Initial Design of OWC WEC Applicable to Breakwater in Remote Islands

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Abstract—**It is not easy to install a power generation system with renewable energy in the island such as wind power or solar power generation system because the space of the island area where the grid connection is difficult is limited. However, the island has a large ocean space, so it is easy to apply wave energy converter(WEC). Particularly, there is a breakwater in the island and it is economically advantageous to apply WEC to the breakwater. This study considers the basic design of an oscillating water column(OWC) and an impulse turbine of a small WEC system applicable to a breakwater in the island where the grid is not connected. Considering the connectivity of the breakwaters and the operability in the island area, an oscillating water column with a sloping shape is adopted. The basic design is carried out through potential flow analysis, CFD analysis, and model tests. The impulse turbine is adopted, which has been applied recently, and the basic design is evaluated through sensitivity analysis on design parameters. Based on these, a method for the basic design of a small OWC wave energy converter(WEC) applicable to breakwater is proposed and discuss what is important in the design of a small OWC wave energy converter.**

Keywords—**Oscillating water column; Impulse turbine; Energy storage system; Micro-grid; Breakwater**

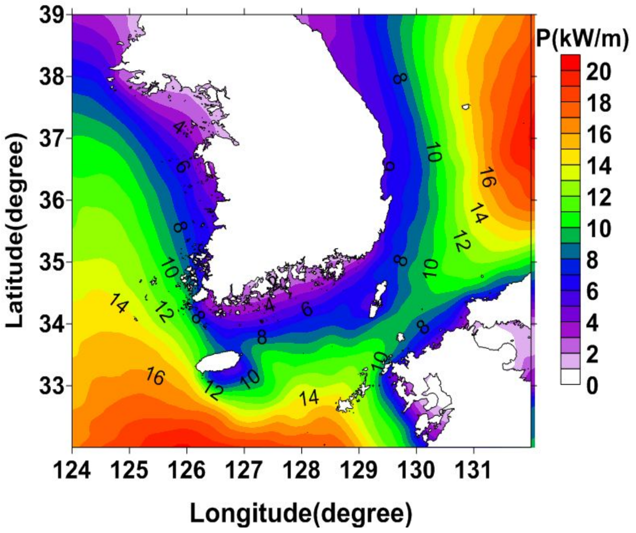
I. INTRODUCTION

Islands far from the land are not easy to connect grid. Linking a grid to a small island far from the land is expensive, and it costs a lot to transport the diesel even if electricity is produced by a diesel generator without connecting the grid. In order to overcome these difficulties, efforts have recently been made to construct a power generation system using renewable energy on the island. The wind and solar powers are mainly applied. However, it is not easy to construct a power generation system such as wind or solar power generation systems because the land space is limited in the island. In the case of wind power, a civil complaint due to noise may occur. On the other hand, the island is surrounded by the sea, so it is easy to utilize the wide sea space and to get infinite energy from the sea. Therefore, it is more advantageous to apply the power generation system using marine energy sources in the island region than to utilize other energy sources. In Korea, an R&D project has been recently conducted to develop a small WEC system using a breakwater on an island where the grid is not connected.

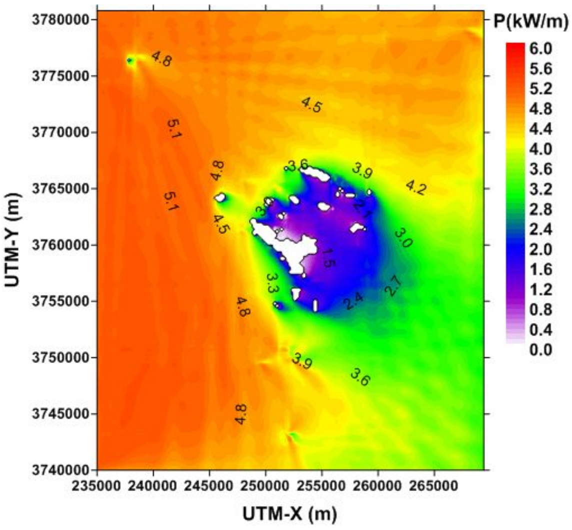
In this paper, the results of the development of the small WEC system implemented in the R&D project are introduced. The WEC is basically considered as OWC type connected with breakwaters, and OWC conceptual shape selection, numerical analysis, and model test results are presented. OWC is a type of wave power generator that has been developed for a long time[1-6]. As a secondary energy conversion module of WEC, basic design results methods through turbine type selection and numerical analysis are introduced on the turbine. Based on these, design method of OWC and impulse turbine of small WEC system are presented and it is discussed what to consider in the design of small WEC system connected to the breakwater.

