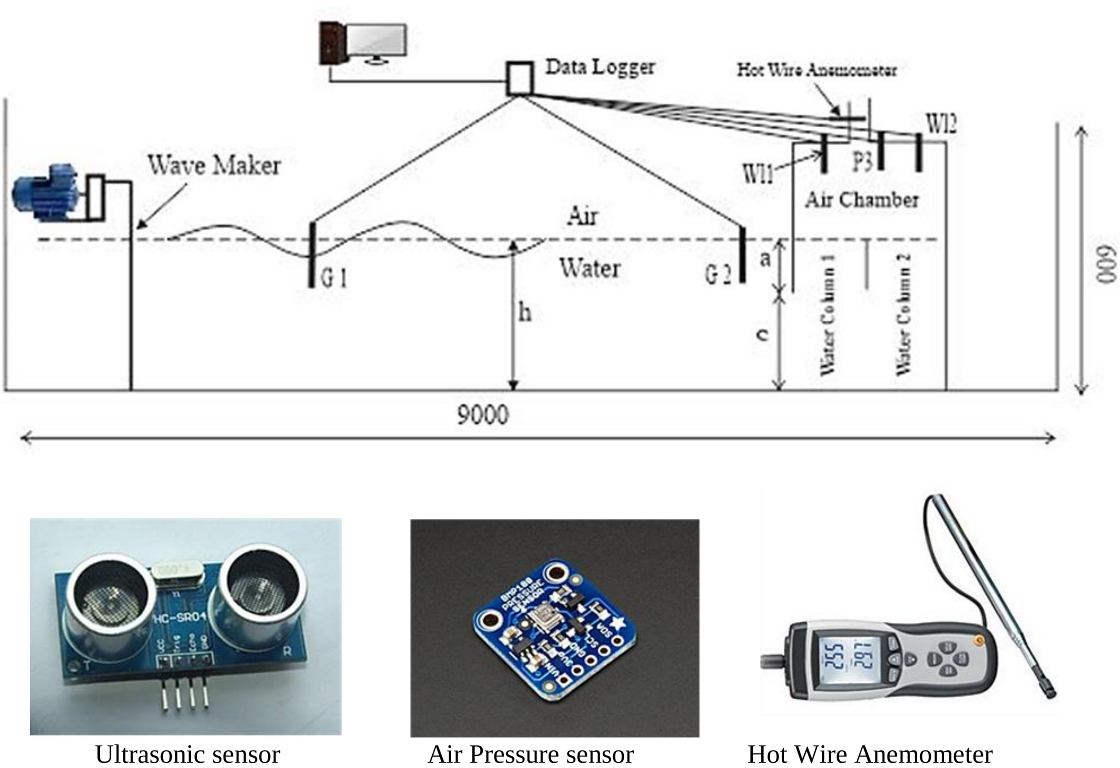


Figure 3. The sketch of experiment set up

Figure Legend: G1, G2 = Wave height used Ultrasonic sensor
Wl1, Wl2 = water surface fluctuations used Ultrasonic sensor
P3 = Air pressure sensor
Hot Wire Anemometer = Air velocity sensor

The dimensions of the OWC model are determined in accordance with the results of previous studies which stated the maximum efficiency of energy conversion is in the range of column width (w) = 0.92h [6] and the length of the submerged front wall (a) = 0.45 h [6,16].

