Energy harvesting capability of single-chamber oscillating water column wave energy device model on controlled wave height and period

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Abstract. The urgency of electricity demand and environmentally friendly power generator made ocean wave energy as one of many renewable energies that could be implemented in Indonesia because many of its coastlines have the power enough to generate electricity locally and regionally. This research is mainly discussing the model’s capability to generate electricity based on various wave height and period. This energy harvester model made in the laboratory with 1:16 scale, so the other variable component also following this scale. The turbine used in this experiment using Wells turbine with seven blades following the profile guidelines of NACA 0024. The result of this research shows that the power generated by the turbine correlates to wave height and wave period. The output generated by this energy harvester model could achieve 21.2 kilowatts in one hour on average or 339.4 kilowatts in one hour if upscaled to its real size.

Keywords: Energy Harvester, Renewable Energy, Oscillating Water Column.

1. Introduction
Southeast Asian countries are facing a “trilemma”—the need to deliver on energy security, economic growth, and development in a sustainable way [1]. As a member of Southeast Asian countries, Indonesia also facing the same problem regarding energy security as mentioned by Lelly et al. [2016], Indonesia’s electricity demand grows each year alongside the population growth [2].

Not only to fulfill the electricity demands in the big cities and industrial areas, but Indonesia is also required to satisfy the electricity needs in the 3T (frontier, outermost, and least developed) areas. As one of the largest archipelagic countries, Indonesia has many islands in which most of them are remote but still inhabited by locals. Those inhabited remote islands almost always have the same problems: coastal erosion and limited electricity. OWC devices can be the solution to these problems because this device can also act as a breakwater to protect the area behind it while also harvesting the energy from the waves [10].

The energy contained in the oceans varies greatly, some of which are ocean current energy, wind energy, and tidal and wave energy. Wave energy is adequately used in electricity generation because the power potential contained in wave energy is promising. The remarkable property of water waves, once created by the wind, to propagate energy over very long distances with little loss has naturally given rise to the desire to harness this energy and convert it to a useful form [5].

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As briefly mentioned earlier, to convert wave energy into electrical power, one can use an Oscillating Water Column (OWC) system. This system includes three energy converting stages: 1) the OWC inside a chamber forces air alternately into and out of the atmosphere through the duct. 2) a turbine with symmetric blades transforms the bi-directional airflow energy into torque. 3) an electricity generator linked to the turbine transforms the torque into electrical power \cite{3}. This device also can use a water turbine to extract wave energy \cite{9}.

The efficiency of oscillating water column (OWC) wave energy devices equipped with Wells turbines is particularly affected by flow oscillations basically for two reasons. First, because of the intrinsically unsteady (reciprocating) flow of air displaced by the oscillating water free surface. Second, because increasing the air flow rate, above a limit depending on, and approximately proportional to, the rotational speed of the turbine, is known to give rise to a rapid drop in the aerodynamic efficiency and in the power output of the turbine. There are plenty of solutions to overcome this obstacle, some of which are determining the turbine’s inlet diameter, creating an auxiliary outlet or air valves to control excess air flow, determine the blades’ profile, and so on \cite{7}. But these are not the topic of the present study.

The main purpose of this work is to analyze the single-chamber OWC harvesting capability on various wave height and period. Tested in laboratory conditions, and using in-house built OWC model and 3D printed bespoke Wells turbine model. The tests consist the total of twenty-two variables of wave height and period to observe the energy harvested by the device. The forces acting on the turbine also analyzed using CFD software to calculate the torque produced by the turbine.

2. Experimental study

2.1. OWC chamber model

The OWC model has slanted front and rear side intended to reduce wave reflection and ease the wave force received by the model so it won’t break mid testing. The OWC model fixed to a seating mount so it won’t move while tested with stronger waves. A schematic of the OWC chamber is shown in Figure 1, where \( L_f \) denotes the chamber width, \( D_s \) is the draft of the chamber skirt, \( \alpha \) is the angle of the chamber’s slope, \( D_w \) is the still water depth, \( W \) is the length of the chamber, and \( h_f \) is the height of the model. The dimensions of the chamber are summarized in Table 1. The incident wave conditions employed by this experiment are summarized in Table 2. \( H_m \) denotes the incident model wave height, \( H_p \) is incident full scale wave height, \( T_m \) and \( T_p \) are for incident wave period at model and full scale respectively.

