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**Abstract:** A fixed oscillating water column (OWC)-type wave energy converter consists of an air chamber, an air turbine and a generator. The energy conversion processes are the primary conversion in an air chamber and the secondary conversion of the turbine. For the practical use, it is necessary to develop a design method which can consider the incident wave motion, the motion of the internal free surface affected in the structure such as a partly submerged wall, the fluctuation of air pressure in an air chamber, and the rotation of the air turbine. At here, the authors carried out the wave tank tests using the model OWC equipped with the impulse turbine and a generator to obtain the experimental data needed to make this design method. As the result, the efficiencies of the three cases with different speed ratio between generator and turbine, and the effects of the curtain wall depth and the wave length on the energy conversion performance were clarified.

Key words: Impulse turbine, oscillating water column, primary conversion, secondary conversion, wave energy.

## **1. Introduction**

Wave energy is a promising resource that reduces  $CO_2$  emissions. Therefore, the wave energy converter (WEC) which turns wave power into electric power has been developed all over the world and many types of WECs [1] such as the point absorber [2] and the overtopping wave type [3] were proposed. Also, the research on the economic feasibility has been conducted in the world [4].

As one of the WECs, there is an oscillating water column (OWC)-type. This device is composed of an air chamber, an air turbine and a generator. Besides, a floating type [5] and a fixed type [6] are proposed, respectively. The coastal fixed type is considered to be safe even under storm conditions. Many studies on this device have been performed experimentally and theoretically since the early 1970s.

Takahashi et al. [7] designed a fixed OWC-type wave power extractor and conducted the field test by installing the Wells turbine and a generator [8]. In this study, the characteristics of the wave-activated power generation by the wave power extracting caisson were investigated and the design method of the unit was verified. Moreover, several experiments to provide the electric power were also carried out.

The main processes of energy conversion in the OWC device are the primary conversion in an air chamber and the secondary conversion of the turbine. In the performance evaluation of the OWC-type WEC, it is necessary to consider the characteristics of the incident wave motion, the motion of the internal free surface affected in the structure such as a curtain wall, the fluctuation of air pressure in an air chamber, and the rotations of the air turbine and a generator. However, most of the past studies were carried out by dividing the energy conversion process into two steps of

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primary conversion and secondary conversion.

The wave flume tests to evaluate the hydrodynamic performance in a double chamber were conducted by Wilbert et al. [9], and John Ashlin et al. [10] measured the force acting on the structure of the OWC to quantify the horizontal and vertical wave forces. Simonetti et al. [11] showed the effects of the air chamber geometry and the model scale on the primary conversion performance using CFD modelling. In the above studies, the secondary conversion of turbine was not clarified. Also, the research of numerical simulation [12] to clarify the system performance and the optimal operating condition of the OWC unit have been performed, but experimental validation is required.

On the other hand, a series of studies on air turbine performance have been carried out experimentally. Setoguchi et al. [13] reviewed a variety of experimental results concerning the performances of the wells turbine and the impulse turbine. Besides, Takao et al. [14] showed that the impulse turbine was superior to the wells turbine in the actual sea with irregular waves.

The authors have been carried out the experimental research on the primary and secondary conversion efficiencies of the fixed OWC-type wave energy convertor with impulse turbine. In the previous research [15], the effects of configurations of impulse turbine and wells turbine were investigated using a model with a motor to turn the turbine at constant speed. Continuously, this paper discusses the energy conversion efficiency in the conditions that the impulse turbine rotates by the action of the waves and a generator provides the electric power. As the main result, the effects of the curtain wall depth and the wave length on the efficiency are clarified.

# 2. Experimental Apparatus

Fig. 1 denotes the arrangement of the experimental devices in the 2-dimensional wave tank. This tank is 18.5 m long, 0.8 m width and contains 0.8 m water depth. An absorbing wave generator was installed at

the end of the tank and the model turbine was located at the other end of the tank. Four wave height gauges (TS-DWG) produced by TECHNO SERVICE Co., Ltd. were arranged to measure the amplitudes of the incident wave and reflected wave accurately. The amplitudes of incident and reflected wave components are analyzed by the FFT technique [16]. The wave data are fed into the computer through the analog-to-digital converter (PCI-3165) from the Interface Corporation. The wave tank tests were carried out in regular waves, and the setting wave height *H* is 0.1 m.