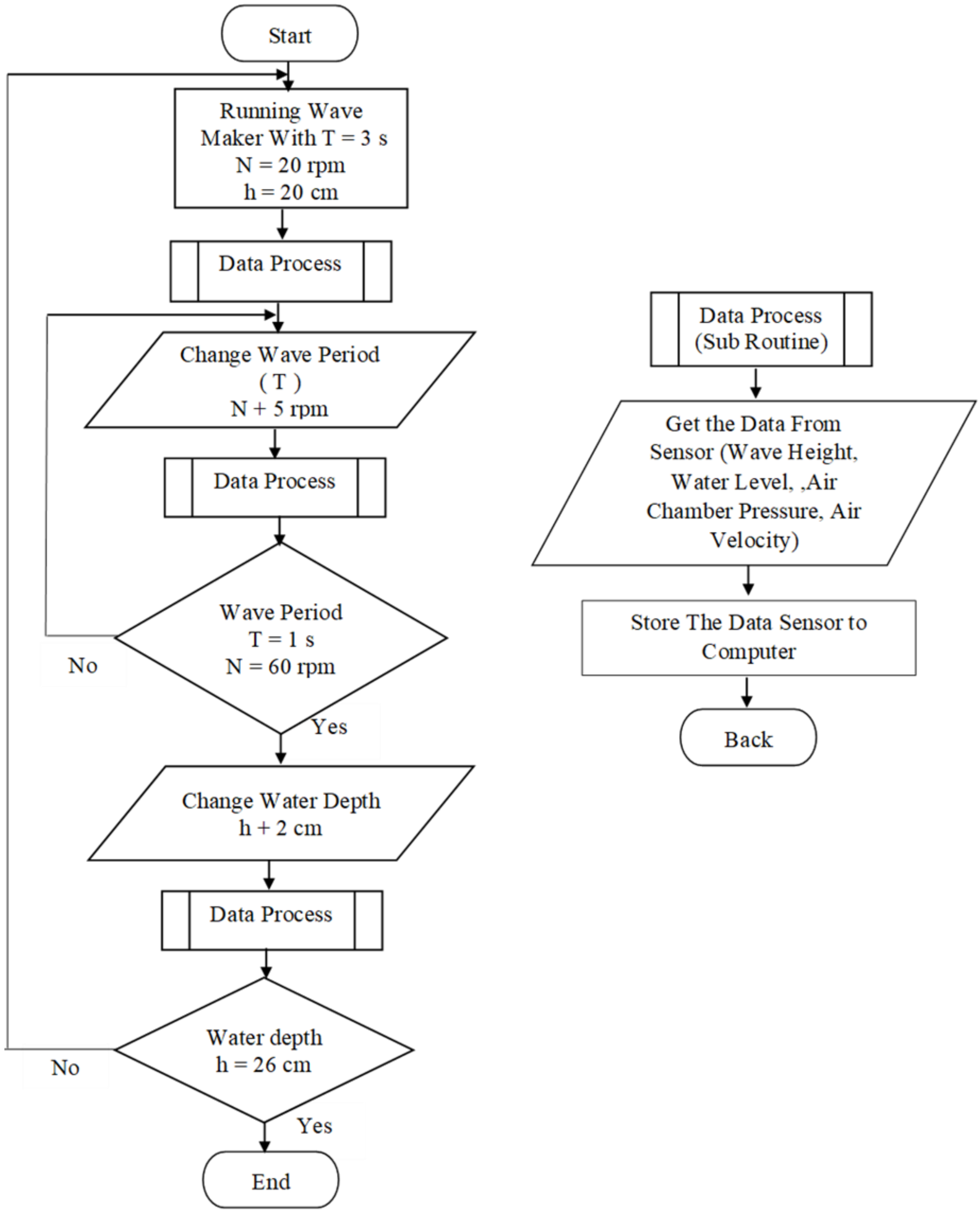


Figure 4. Flow chart the process in retrieval data

RESULTS

The Average Velocity of Air Coming Out Through the Exhaust Duct

In general, changes in the average velocity of air that flows through the air exhaust duct, which is the parameter for the efficiency of OWC devices, are influenced by wave characteristics, geometric shape of OWC, and air exhaust system [2, 3, 17]. In this study, several wave characteristics tested at water depths of 20 cm, 22 cm, 24 cm, and 26 cm for the wave period of 1 second to 3 seconds in three geometric shapes of water columns with the same exhaust duct dimension in all testing conditions. Figure 5 presents a graph of the average velocity of air that flowed through the exhaust ducts of the three types of water column testing models of the OWC devices, namely, single water column, double water column arranged in series, and double water column arranged in parallel.