![Figure 1. Schematics of the oscillating water column energy device model.](image1)

![Figure 2. Side profile of the oscillating water column energy device model.](image2)
Table 1. OWC device dimensions.

|        | Lf    | Ds   | Dw   | hf   | W    | α     |
|--------|-------|------|------|------|------|-------|
| Model Scale | 0.48 m | 0.22 m | 0.6 m | 0.82 m | 0.96 m | 60°   |
| Full Scale | 7.68 m | 3.52 m | 9.6 m | 13.12 m | 15.36 m | 60°   |

Table 2. Summary of incident wave conditions setup

(a) Incident wave height

|        | Model Scale, Hm | 0.15m | 0.075m |
|--------|-----------------|-------|--------|
| Full Scale, Hp | 2.4m | 1.2m   |

(b) Incident wave period

|        | Model Scale, Tm | 1.4s  | 1.5s  | 1.6s  | 1.7s  | 1.8s  | 1.9s  | 2.0s  | 2.1s  | 2.2s  | 2.3s  | 2.4s  |
|--------|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Full Scale, Tp | 5.6s | 6.0s | 6.4s | 6.8s | 7.2s | 7.6s | 8.0s | 8.4s | 8.8s | 9.2s | 9.6s |

Figure 3. Schematics of Wells turbine rotor

Figure 4. Schematics of the turbine housing

Table 3. Summary of turbine dimensions

(a) Turbine rotor dimensions

|       | Rt    | Rh    |
|-------|-------|-------|
| Model Scale | 50 mm | 20 mm |
| Full Scale  | 800 mm | 320 mm |

(b) Turbine housing dimensions

|       | Din   | Dout  |
|-------|-------|-------|
| Model Scale | 90 mm | 110 mm |
| Full Scale  | 1440 mm | 1760 mm |

2.2. Wells turbine model

The Wells turbine model made using 3D printed ABS plastic filament. The rotor’s blade designed following NACA 0024 profile and having seven blades. The study for blade profile and number has been conducted by Bagus et al. [2015], analyzing the optimum blade profile and number to be used in OWC devices. Schematics of turbine rotor and housing shown in Figure 3 and Figure 4 respectively, Rh
denotes the hub radius, and Rt is tip radius. In Figure 4, Din denotes the inlet diameter, and Dout is outlet diameter. The dimensions of both schematics are summarized in Table 3.

Wells turbine, which was invented by Prof. Alan Arthur Wells is the most common type of self-rectifying air turbine employed by OWC wave energy devices due to its technical simplicity, reliability, high rotational speed, and design robustness. The Wells turbine is an axial-flow air turbine composed of a rotor with fixed pitch symmetrical airfoil (commonly four digits, double zero, NACA profiles) blades staggered at 0° relative to the plane of rotation around the hub.

Due to the use of symmetrical airfoil blades about the chord line, Wells turbine rotates in the same direction by OWC’s cyclically reversing outlet flow. Figure 5 illustrates the forces acting on a blade of a Wells turbine and also the basic principle of unidirectional rotation of the Wells turbine.

Where $V_A$ indicates the inlet velocity, $V_T$ is the circumferential velocity at mean radius and $W_R$ is the relative airflow velocity. Angle of incidence, $\alpha$, is the angle between $W_R$ and blade chord, $F_L$ is the lift force normal to the $W_R$, and $F_D$ is the drag force parallel to $W_R$. The forces $F_L$ and $F_D$ are resolved into the axial force, $F_A$ and tangential force, $F_T$, where $F_T$ direction is independent of the axial flow direction.

![Figure 5. Aerodynamic forces acting on a blade of a Wells turbine rotor](image)

3. Methods

The experiment was conducted in the 24 m long, 1 m wide, and 1.2 m deep wave flume of the Ocean Engineering Department, Engineering Faculty of Hasanuddin University. The OWC model is made of 120 mm thick plywood and polymethyl methacrylate (PMMA) acrylic acting as the front plate. Incident and transmitted waves are measured with five wave probes starting from the front of the wavemaker to the front of the model. The testing variables are as shown in Table 2.