Fig. 2 shows the model OWC-type wave energy converter with the impulse turbine. In the experiments, the turbine is rotated by the action of the wave. The electromagnetic rotation detector (MP-981) produced by ONO SOKKI Co., Ltd. was located at the end of the turbine shaft. The permanent magnet alternating current generator was coupled on contact with the pulleys and the belt. In Fig. 2 of the base case, the rotational speed of generator is half the one of turbine. To rectify the three-phase alternating current, the (S15VT80) of Shindengen Electric converter Manufacturing Co., Ltd. was installed. The generating output was absorbed by a cement resistor, and the voltage was measured by a power meter (PW3335) of HIOKI E. E. Corporation.

The basic curtain wall depth  $d_c$  is 0.1 m and the thickness of the curtain wall is 0.005 m. The air chamber length *L* is 0.7 m. The schematic design of the air chamber was conducted in a series of numerical studies [17].

Fig. 3 shows the placement of the pressure gauge (AP-10S) and the wave height gauges (FW-H07 and UD320) made by KEYENCE CORPORATION at the top of the air chamber. The rectangular orifice of the air chamber is located at the center. The data of waves, the turbine rotational speed, the pressure and the water surface elevation in the air chamber were measured simultaneously. The sampling frequency is 50 Hz.

Fig. 4 shows the configuration of the impulse rotor and the fixed guide vanes. The numbers of the rotor



Fig. 1 Arrangement of model turbine and wave height gauges in 2D wave tank.



Fig. 2 Model OWC with impulse turbine and generator.

blades and the single-stage guide vanes are 30 and 26, respectively. The inlet/outlet angle  $\gamma$  of the rotor is 60 degrees and the setting angle  $\theta$  of the guide vane is 30 degrees.

The turbine configuration was adopted on basis of the test results [15]. The inner diameter D of the turbine casing is 170 mm, the hub ratio v is 0.7 and the clearance between the rotor blade tip and the casing is 0.3 mm. The diameter D was calculated by Eqs. (1)-(4).



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$$\varepsilon = S_N / S_A \tag{1}$$

$$\Delta p_N = 0.5 C_p \rho_{air} v_N^2 \tag{2}$$

$$\Delta p_T = 0.5 \psi \rho_{air} v_a^2 \tag{3}$$

$$C_p = (1 - \varepsilon)(2.75 - 1.56\varepsilon) \tag{4}$$

where  $\varepsilon$ ,  $S_N$ ,  $S_A$ ,  $\Delta p_N$ ,  $C_p$ ,  $\rho_{air}$ ,  $v_N$ ,  $\Delta p_T$ ,  $\psi$  and  $v_a$  are the nozzle ratio, the cross-section area of nozzle, the cross-section area of air chamber, the total pressure



Fig. 3 Positions of pressure and wave height gauges.



Fig. 4 Configuration of rotor and guide vane.

difference at nozzle, the pressure loss coefficient, the air density, the flow velocity in nozzle, the total pressure drop at turbine, the turbine pressure coefficient and the axial flow velocity in turbine, respectively. The pressure loss coefficient of  $C_p$ containing the nozzle ratio  $\varepsilon$  (= 1/100) can be calculated by Eq. (4), and the turbine pressure coefficient  $\psi$  is determined by Eq. (3) which is composed of the total pressure drop  $\Delta p_T$  and the axial flow velocity  $v_a$  in the condition giving the maximum turbine efficiency. The  $\Delta p_T$  and  $v_a$  are the experimental results obtained by the preliminary turbine tests [14]. Moreover, the total pressure difference at the nozzle is equal to the total pressure drop at the turbine ( $\Delta p_N =$  $\Delta p_T$ ), and the flow rate in the turbine is the same as in the case of the nozzle ( $v_a S_T = v_N S_N$ ). These relations result in Eq. (5).

$$S_T / S_N = \sqrt{\psi / C_p} \tag{5}$$

Therefore, the inner diameter *D* as the hub ratio v = 0.7 is derived from the known  $S_N$ ,  $\psi$  and  $C_p$ .

