The Performance evaluation of 30kW class OWC wave power plant integrated with breakwater

Kilwon Kim, Sewan Park, ChangHyuck Lim, Kyong-Hwan Kim, Seung-Ho Shin

***Abstract*— In 2016, Korea started to develop a 30kW class wave power plant connected to a breakwater. After designing, manufacturing and performance testing of each energy conversion device, a demonstration plant was installed in Mukri Port, Jeju Island, Korea in 2021. After passing the completion inspection of the power generation facility, a full-scale grid-connected trial operation began in October 2021. The power plant consists of a sloped Oscillating Water Column, impulse air turbine, permanent magnet synchronous generator, AC-DC converter, energy storage system and integrated control system.**

This study introduces the performance evaluation results based on real sea operation data. The performance evaluation of the wave power plant under various wave height and period conditions was performed to evaluate the output power and efficiency of each bin. In addition, performance evaluations were conducted according to wave direction and tidal conditions to examine the effects. The correlation coefficient was derived by analysing the correlation between wave height, period, wave directions, tide level and output power.

Keywords—Breakwater integrated WEC, OWC wave energy converter, Real-sea operating, Performance evaluation.

I. INTRODUCTION

Oscillating water columns (OWCs) are the most popular among various wave energy converters owing to their stable operating conditions. The primary advantage of OWC-type wave energy converters is that the energy converting equipment does not remain in contact with seawater. Moreover, the feature of generating electricity only by the air movement improves the life of the equipment significantly.

Thus far, numerous studies have investigated the operating performance of the air turbines used in OWC wave energy converters. Several researchers have optimized the impulse turbines using numerical and experimental methods [1–4]. For instance, the rotor shape of an impulse turbine was optimized using a numerical method. Additionally, the optimum number of blades and guide vanes along with optimal tip clearance ratios and angle of the guide vane have been reported. The maximum efficiency of the optimized impulse turbine was approximately 49%. Modified turbines, namely the ring-type and sweep-angle-type turbines, were proposed to improve the efficiency, and the ring-type turbine exhibited the best performance at 52% efficiency. Furthermore, a new turbine using rotor blades with non-zero setting angles was proposed.

Falcão reviewed the results of most studies on air turbines for OWC-type wave energy converters [5]. A Pico plant rated 400 kW was equipped with a Wells turbine and completed in 1999. This was followed by the LIMPET plant in 2000, equipped with a Wells turbine at a rated power of 500 kW. The Sakata plant in Japan, with a Wells turbine and rated power of 60 kW, initiated the integration of plants with breakwaters. The Mutriku plant in northern Spain is a typical breakwater-integrated plant that was completed in 2008. This plant comprises 16 chambers and 16 Wells turbines rated 18.6 kW for each system [6-9].

In this study, we analysed the results obtained from the Mukri plant, which is a 30kW class wave power plant connected to a breakwater. The performance evaluation of the wave power plant under various wave height and period conditions was performed to evaluate the output power and efficiency of each bin. In addition, performance evaluations were conducted according to wave direction and tidal conditions to examine the effects. The correlation coefficient was derived by analysing the correlation between wave height, period, wave directions, tide level and output power.

II. MUKRI POWER PLANT

Mukri power plant is a 30kW class wave power plant connected to the breakwater. The performance testing of each energy conversion device is performed in lab-scale

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such as OWC chamber, Impulse turbine and generator. The OWC chamber was designed in a slope shape in consideration of the cross section of the breakwater at the proposed site and the convenience of installation. A fixed guide vane type impulse turbine was selected, and a ring type impulse turbine was manufactured through optimal design. It is connected with Energy Storage System (ESS) system to overcome the fluctuation of wave power output. The generated power is converted into direct current through an AC (Alternating Current) - DC (Direct Current) converter and then stored in the ESS system. The system is designed to supply the required power to the grid using a power management system. The advantages of this system are like that DC voltage of the battery is stable due to its own voltage, and AC-DC converter has a relatively small decrease in efficiency even if the capacity is large. It can reduce the cost because only the AC-DC converter needs to be configured compare to the Back-to-Back power converting system. The grid connection diagram of a wave power plant is shown in Fig. 1.