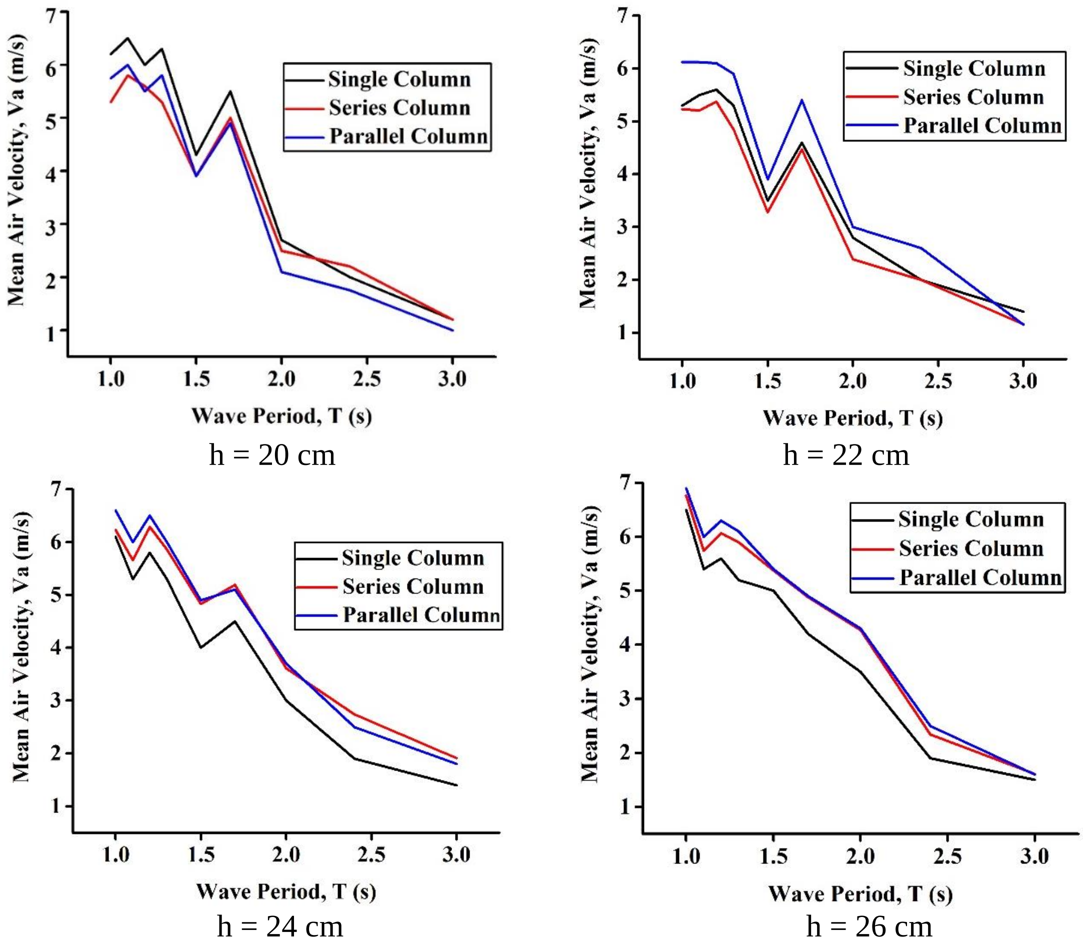


Figure 5. Mean air velocity versus wave period for several depth with array of water column

The graph in Figure 5 shows at 20 cm water depth, the maximum air velocity in the exhaust duct of the single water column is 6,5 m/s better than that of the double water column in both series and parallel arrangement with a maximum air velocity respectively of 5,8 and 6 m/s. Then at 22 cm water depth there was a change, namely two parallel columns of water resulting in a maximum air velocity of 6.12 m / s followed by one column of water of 5.6 m / s and two columns of a series arrangement of 5.4 m / s. However, at 24 to 26 cm water depth, the highest maximum air velocity was in the double water column in a parallel arrangement of 6,9 m/s, followed by maximum air velocity in double water column arranged in series of 6,76 m/s and single water column of 6,5 m/s. The pattern of air velocity changes in the three geometric shapes of the water columns showed the same tendency, although the results were different in the wave period of 1 second to 3 seconds. The results indicated the DCOWC devices could absorb better wave energy at deeper water depths than the SCOWC device. The results are in line with research Dorrell et al. [12], who have stated that adding the number of water columns increase the effectiveness of wave energy absorption in a multi-chamber oscillating water column.

The geometry changes from one water column to two water columns arranged in both series and parallel caused significant air velocity change during the wave periods 1.3 and 1.7 seconds at water depths of 20 cm, 22 cm, and 24 cm. These results showed that in those wave periods, the absorption of wave energy was better. Except at 26 cm water depth, power produced by OWC device increased consistently from the wave period of 2.4 seconds to 1.3 seconds. The power absorbed by the OWC device shown in Figure 6, which is calculated based on Eq. (1) [19].

$$P_{owc} = V\left(\rho_a \frac{V^2}{2}\right)\left(\frac{\pi D^2}{4}\right) \qquad (1)$$

where V is the velocity of the air coming out of the exhaust duct (m/s), ρ_a is air density (kg/m3), and D is diameter of the exhaust duct (m).

Another highlight results, at a water depth of 20 cm, it sawed that a single column OWC can absorb the energy of 0.16 watts, better than a double column parallel arrangement of 0.13 watts and a series arrangement of 0.11 watts. At a water depth of 22 cm, OWC double column parallel arrangement becomes the best with energy absorption of 0.14 watt followed by a single column of 0.11 watt and double column series arrangement of 0.09 watt. At water depths of 24 and

26 cm has a same trend where the OWC double column parallel arrangement can absorb the highest energy of 0.20 watt, followed by a double column series arrangement of 0.19 watt and a single column of 0.16 watt. This change of power absorption is closely related to the pattern of barometric pressure changes in the column due to water-level fluctuations in the air column. Barometric pressure changes at depths of 20 cm, 22 cm, 24 cm, and 26 cm shown in Figure 7. The Figure 7 shows that the pattern of pressure changes at depths of 20 cm and 22 cm were different from pressure changes at depths of 24 cm and 26 cm. This difference was because of the increase of wave energy due to the increase in water depth.