## 3. Experimental Results

Fig. 5 is the examples of experimental results. These time-series data were obtained after the start of the wave generator. Fig. 5a is the water level in middle section of wave tank, Fig. 5b is the water level measured with the wave height gauges in air chamber at the ratio  $\lambda/L = 6.3$  giving the high efficiency, where the  $\lambda$  is wave length. Fig. 5c is the rotational speed of turbine at  $\lambda/L = 6.3$ . As shown in Fig. 5a, the almost regular wave pattern can be confirmed after a lapse of 30 seconds from the start of the wave generator regardless of the  $\lambda/L$ . These waves are composed of the incident waves and reflected waves. Besides, it is found that the water surface elevation can be uniformed in air chamber as shown in Fig 5b. On the other hand, the turbine can be maintained the high rotational speed with the fluctuation due to the oscillating air flow as shown in Fig. 5c. The result in Fig. 5 denotes that this experiment for the qualitative performance evaluation of OWC with turbine is valuable as the research to pursue the development of optimal design method. In addition, the regular wave is a useful condition for experiment in confirmation of maximum energy conversion efficiency, and it seems that the irregular wave condition such as the sea makes it difficult to measure the accurate experimental data. Therefore, the data in the regular wave condition collected after the lapse of 30 seconds from the start of the wave generator were adopted for the performance evaluation in this research.

Fig. 6 shows a comparison of the efficiency between three cases with different rotational speed ratio  $N_G/N_T$ ( $N_G$ : the rotational speed of generator,  $N_T$ : the rotational speed of turbine), where Fig. 6a shows the change due to the wave length  $\lambda$  at electric resistor  $R = 3,040 \Omega$  and Fig. 6b shows the change due to the electric resistor Rat the  $\lambda/L = 6.3$ . The primary conversion efficiency  $\eta_1$ , the secondary conversion efficiency  $\eta_2$ , the  $\eta$  and the

 $\eta_3$  of generator are defined as follows:

$$\eta_1 = P_{air} / P_{wave} \tag{6}$$

$$\eta_2 = P_{turbine} / P_{air} \tag{7}$$

$$\eta = \eta_1 \eta_2 \tag{8}$$

$$\eta_3 = P_{out} / P_{turbine} \tag{9}$$

where  $P_{air}$  is the time-averaged air power in air chamber,  $P_{wave}$  is the time-averaged incident wave power,  $P_{turbine}$  is the time-averaged turbine output power, Pout is the time-averaged generator output

0.2 0.2 Water level (m) Water level (m)  $\lambda/L = 7.1$ 0.1 0.1 0 0 -0.1 -0.1 Weather side -0.2 -0.2 10 20 30 40 10 20 30 40 0 0 Time (s) Time (s) 0.2 0.2 Water level (m) Water level (m) 6.3 0.1 0.1 0 0 -0.1 -0.1 Middle section -0.2 -0.2 10 20 30 40 10 20 30 40 0 0 Time (s) Time (s) 0.2 0.2 Water level (m) Water level (m)  $\lambda/L = 4.6$ 0.1 0.1 0 0 -0.1 -0.1 Lee side -0.2 -0.2 10 20 30 40 0 10 20 30 40 0 Time (s) Time (s) (a) Water level in middle section of wave tank at (b) Water level in air chamber at length length ratio  $\lambda/L = 7.1$ , 6.3 and 4.6 ratio  $\lambda/L = 6.3$ 1200 Rotational speed  $N_T$  (rpm) 800 400

(c) Rotational speed of turbine at length ratio  $\lambda L = 6.3$ 

10

20

Time (s)

30

40

0

0

Fig. 5 Examples of time-series data.

power. The definitions of the  $P_{air}$ ,  $P_{wave}$ ,  $P_{turbine}$  and  $P_{out}$  are as follows:

$$P_{air} = \frac{S_A}{T} \int_0^T p(t) \frac{\partial z}{\partial t} dt$$
 (10)

$$P_{wave} = 0.5 \rho_w g \zeta_{wave}^2 C_g W \tag{11}$$

$$P_{turbine} = \frac{1}{T} \int_0^T T_0 \omega dt \tag{12}$$

$$P_{out} = \frac{1}{T} \int_0^T \frac{V^2}{R} dt$$
(13)