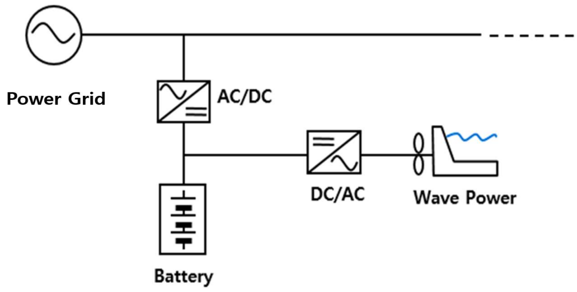

Fig. 1. Grid connection diagram of the wave power plant.

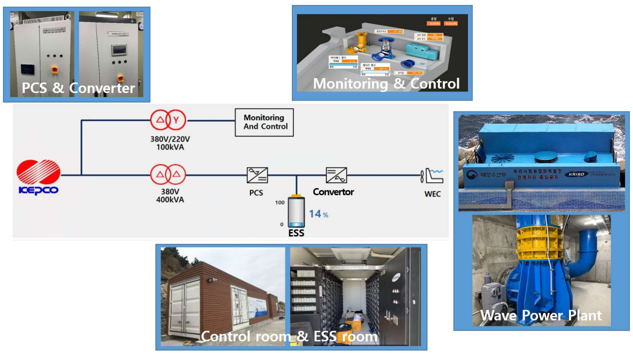

Fig. 2. System configuration of the wave power plant.

The system configuration of the wave power plant is shown in Fig. 2. The wave energy converter is fixed oscillating water column type. It consisted with slope shape OWC chamber, standing energy converting unit, and bypass system. The electrical power is transferred through a 300 m cable to the converter which is located in control room. The power converted to DC by the converter is stored in the ESS system, and the Power Conversion System (PCS) provides stable power to the grid. The capacity of turbine-generator system is 30 kW. Considering the variability of wave energy, the converter was designed with a capacity of 100 kW. The ESS is designed with a capacity of 1 MW, and the PCS for power control is designed with a capacity of 250 kW. All systems are remotely controlled by Supervisory Control and Data Acquisition (SCADA). The generator speed, chamber pressure and power were monitored and recorded in real time for performance evaluation.

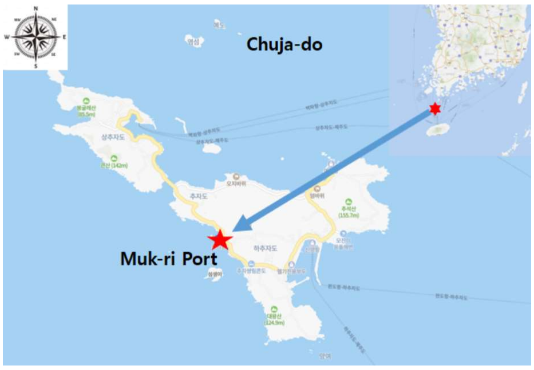

Fig. 3. Installed location of the wave power plant.

The power plant is installed in Chuja Island, Mokri port shown in Fig. 3. Chuja-do is an island between Jeju Island and the Korean Peninsula, about 50 km in a straight line from Jeju Island. The main direction of wave power plant is SW.

III. PERFORMANCE EVALUATION OF TURBINE-GENERATOR UNIT

The prototype of the energy converting unit consists of a ring type impulse turbine, a fixed guide vane, and a permanent magnet synchronous generator as shown in Fig. 4. The connection between the turbine and the generator is completed by a coupling. The diameter of the turbine is 0.8 m, and the diameter of the generator is 0.56 m. The total height of the energy converter is 3.56 m, and the total weight is 6,253 kg.

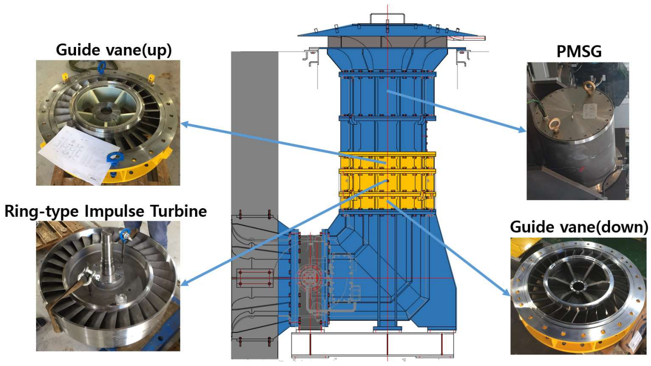

Fig. 4. Components of energy converting unit.