![Figure 6. Experiment setup](image)

After wave conditions have been set for the OWC device model inside the flume tank, the experiment could begin. From the wave data, the energy harvest rate could be determined. The wind speed data obtained by using an anemometer near the turbine inlet to determine the torque of the rotor and
numerically analyze the force acting on each blades using Computational Fluid Dynamics (CFD) software. The power generated by this model is obtained using an electrical multitester device connected to the turbine’s dynamo to obtain voltage, and electric current to be used to calculate the power generation.

4. Experiment data processing

The experiment data summarized in Table 4 and Table 5 are showing the energy harvested by this OWC model, also the lift and torque of the turbine. T denotes wave period, Hi is the incident wave height in running conditions, λ is the wavelength, PW is the wave power captured by the OWC model, U is wind speed, FL is lift force of the rotor’s blade, τ is the torque of the turbine, and PE is the electrical power generated by the turbine.

The incident wave in running conditions obtained by measuring the highest and the lowest wave height in front of the model using wave probe sensor to later calculated using this formula,

\[ Hi = \frac{H_{max} + H_{min}}{2} \]  

(1)

the wave length obtained from iterating the formula,

\[ L = \frac{gT^2}{2\pi} \tanh \frac{2\pi d}{L_0} \]  

(2)

the still water depth is denoted by d, and L0 can be obtained using the following formula,

\[ L_0 = 1.56T^2 \]  

(3)

for wave power can be calculated by using this formula,

\[ P_W = \left( \frac{\rho g a^2 W}{2} \right) \left( \frac{\lambda}{T} \right) \]  

(4)

to calculate the torque of a blade, this formula is used,

\[ \tau = F_\theta \cdot R \]  

(5)

where F_\theta is the tangential force, calculated using,

\[ F_\theta = F_L \sin \alpha - F_L \cos \alpha \]  

(6)

where,

\[ \rho \] = Sea water density (kg/m^3)  
\[ g \] = Gravitational acceleration (m/s^2)  
\[ a \] = Amplitude of incident wave (m)  
\[ W \] = Length of the model chamber (m)  
\[ \lambda \] = Wave length (m)  
\[ T \] = Wave period (s)  
\[ F_L \] = Lift force (N)  
\[ R \] = Blade length (m)  
\[ \alpha \] = Angle of attack
The lift force for each blade could be acquired using ANSYS Fluent with predetermined wind speed variables from the experiment conducted beforehand. Figure 7 visualise the wind forces acting on one blade. The torque shown below in Table 4 and Table 5 are already in total from all seven blades.

**Figure 7. CFD simulation for turbine blade**

The lift force for each blade could be acquired using ANSYS Fluent with predetermined wind speed variables from the experiment conducted beforehand. Figure 7 visualise the wind forces acting on one blade. The torque shown below in Table 4 and Table 5 are already in total from all seven blades.

**Table 4. Summary of OWC model test result with 0.15 m wave height**

| T (s) | Hi (m) | λ (m) | P_W (Watt) | U (m/s) | F_L (N) | τ (Nm) | P_E (Watt) | P_E/P_W (%) |
|-------|--------|-------|------------|---------|---------|--------|------------|-------------|
| 1.4   | 0.16   | 2.71  | 59.61      | 1.82    | 2×10^-4 | 4.47×10^-3 | 0          | 0           |
| 1.5   | 0.17   | 2.99  | 72.99      | 3.59    | 8.65×10^-4 | 1.93×10^-4 | 2×10^-3 | 2×10^-3   |
| 1.6   | 0.18   | 3.27  | 76.55      | 5.59    | 2.3×10^-3 | 5.14×10^-4 | 0.55       | 0.72        |
| 1.7   | 0.17   | 3.55  | 73.46      | 7.41    | 4.3×10^-3 | 9.59×10^-4 | 0.68       | 0.92        |
| 1.8   | 0.14   | 3.82  | 53.36      | 8.16    | 5.31×10^-3 | 1.19×10^-3 | 0.26       | 0.49        |
| 1.9   | 0.25   | 4.09  | 161.63     | 10.48   | 9.19×10^-3 | 2.05×10^-3 | 1.21       | 0.75        |
| 2.0   | 0.17   | 4.36  | 77.33      | 9.60    | 7.58×10^-3 | 1.69×10^-3 | 0.45       | 0.58        |
| 2.1   | 0.28   | 4.63  | 210.81     | 14.92   | 1.99×10^-2 | 4.45×10^-3 | 5.41       | 2.57        |
| 2.2   | 0.18   | 4.89  | 87.66      | 10.45   | 9.13×10^-3 | 2.04×10^-3 | 0.07       | 0.08        |
| 2.3   | 0.33   | 5.15  | 291.77     | 14.16   | 1.75×10^-2 | 3.91×10^-3 | 5.89       | 2.02        |
| 2.4   | 0.20   | 5.41  | 108.32     | 13.11   | 1.49×10^-2 | 3.32×10^-3 | 0.53       | 0.49        |
Table 5. Summary of OWC model test result with 0.075 m wave height