II. DESIGN CONDITION

In order to design a breakwater-connected small WEC system, the function of the WEC system should first be defined. The most important element of the design condition is the location where the developed WEC is installed and the environmental condition of the ocean. The location of the power generation system to be installed is selected based on the grid status, wave energy density, tide, construction environment, and operability in the Korean islands. The wave energy density is derived from the long-term wave data of KIOST(Korean Institute of Ocean Science and Technology). More than 20 islands of the Korean islands were selected as candidate sites, and more accurate wave energy density distributions were evaluated using SWAN, a wave analysis program, for the five candidate islands. Chuja Island located at the south sea of Korea was selected as the installation location considering the wave energy density and its environmental condition. Fig. 1 shows the annual wave energy density in the sea of Korea and Chuja Island.



(a) Sea around Korea



(b) Sea around Chuja Island

Fig. 1 Wave energy density

In order to design a WEC, environmental data, an important element in the design of WEC, are required such as wave, current, tide, and bottom topology. WECs should be designed considering operating and survival conditions. It is essential to derive the wave information from the measured real sea data. However, in this study, the wave scatter diagram based on the simulation is applied for an initial design. In the wave scatter diagram, the wave energy for each sea state can be calculated. When the wave energy is multiplied by the occurrence rate of sea state, the actual maximum wave power for each sea state can be obtained. From this, the wave period can be selected from which the most energy can be obtained as the design period of WEC. The wave period of 6 sec was selected for Chuja Island.

III. DESIGN OF OSCILLATING WATER COLUMN

A. *Concept Selection*

It is known that WEC of OWC type has lower efficiency than WECs of movable type, but it is structurally stable and easy to maintain power generation equipment. It is difficult for experts maintaining WEC to stay on the remote island, and therefore the power generation system itself should be stable and durable. The OWC is relatively not weak from the fatigue and is structurally stable. The OWC is advantageous also in terms of the connection of breakwaters. It is possible to reduce the construction cost when the OWC is applied to small breakwaters. In this study, the OWC was selected as the conceptual shape of WEC.

In the case of applying the OWC WEC to the breakwater, the vertical shapes were mainly applied. Since the vertical OWC has been developed and linked to the breakwaters, the shape and influence of the existing breakwaters to the OWC WEC have not been thoroughly considered much. The shapes of breakwaters can be categorized to sloped, vertical, and hybrid shapes. The breakwaters of Korean islands are mostly sloped type. To connect the vertical OWC to the sloped breakwater, the gap between the OWC and the slope of breakwater should be buried as shown in Fig. 2. Furthermore, the OWC is arranged in front of the tetrapod and the wave load can be concentrated. The vertical structure is also weaker from the wave load than the sloped structure. In this study, sloped OWC was proposed as a concept to solve these problems. Previously proposed types of OWC are conventional OWC, U-type OWC, and projecting wall OWC as shown in Fig. 3[7-8]. In order to confirm that the sloped OWC has superior performance compared with the previously proposed OWCs, the analysis based on the potential flow and the two-dimensional tank model test were performed [9].

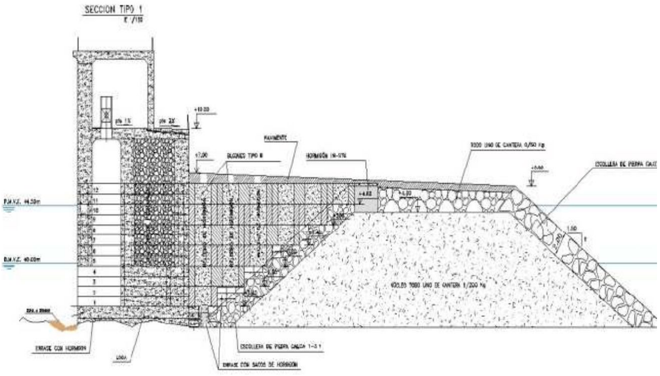
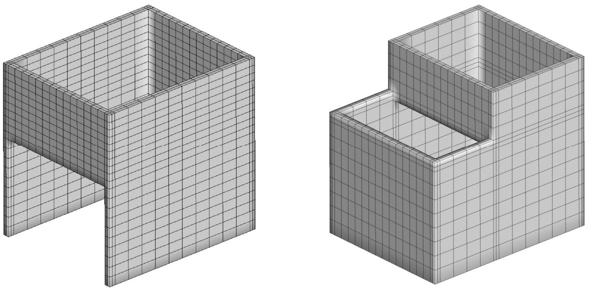
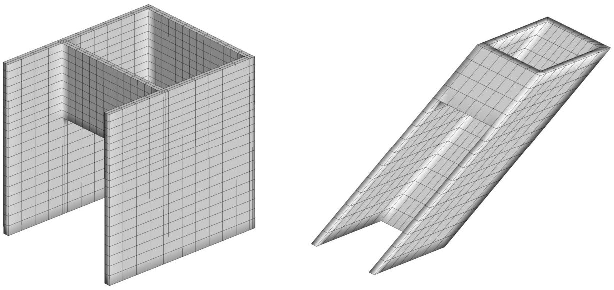