The energy converting unit is constructed in a standing type for space utilization and maintenance convenience. To monitor the condition of the energy converting unit during operation, temperature sensors were installed to measure the bearing temperature of the generator and turbine. Three 1-axis vibration sensors were installed on the top of the generator to measure the vibration of the generator and duct, and two 1-axis vibration sensors were installed to measure the vibration of the duct.

To evaluate the performance of the prototype energy converting unit, a large wind blower was used. To install the energy converting unit in the wind blower, a duct system and base were made. A CP210 Pitot tube velocimeter was used to measure the flow rate into the duct, and a D5151 pressure gauge was used to measure the pressure. To measure the output of the turbine, a TF213/014 flange-type torque sensor from MAGTROL was used to measure torque and rotational speed. All commercially available sensors were calibrated and certified. The schematic diagram of the experimental setup and the locations of the sensors are shown in the Fig. 5.

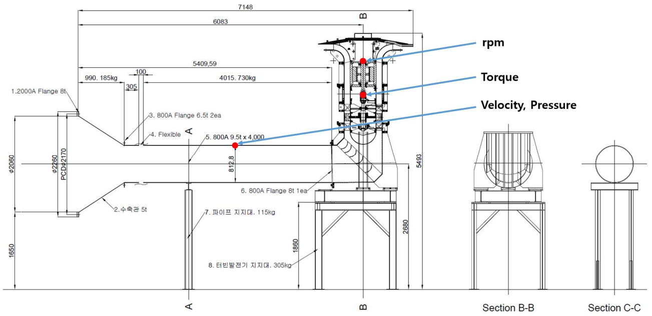

Fig. 5. Schematic diagram of the experimental setup.

The flow rate was generated by using a blower and input to the test device, and the pressure and flow rate in the duct were measured. For the output measurement, the generator load was applied using a variable resistance load, and the torque and rotational speed of the turbine according to the load were measured at a constant blower speed. Efficiency, torque coefficient, and input coefficient are defined as follows. Where Δp, Q, ρ_a, T represent total pressure drop between setting camber and atmosphere, air flow rate, air density and turbine output torque; v_a, r_R, ω, U_R, b and z represent mean axial flow velocity, mean radius, angular velocity of the turbine, circumferential velocity at r_R, blade height and number of rotor blades, respectively.

$$Eff. = \frac{Tw}{\Delta PQ} \tag{1}$$

$$C_A = \frac{2\Delta PQ}{\rho_a(v_a^2 + U_R^2)bl_r z v_a} \tag{2}$$

$$C_T = \frac{2T}{\rho_a(v_a^2 + U_R^2)bl_r z r_R} \tag{3}$$

Efficiency is expressed as the ratio of mechanical output to input energy. The torque coefficient is the dimensionless value of torque, and the input coefficient is the dimensionless value of input energy. The flow coefficient is the ratio of the input flow rate to the rotational speed. In the case of torque coefficient, it tends to increase with the increase of flow coefficient. It can be seen that the input coefficient converges at a certain flow coefficient. The efficiency expressed as the ratio of the torque coefficient and the input coefficient is the highest at a flow coefficient of 1. The maximum efficiency of this energy converting unit is evaluated to be 48.1%.

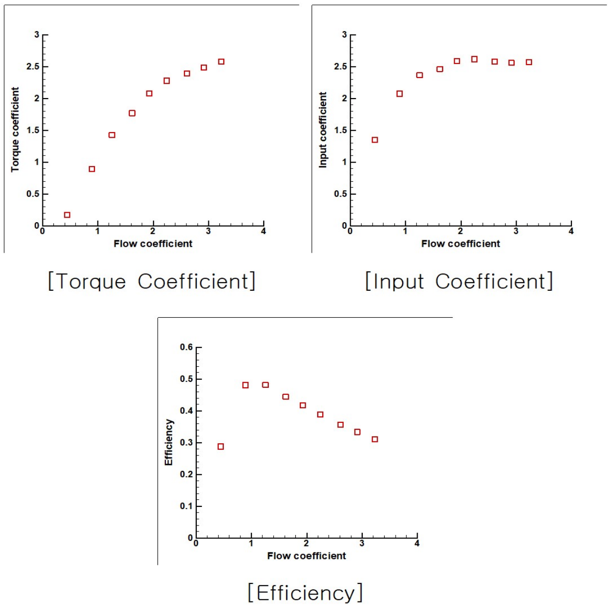

Fig. 6. Performance of energy converting unit.