(a) Change of efficiencies due to length ratio  $\lambda L$ 



(b) Change of efficiencies due to electric resistor R

Fig. 6 Comparison of efficiencies between three cases of rotational speed ratio  $N_G/N_T$ .

where *T*, *p*, *z*,  $\rho_w$ , *g*,  $\zeta_{wave}$ ,  $C_g$ , *W*,  $T_0$ ,  $\omega$ , *V* are the period of incident wave, the pressure in air chamber, the five averaged water level in air chamber, the water density, the gravitational acceleration, the amplitude of incident wave, the group velocity, the width of air chamber, the turbine output torque, the turbine angular velocity, the induced voltage of generator, respectively.

In Fig. 6a, the wave periods corresponding to the abscissa  $\lambda/L$  are 1.15 s, 1.30 s, 1.41 s, 1.50 s, 1.56 s, 1.65 s, 1.73 s, 1.87 s, 2.03 s, 2.30 s and 2.63 s. As shown in this figure, the peak of the efficiency  $\eta$  (=  $\eta_1\eta_2$ ) appeared at the  $\lambda/L = 6.3$  in all three cases of the  $N_G/N_T$ . Besides, in Fig. 6b,  $\eta_2$  became high with the increase of *R* from 410  $\Omega$  to 3,040  $\Omega$  in all three cases of the  $N_G/N_T$ , and the maximum value  $\eta = 0.27$  was obtained in the case of  $N_G/N_T = 0.5$ .

Fig. 7 shows the efficiencies of two cases with different number of poles in a generator at  $\lambda/L = 6.3$  and  $N_G/N_T = 0.5$ . The external diameters of the 24-pole generator and the 32-pole generator are 126 mm and 162 mm, respectively. As shown in Fig. 7, the primary conversion efficiencies are almost the same. In addition, the  $\eta_2$  and  $\eta$  in case with 32-pole are low.

Next, Fig. 8 shows the turbine rotational speed. The speed of the case with 32-pole is low compared with the case 24-pole. This is the reason why the  $\eta_2$  and  $\eta$  are low in Fig. 7, and it seems that the turbine operating

condition of the case with 32-pole is in a higher flow rate range away from the flow rate giving the maximum  $\eta_2$  discussed later. Based on the above fact, the generator with 24-pole and the conditions that R =3,040  $\Omega$  and  $N_G/N_T = 0.5$  were applied in the following generating experiments.

Fig. 9 shows a change in the efficiency due to the  $\lambda/L$ in four cases of the ratio  $d_c/H = 0.7$ , 1.0, 1.5 and 2.0, where  $d_c$  is the curtain wall depth and H is the incident wave height. The  $d_c$  was changed while keeping the setting wave height of wave generator at 0.1 m and the water depth at 0.8 m. As shown in Fig. 9, the maximum  $\eta_1$  increased as the decrease of the  $d_c/H$  from 2.0 to 1.0, and the maximum  $\eta_1$  in the case of  $d_c/H = 0.7$  is almost the same value as the one of  $d_c/H = 1.0$ . On the other hand, the remarkable difference of maximum  $\eta_2$  due to the  $d_c/H$  does not appear. As the results, the higher  $\eta$  of 0.27 was achieved in both cases  $d_c/H = 0.7$  and 1.0.

Fig. 10 shows the energy conversion efficiency  $\eta_3$  of the generator, the pulleys and the belt. In all four cases of the  $d_c/H$ , the  $\eta_3$  became high rapidly with the increase of the wave length in a range from  $\lambda/L = 2.9$  to 4.9, and this tendency of  $\eta_3$  is moderate at the  $\lambda/L$  longer than 4.9. The above trend of  $\eta_3$  depends on the rotational speed of the turbine in Fig. 11.

Fig. 12 shows the amplitudes of the pressure and the water surface elevation in the air chamber. The

pressure amplitude  $\Pi$  was divided by  $\rho_w$ , g and  $\zeta_{wave}$ , and the five-averaged amplitude  $\zeta$  of the water surface elevation in the air chamber was normalized by  $\zeta_{wave}$ . In all four cases of  $d_r/H$ , it seems that the maximum



Fig. 7 Comparison of efficiencies between two cases with different generator.