Fig. 2 Mutriku OWC [6]

Fig. 3 shows the panel models applied to the potential flow analysis. Fig. 4 shows two-dimensional models of conventional OWC and sloped OWC. The results of the numerical analysis and the model test are shown in [9], showing that the performance of the sloped OWC is not much different from the performance of the OWCs presented previously. Based on the above results, the sloped OWC was selected as WEC applicable to the island.

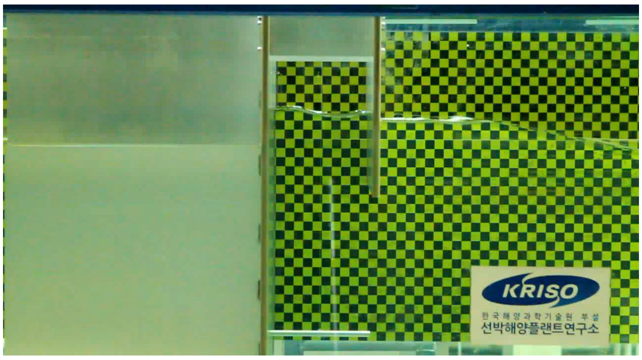


(a) Conventional OWC (b) U-type OWC

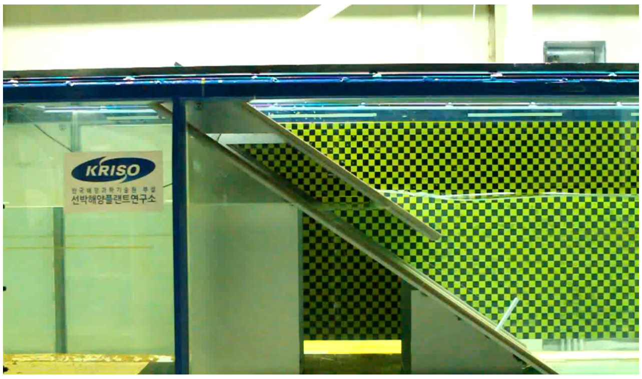


(c) Projecting wall OWC (d) Sloped OWC

Fig. 3 Panel models for numerical analysis on various OWCs [9]



(a) Conventional OWC



(b) Sloped OWC

Fig. 4 Model test on conventional and sloped OWCs [9]

B. Basic Design

For the basic design of the sloped OWC, the main design variables of the 2D shape were derived and sensitivity analysis on the design parameter was performed by the potential flow analysis. The potential flow analysis program is a time-domain finite element analysis program developed by KRISO. The major design variables are the slope angle and the length of the OWC, the slope, the height, and the thickness of the skirt as shown in Fig. 5. The average volume change was calculated from the wave elevation inside the OWC and was converted to the airflow rate. The response function of power generation amount by airflow rate can be derived based on the turbine design result. The response spectra and the root mean square (RMS) for power generation are obtained by multiplying the wave spectrum by the response function of power generation. The performance of OWC was judged by comparing the power generation RMS for irregular wave conditions for each design variable.