IV. REAL-SEA OPERATING EVALUATION

A. *operating sequence and data*

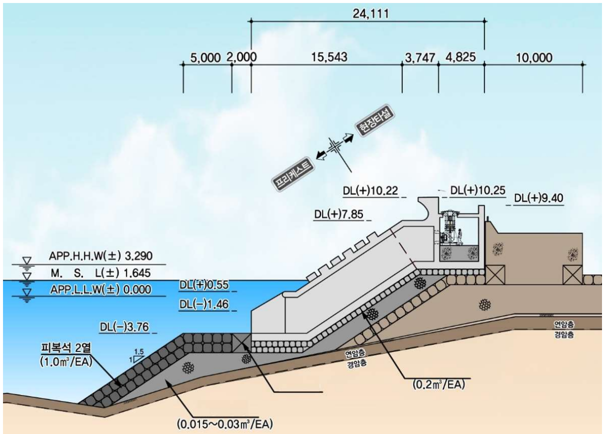

Fig. 7. Cross-section of Mukri Power Plant.

Fig. 7 shows the cross-section of Mukri Power Plant. A sloped OWC is adopted, and the slope ratio of the OWC is designed to be 1:1.5, the same as that of the breakwater slope. The vertical length of the OWC is 3.6 meters. The total height of the wave plant is 10.22 meters above Datum Level (DL), including the wave breaking structure.

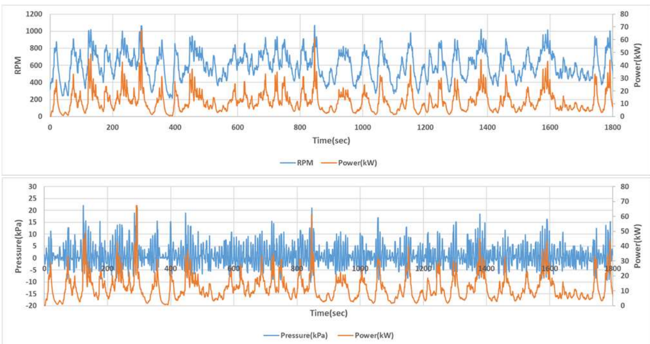

Fig. 8. Time history data. (Power and RPM, Power and Pressure)

The Mukri Power Plant passed its statutory safety inspection in October 2021. The performance evaluation was conducted using data from October 21 to September 22. The plant is located close to residential areas and was operated from 09:00 to 18:00 on working days to avoid inconvenience to daily life.

To evaluate the real sea state performance of the system, the generator speed and power and the pressure in the chamber were measured and stored in real time during operation.

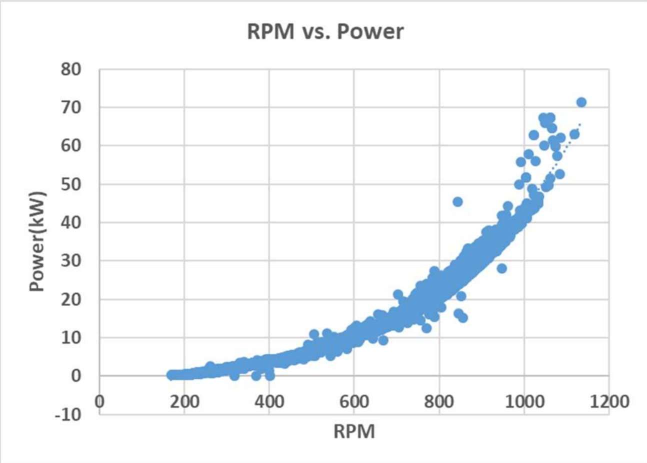

Fig. 9. Relationship between generator speed and power.

The time history of rotational speed and power, chamber air pressure and power are shown in Fig. 8. It can be find that the power generation system operates stably during medium wave conditions. It was confirmed that the system operated stably within the range of power and turbine speed, and the chamber pressure, turbine speed, and power were significantly correlated. The generators are operating at speeds between 200-1000 rpm and power between 10-70 kW. The rated speed of the system is 800 rpm and the rated power is 30 kW, but the instantaneous power and speed are allowed to vary due to the variability of wave power generation.