| T (s) | Hi (m) | λ (m) | P_W (Watt) | U (m/s) | F_L (N) | τ (Nm) | P_E (Watt) |
|-------|--------|------|------------|--------|--------|--------|-----------|
| 1.4   | 0.069  | 2.71 | 11.16      | 1.32   | 1.05×10^{-4} | 2.34×10^{-5} | 0         |
| 1.5   | 0.090  | 2.99 | 19.70      | 2.90   | 5.43×10^{-4} | 1.21×10^{-4} | 0         |
| 1.6   | 0.081  | 3.27 | 16.28      | 4.07   | 1.14×10^{-3} | 2.55×10^{-4} | 0         |
| 1.7   | 0.077  | 3.55 | 15.19      | 4.41   | 1.36×10^{-3} | 3.04×10^{-4} | 0         |
| 1.8   | 0.069  | 3.82 | 12.31      | 4.93   | 1.74×10^{-3} | 3.89×10^{-4} | 0         |
| 1.9   | 0.098  | 4.09 | 24.89      | 7.46   | 4.36×10^{-3} | 9.73×10^{-4} | 0         |
| 2.0   | 0.070  | 4.36 | 13.02      | 5.56   | 2.27×10^{-3} | 5.07×10^{-4} | 0         |
| 2.1   | 0.120  | 4.63 | 38.75      | 9.30   | 7.07×10^{-3} | 1.58×10^{-3} | 0         |
| 2.2   | 0.071  | 4.89 | 13.70      | 6.36   | 3.07×10^{-3} | 6.84×10^{-4} | 0         |
| 2.3   | 0.093  | 5.15 | 23.37      | 8.53   | 5.85×10^{-3} | 1.31×10^{-3} | 0         |
| 2.4   | 0.094  | 5.41 | 23.99      | 8.82   | 6.29×10^{-3} | 1.41×10^{-3} | 0         |

5. Results and conclusions

After forty-four different testings, the result of this experiment can be concluded. The wave energy harvest rate by this OWC model is shown in Figure 8. From the graph, we can see there are “spikes” in the fluctuation of energy harvested, and every 0.1-second difference in the period, the energy fluctuates. The highest energy harvest ratio achieved at period 2.1 second with a 2.57 % conversion rate from wave power to electricity.

For harvesting capability on 0.075 m wave height setup, this model with current design iteration and testing variables could not convert any wave power into electricity. Another design approach is necessary for future research, such as reducing the turbine diameter, widens the chamber width, or change the model into multi-chamber type OWC device.

The torque achieved in Figure 9 could translate into how significant the conversion rates are. The highest torque achieved was 4.45×10^{-3} Nm in 2.1 s wave period, the conversion ratio from Figure 8 also achieved peak conversion in 2.1 s wave period. This could be mean that current blades profile is the most effective on converting high wind speed and the power produced doesn’t increase linearly in regards to wave periods, hence the need of inlet and turbine diameter adjustments, blades profile redesign, and oscillating chamber reconfiguration for future experiment.

Thus concludes this study, current design iteration still has its flaws and still have many areas that could be improved, but, according to a study conducted by Utami [2010], on Southern of Banten through Southern of East Java coastlines, this model with current design could still convert some energy although very little, theoretically.
Figure 8. Oscillating water column model harvesting capability on 0.15 m wave height

Figure 9. Maximum torque achieved on every wave period (0.15 m wave height)
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