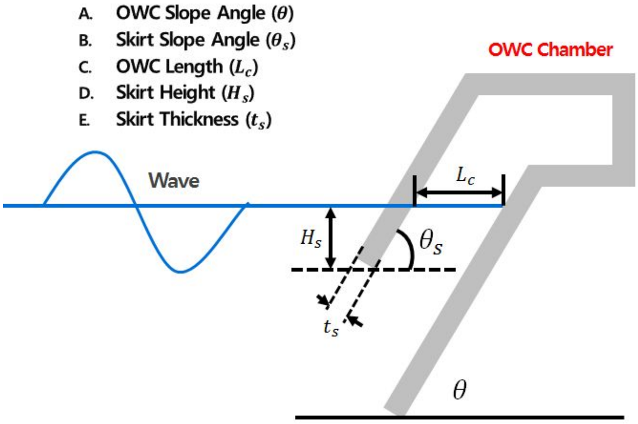


Fig. 5 Design variables of OWC chamber

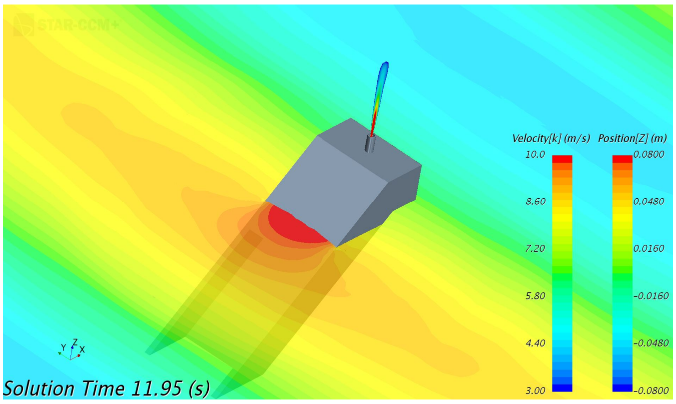


Fig. 6 CFD analysis for OWC chamber

Through the above process, the dimension of OWC can be decided considering that the OWC performance is best at the wave period of 6 sec. The performance of designed OWC can be verified through CFD analysis and model test. Figs. 6 and 7 show examples of CFD analysis and model test. In the CFD analysis and model test, an orifice was applied to consider the effect of the turbine. The efficiency of the OWC can be finally calculated by measuring the speed of airflow and differential pressure in the duct and comparing it with the incident wave energy. Fig. 8 shows the efficiency results by CFD analysis and model test. It can be seen that the efficiency is high at a design period of 6 sec.