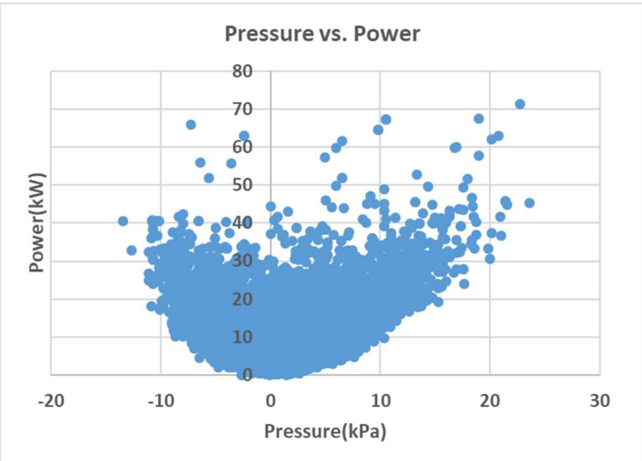

Fig. 10. Relationship between chamber pressure and power.

The relationship between the generator speed and the power output was confirmed to be cubic, which is determined by the output control algorithm of the power converter, and it was confirmed that it is working correctly according to the control logic. As shown in Fig. 9, it can be seen that it does not decrease below 150 rpm because no load was applied.

Fig. 10 shows the relationship between chamber pressure and power. The pressure in the chamber is positive at the exhaust and negative at the intake, and it is confirmed that a larger pressure is applied at the exhaust than at the intake, and the output is also confirmed to be large. Since the pressure and flow formed by the variation of the water level in the chamber is the energy that drives the turbine, the relationship between pressure and power is proportional.

B. Statistical analysis of power output

As mentioned above, the plant operated from 09:00 to 18:00. During the operating period, the input energy to the proposed site was measured using an ultrasonic wave measuring instrument called AWAC. It was located 150 meters in front of the wave power plant at a depth of 15 meters.

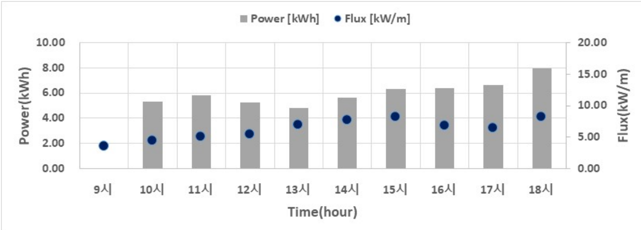

Fig. 11. Relationship between incident energy and average power generation.

The hourly power generation was calculated by averaging the real-time output. Since the AWAC provides hourly significant wave and zero-up crossing period by statistical processing, the input energy was calculated using the incident wave information of the corresponding time.

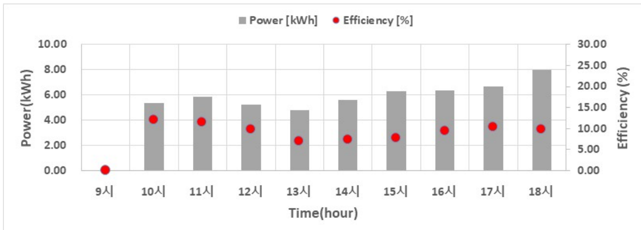

Fig. 12. Relationship between efficiency and average power generation.

Fig. 11 shows the relationship between average hourly power generation and input energy, and Fig. 12 shows the average efficiency for each hour. The average efficiency of the system is the average hourly power generation divided by the input flux multiplied by the width of the Plant, which is 10 meters.

The incident wave condition of the day is a high wave condition with a significant wave height of 1-1.6 meters. Under this condition, the maximum instantaneous power output is 59 kW, and the maximum hourly power generation is 7.96 kWh. The input energy increases until 15:00 and then tends to decrease. However, it can be seen that the average hourly output is the lowest at 13:00, which means that the relationship between input energy and output is not proportional.

The efficiency was highest at 10:00 and lowest at 13:00. The maximum efficiency is about 12.05% under that incident wave energy conditions. Since this system is a fixed frequency wave generator, it can be seen that other design variables other than the input energy affect the efficiency.