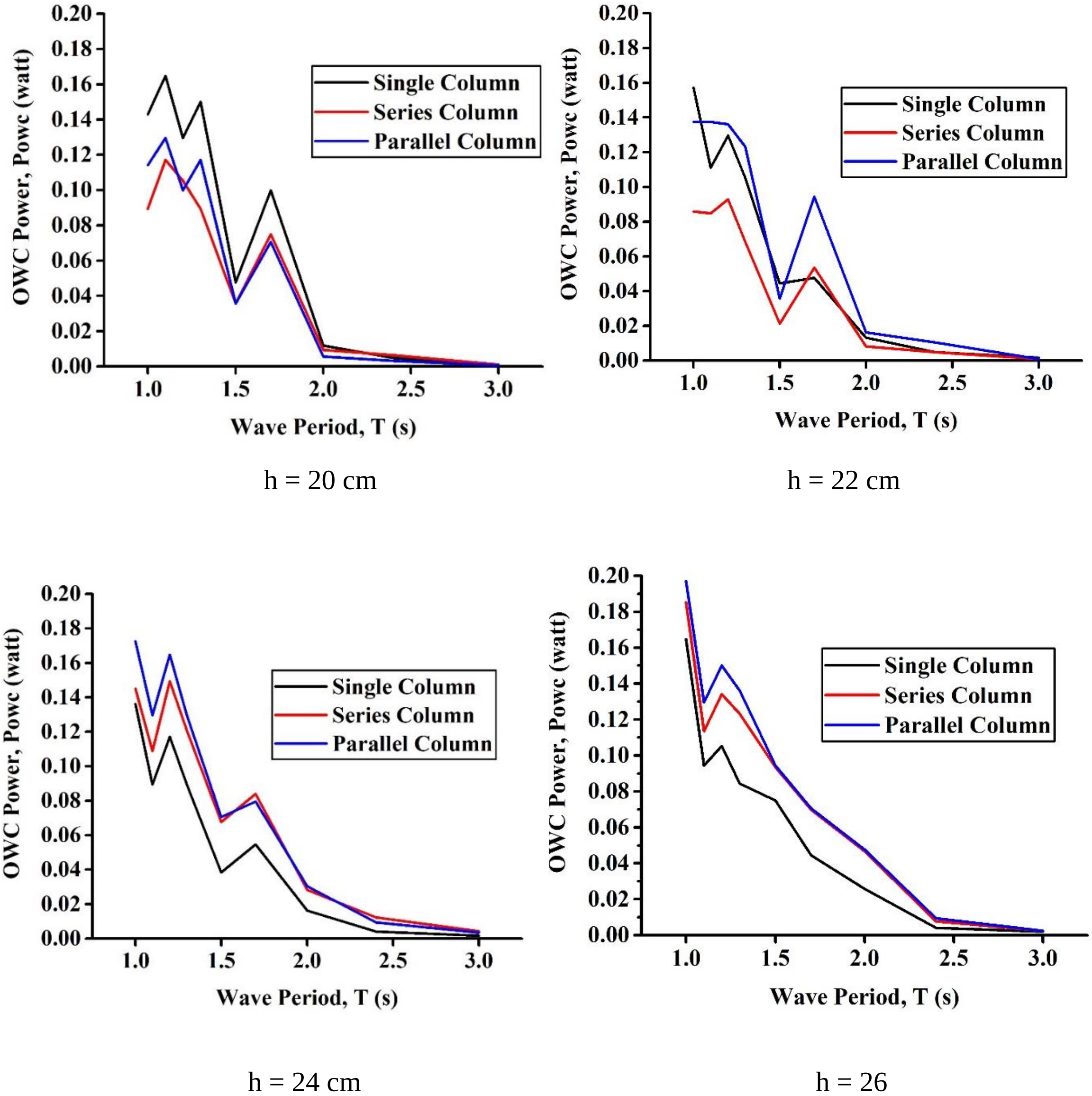


Figure 6. OWC power vs wave period for several depth with array of water column

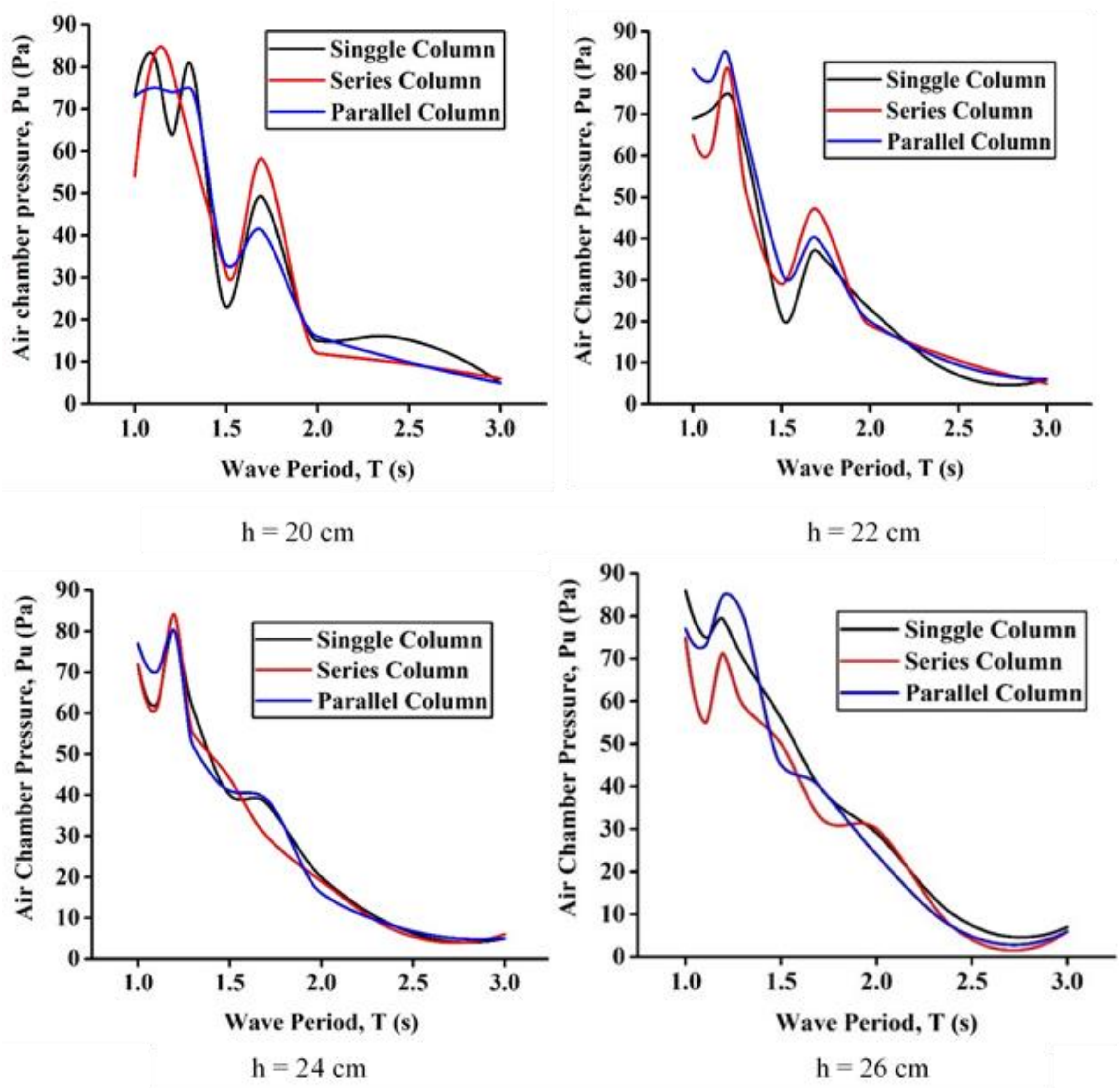


Figure 7. Air chamber pressure vs wave period for several depth with array of water column

Referring to the results of research conducted by previous researchers, air pressure changes in the air column become very large when resonance occurs [8, 19, 20]. The results of this study were very consistent with this finding. It can prove by the occurrence of the beating phenomenon in the 1.7 seconds of wave period. Beating phenomenon is another form of resonance [20], and in this study, it could even be considered to be resonance because it characterized by the pattern of regular air pressure changes in the 1.3 seconds of wave period as it shown in Figure 8.

Comparison of air velocity changes in the exhaust ducts of the three testing models as a result of the incident wave characteristics and geometry changes in the testing models will discussed in section below.

DISCUSSION

The Effect of Wave Characteristic

According to Celik et al. [21], the surface profile of the water column is strongly related to the frequency of incoming waves that enter through the duct into the OWC device. The wave frequency, in reality, is closely related to water depth and wavelength so water depth and wavelength also determine barometric pressure changes in the air column. To analyze the effect of wave characteristics on power absorption effectiveness that occurred in SCOWC and DCOWC devices in both series and parallel arrangement, non-dimensional kh parameters used, where $k = \frac{2\pi}{L}$ d and h is water depth. The results shown in Figure 9.