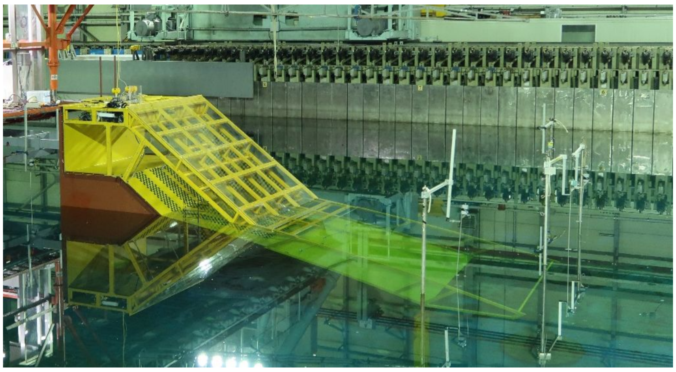


Fig. 7 Model test for OWC chamber

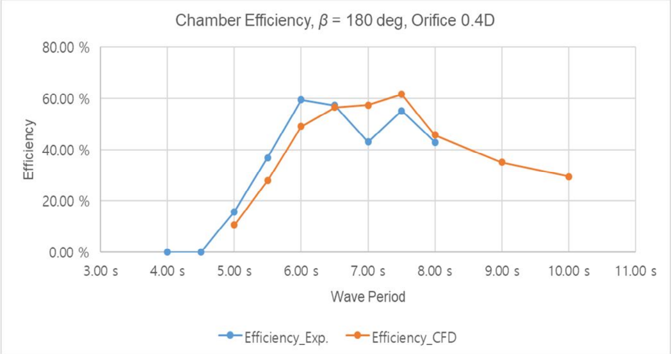


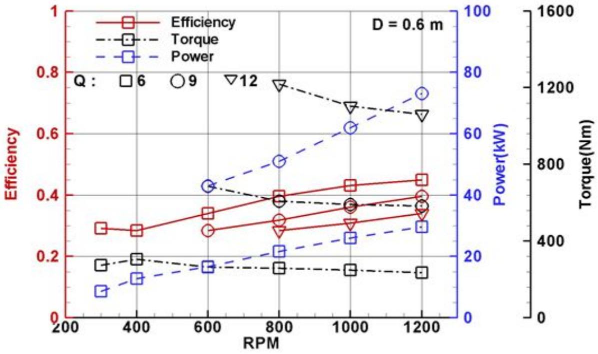
Fig. 8 Efficiency of OWC

IV. DESIGN OF TURBINE

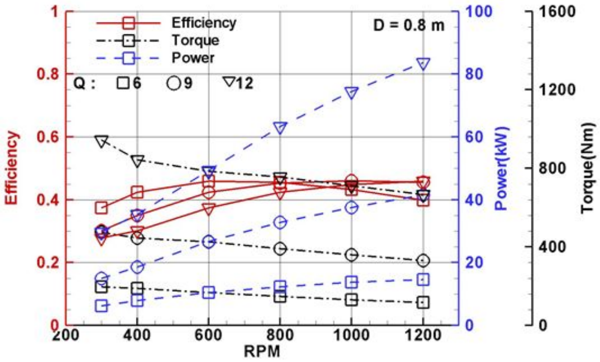
A. Conceptual Design

Compressed air generated by wave elevation inside the OWC repeats venting and sucking through the duct, and it produces power by rotating the turbine and generator. The wells and impulse turbines are mainly applied to OWC WEC. The wells turbine has higher efficiency than the impulse turbine at some operational range, but the impulse turbine has good efficiency in wider operating conditions than the wells turbine. The wells turbine has a high rotational speed, while the impulse turbine has a low rotational speed, which is advantageous in noise.

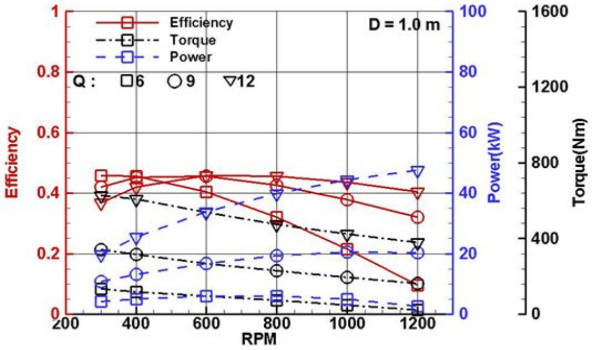
In the initial design of the turbine, the type, diameter, and rated speed of the turbine must be determined to match the design capacity. In this study, the capacity of the WEC was determined as 30kW considering the wave energy of the candidate site. The turbine type was selected as the impulse turbine considering characteristics of the input energy variation and characteristics of the generator.



(a) D=0.6m



(b) D=0.8m



(c) D=1.0m

Fig. 9 Performance chart of impulse turbine (D=0.6, 0.8, 1.0m)

In order to select the diameter of the turbine, efficiency, torque, and power for various diameters and rotational speeds are derived as shown in the Fig.9 using the performance curve of Yongsoo OWC turbine developed previously[10]. The results obtained from the previous studies were scaled down. The input flow rate was estimated by evaluating the wave energy of the candidate site and then taking into account the size and efficiency of the OWC. The diameter and rated rotational speed were determined in terms of output and efficiency. As the diameter is small, the power output is large, but the efficiency fluctuates depending on the input flow rate. If the diameter is large, the efficiency fluctuation according to the flow rate is not severe in the low-speed range, but the output power is also reduced. The diameter was determined to be 0.8m and the rated speed was determined to be 800rpm in consideration of the efficiency and the target output.

B. Basic Design

The basic design of the turbine was performed through numerical sensitivity analysis of various turbine design parameters. The number of the turbine blade, guide vane angle, hub ratio, tip clearance, rotor and guide vane gap were selected as design variables and the performance of turbine in steady state was analyzed through CFD analysis(FLUENT). Fig. 10 shows the modeling of a turbine blade for CFD analysis.