C. Correlation analysis

To investigate the influence of design variables on power generation, we analyzed the correlation between incident wave direction and skirt depth of the oscillating water chamber and power generation. The correlations were compared by calculating the Pearson correlation.

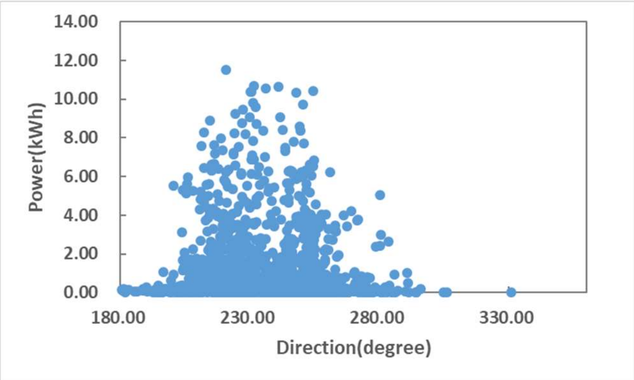

Fig. 13. Correlation between power generation and incident wave direction. (Cor. Coefficient = -0.008)

The Pearson correlation coefficient between power generation, skirt depth, and wave direction in terms of cumulative power generation per hour was derived using operational data for about a year. The Pearson correlation coefficient is a measure of the linear relationship between two variables. The number of data used for the correlation analysis is 1284, which includes wave observations, and the results with cumulative power generation were selected and analyzed.

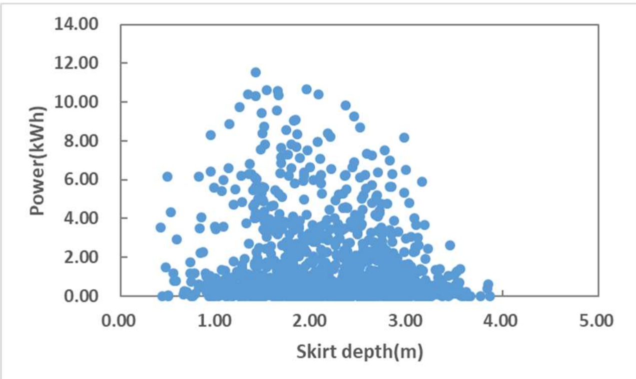

Fig. 14. Correlation between power generation and skirt depth. (Cor. Coefficient = -0.13)

Fig. 13 shows the correlation between power generation and incident wave direction and Fig. 14 shows the Correlation between power generation and skirt depth. The direction of the incident wave was not found to be significant over the year. Since the power plant is installed on the breakwater of the harbor, the direction of the waves entering the harbor is not significantly affected by the direction of the offshore sea. Significant wave height and input energy were found to have a strong positive correlation, while skirt depth and wave direction were found to have a negative correlation.

It was found that the most power was generated when the incident wave was directed at 90 degrees to the chamber. As the direction of the wave changes, the power generation tends to decrease.

The skirt depth of the chamber was found to be the most influential variable on power generation. It was found that there is a noticeable change in power generation due to the difference in tides, which in turn affects the skirt depth due to the change in water level. A skirt depth of 1.5 meters was found to generate the most power. This verifies that a smaller skirt depth is more favorable for power generation. However, it should not be so low that the chamber is exposed to the air.

V. CONCLUSION

We built a 30kW breakwater-integrated wave power plant and conducted a real-sea performance evaluation based on data from one year of operation. First, we conducted an onshore performance evaluation of the manufactured energy conversion unit. The energy conversion unit was installed in a large blower and tested for performance, and the final efficiency was evaluated as 48.1%.

Using the data from the operation under the condition of incident wave height of 1-1.5 meters, the relationship between the rotation speed of the generator and the output and the relationship between the pressure in the chamber and the output were examined. It can be seen that the output according to the rotation speed shows a cubic relationship, and it is confirmed that it is being operated accurately according to the Maximum Power Point Tracking (MPPT) control algorithm.

The average power generation per hour was statistically analyzed to evaluate the efficiency. It was confirmed that the incident energy and wave direction are important factors that determine the power generation. In addition, there is a design variable that affects the power generation apart from the incident energy, which is the depth of the chamber skirt. Skirt depth was found to have a strong negative correlation with power generation. Under optimal conditions, the average hourly efficiency of the system was evaluated to be 28.8%.

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