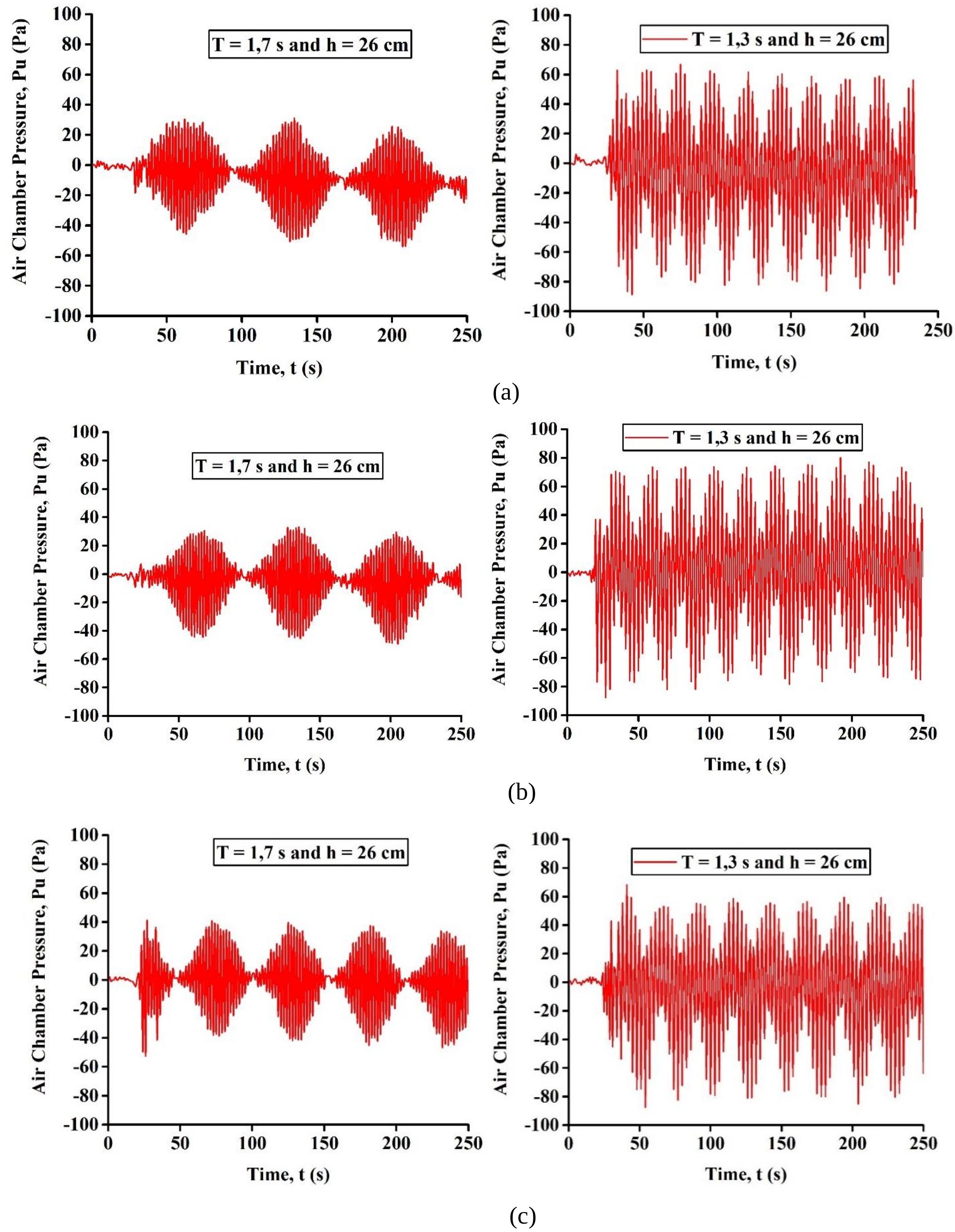


Figure 8. Air chamber pressure for (a) single column, (b) series column, (c) parallel column

The hydrodynamic power of the device (P_{OWC}) was calculated by Eq. (1) while wave power (P_W) was calculated by Eq. (2) [19].

$$P_w = \frac{1}{32\pi} \rho_w g^2 H^2 T.w \tag{2}$$

where ρ_w is water density (kg/m^3), g is gravitational acceleration (m/s^2), H is the height of the wave (m), T is wave period (second), and w is the width of the column (m).

In Figure 9, it can see that both SCOWC and DCOWC that arranged in series and parallel tended to change the absorption of the same wave energy due to wave characteristics changes. Furthermore, the maximum value of wave power absorption occurred in the kh range 0.7 to 0.9. The test results show that if the water depth increases in the range of kh 0.7 to 0.9, then the performance of the double chamber oscillating water column (DCOWC) device is better than the single chamber oscillating water column (SCOWC) device with maximum efficiency for the parallel arrangement 22,4%, series arrangement 20.8% and single column 20.7%. This result corresponded to the result reported by Sundar et al. [10], which stated that the maximum absorption of wave energy occurs at h/L of around 0.131 (kh = 0.82). However, there was a significant difference between the three models tested. The DCOWC device arranged in parallel had more stable absorption power compared to the two other devices. This result has shown that the DCOWC device in parallel arrangement could absorb wave power for a broader range of wave frequencies. It can also see that in the kh range 0.3 to 0.5, absorption of wave power by the three OWC device models was deficient and as the kh value increased to more than 0.9, the absorption of wave power decreased.