Fig. 8 Comparison of turbine rational speed between two cases with different generator.



Fig. 9 Comparison of efficiencies between four cases with different ratio of  $d_{e}/H$ .



Fig. 10 Energy conversion efficiency of generator, pulleys and belt.



Fig. 11 Variation of time-averaged rotational speed of turbine.



(b) Amplitude of water surface elevation

Fig. 12 Amplitudes of pressure and water surface elevation in air chamber.



Fig. 13 Change of reflection coefficient  $k_r$  due to length ratio  $\lambda/L$ .

amplitude of pressure is obtained at the  $\lambda/L$  giving the maximum  $\eta_1$  in Fig. 9. On the other hand, the  $\zeta/\zeta_{wave}$  monotonically increased as the increase of the wave length in a whole range of  $\lambda/L$ .

Fig. 13 is a comparison of the reflection coefficient  $k_r$  (reflected wave amplitude/incident wave amplitude) in the four cases of  $d_c/H$ . The values in the cases  $d_c/H = 0.7$  and 1.0 are low at the  $\lambda/L = 5.7$  and 6.3 giving the maximum  $\eta_1$  in Fig. 9 compared with the values at the  $\lambda/L = 7.1$  in the cases  $d_c/H = 1.5$  and 2.0. The increase of the reflection coefficient generally means the decrease of the primary conversion efficiency. This trend in Fig. 13 corresponds to the results in Fig. 9 basically.

Fig. 14 is a comparison between the steady air flow tests and the above wave tank tests on the turbine performance. In the steady air flow test using the same turbine of D = 0.17 m as the above wave tank test, the bottom of the air chamber was closed, and the steady air flow was generated by a centrifugal fan as shown in Fig. 15a. The turbine was driven by a motor. On the other hand, D = 0.30 m in Fig. 14 denotes the result of the previous turbine test using the measuring system with a piston-cylinder for generating the steady air flow as shown in Fig. 15b [14]. The turbine of D = 0.30 m is geometrically similar to the other cases. The torque coefficient  $C_{torque}$ , the input coefficient  $C_{input}$  and the flow coefficient  $\phi$  were calculated by Eqs. (14)-(16).

$$C_{torque} = \eta_2 C_{input} \phi \tag{14}$$

$$C_{input} = \Delta p_T / \left[ 0.5 \rho_{air} \left( v_a^2 + U^2 \right) \right]$$
(15)

$$\phi = v_a / U \tag{16}$$

where *U* is the circumferential velocity at mean radius r [= D(1+v)/4] of turbine.

In Fig. 14, the turbine operating condition in four cases of the  $d_c/H$  shifts to the small flow rate with the increase of the rotational speed of the turbine as shown in Fig. 11. Based on the fact, the maximum  $\eta_2$  of about 0.45 was achieved in all cases  $d_c/H = 0.7$ , 1.0, 1.5 and 2.0. Although this value of  $\eta_2$  is low slightly in comparison to the maximum  $\eta_2$  of the steady air flow



Fig. 14 Comparion between steady air flow and oscillating air flow on turbine performance.



(a) Wave tank test model



(b) Test rig with piston-cylinder

Fig. 15 Steady flow test devices.

tests because of the higher  $C_{input}$ , it was shown that almost the same high turbine performance as the steady air flow tests can be achieved.

## 4. Conclusions

This present paper discussed about the primary and secondary conversion efficiencies of the fixed OWC-type WEC equipped with the impulse turbine and a generator in regular waves. In the experiment, the efficiencies of the cases of two generators and the three cases of the speed ratio  $N_G/N_T$  were investigated, and the curtain wall depth was changed between the four cases  $d_c/H = 0.7$ , 1.0, 1.5 and 2.0. The wave length was varied from  $\lambda/L = 2.9$  to 9.7. As the results, the high

primary conversion efficiency was achieved in both cases  $d_c/H = 0.7$  and 1.0. The reflected wave can be suppressed in above two cases. On the other hand, the high secondary conversion efficiency was obtained in all four cases of  $d_c/H = 0.7$ , 1.0, 1.5 and 2.0.

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