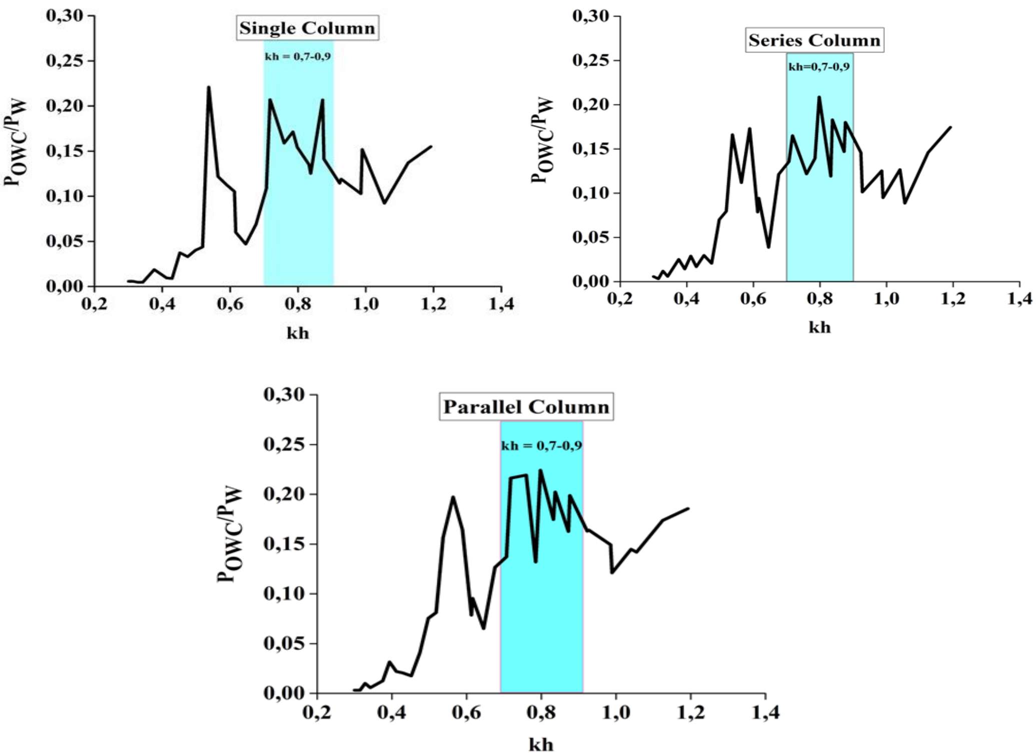
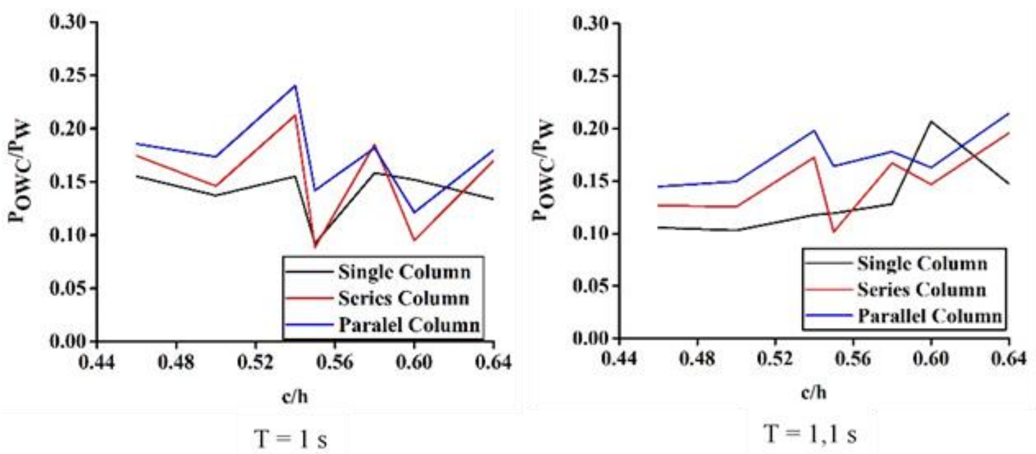


Figure 9. Effect wave characteristic on wave power absorption at single and double column

The Effect of Inlet Openings Ratio (c/h)

In addition to the effect of dynamic pressure, the width inlet valve of the OWC device also related to the magnitude of the force acting to produce fluctuations on the surface water column. Therefore, in this study a discussion of the relationship of non-dimensional c/h factors to the absorption of wave power was conducted by SCOWC and DCOWC are series and parallel arrangements, as shown in Figure 10.



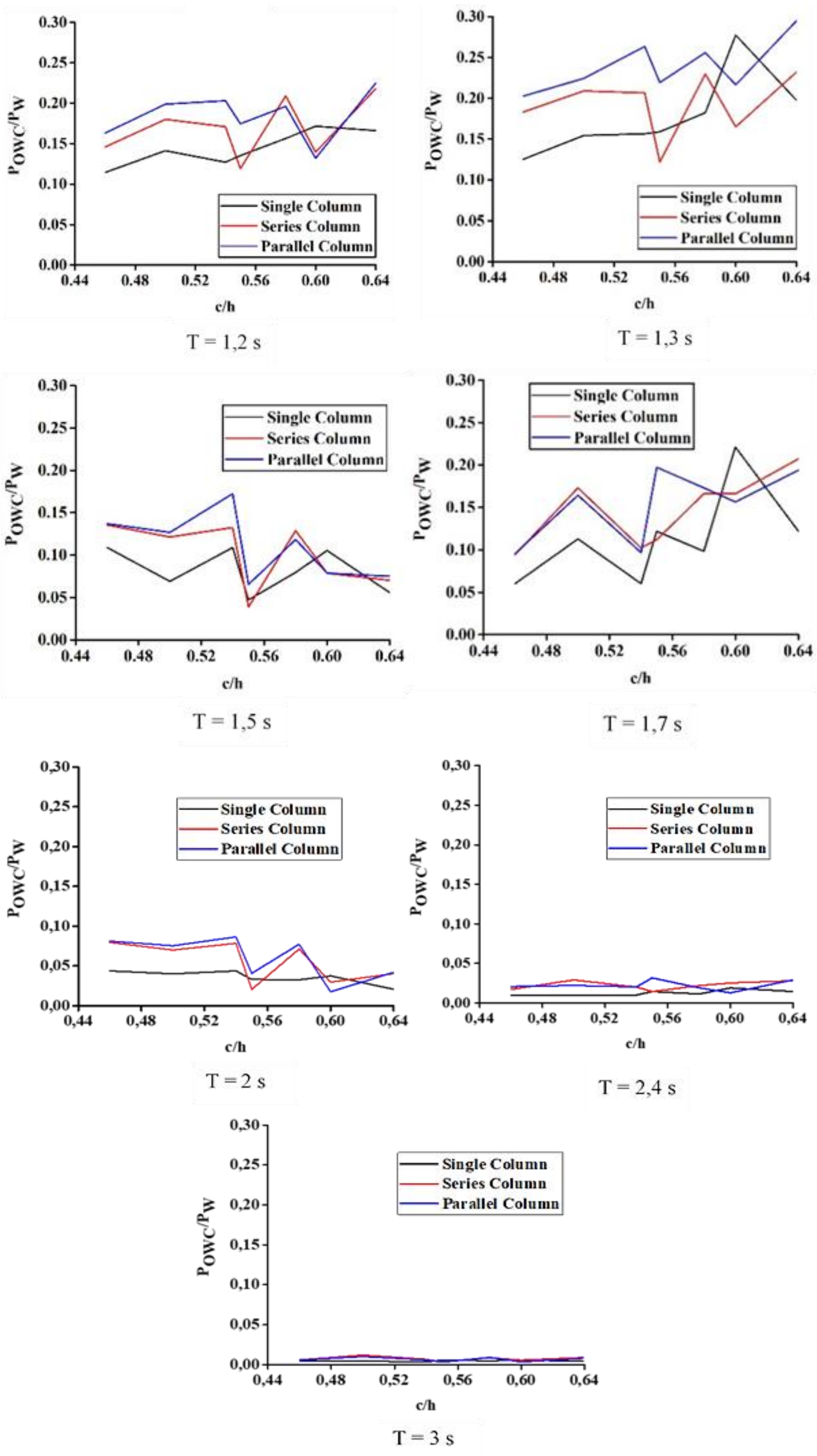


Figure 10. Effect of opening channel ratio on wave power absorption at single and double chamber

Figure 10 shows that the pattern of power absorption changes in SCOWC was different from those in DCOWC devices arranged in both series and parallel. This result indicated a difference in force due to the pressure acting on the inlet of each column. Theoretically, it can explain that the larger the inlet is, the higher the force that occurs. Therefore, it can see that the larger the inlet opening ratio (c/h) was, the higher the wave power absorbed by the OWC device.

The greatest power absorption occurs in the wave period T = 1.3 s. For SCOWC it occurs at c/h 0.6 with an efficiency of 27.7% but for DCOWC the series and parallel arrangement at c/h 0.64 with efficiency for series arrangement 23.2% and parallel arrangement 29.5%. This result explained that DCOWC parallel arrangement devices had better power-absorbing effectiveness when higher wave power was available. Dean et al. [22] in their book on the mechanics of water waves have explained that the forces acting on a structure are largely determine d by the dynamic pressure around it this explanation expressed in Eq. (3).

$$p\,(x,z,t) = \frac{\rho g H \cosh k(h+z)}{2\cosh kh}\cos(kx-\omega t) \tag{3}$$

Equation (3) shows that there was no dynamic pressure variation in *the* y-direction. This result confirmed that dynamic pressure only determined by height and wavelength. For the specific area in the OWC device's water column inlet, the total pressure force in that area expressed in Eq. (4).

$$F_1 = \frac{w\rho_w g H \cos(kx_1-\omega t)}{2\cosh kh}\int_{-c/2}^{c/2}\cosh k(h+c)dc \tag{4}$$

Because waves propagated in x-direction, the total pressure force on the back wall (F_2) was:

$$F_2 = \frac{w\rho_w g H}{2\cosh kh}\,cos[k(x_1+l)-\omega t]\int_{-c/2}^{c/2}\cosh k(h+c)dc \tag{5}$$

where w and c are the width and the height of the inlet while x is the location of the pressure force.

From the equation above, it is clear that the inlet valve ratio (c/h) significantly affected the magnitude of the compressive strength as a function of the dynamic pressure acting on the inlet. Also, it should be noted that because the compressive strength works according to the length of the column, the position of the compressive strength also affects the magnitude of the compressive strength. This condition causes differences in the amount of power that can be converted by SCOWC device and DCOWC devices, both in series and parallel arrangement, as a result of the correlation between variables.

CONCLUSIONS

The analysis in this study involved 9 series of wave periods, 4 variations of water depths, and 7 ratios of wave inlet valves. From the analysis, increasing the water depth would result in the largest air velocity coming out of the exhaust duct. The largest velocity was achieved by double water column device arranged in parallel, followed by double water column device arranged in series and single water column device. Furthermore, compared to the two other forms of devices, double water column device in parallel arrangement had the ability to absorb wave power in a wider frequency range. The test results show that if the water depth increases in the range of kh 0.7 to 0.9, then the performance of the double chamber oscillating water column (DCOWC) device is better than the single chamber oscillating water column (SCOWC) device with maximum efficiency for the parallel arrangement 22,4%, series arrangement 20.8% and single column 20.7% .Several wave periods were tested and the largest absorption of wave power by SCOWC occurred at T = 1.3 s and c/h = 0.6 with efficiency 27,7 % while by DCOWC in series and parallel arrangements occurred at T = 1.3 s and c/h = 0.64 with efficiency 23,2 % and 29,5 %.

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