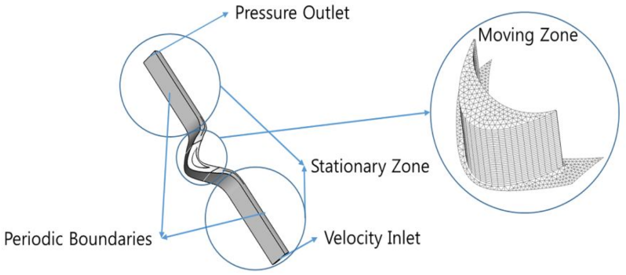
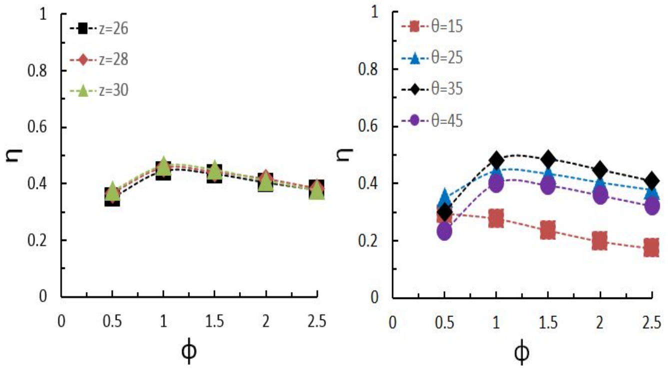
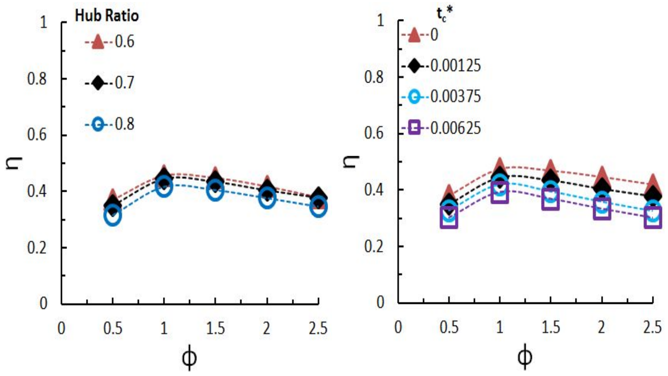


Fig. 10 Modelling of a turbine blade for CFD analysis



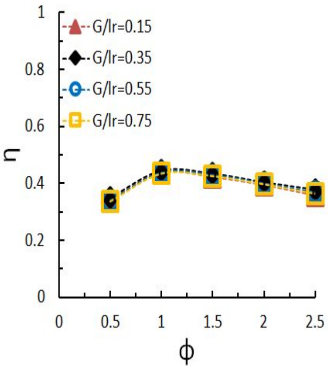
(a) Number of blade

(b) Guide vane angle



(c) Hub ratio

(d) Tip clearance



(e) Gap between the rotor and guide vane

Fig. 11 Numerical results of sensitivity analysis for impulse turbine

Fig. 11 shows the numerical results of sensitivity analysis. From the results of the numerical analysis, specifications with optimal performance can be selected as follows: the turbine has 30 blades, the guide vane angle is 35 deg, the hub ratio is 0.7, the blade tip gap is 1 mm, and the gap between the rotor and the guide vane is 56 mm. The shape and major dimensions of the designed turbine are shown in Fig. 12.

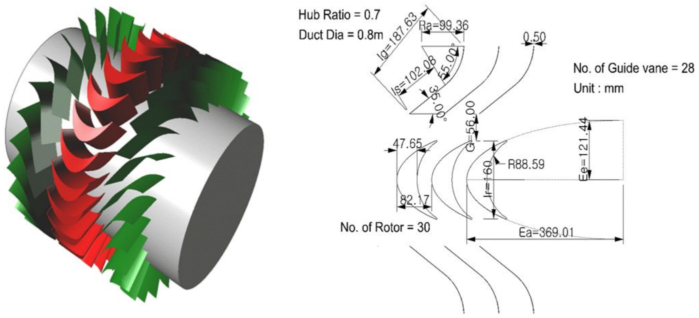


Fig. 12 Geometry of impulse turbine

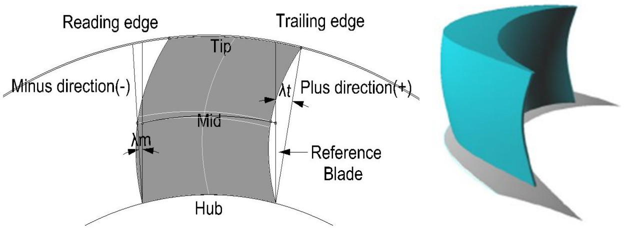


Fig. 13 Sweep angle blade

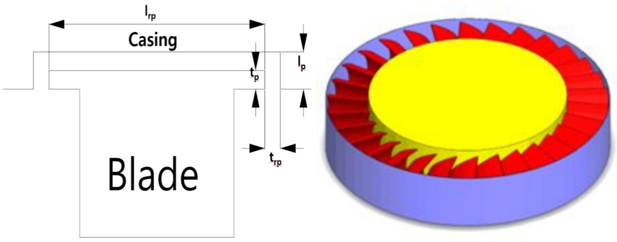


Fig. 14 Ring-type turbine

In order to improve the efficiency of impulse turbine, the method of attaching the ring to the end of the blade and the method of applying the sweep angle to the blade were proposed. Figs. 13 and 14 show the ring-type blade and sweep angle blade, respectively. The optimum design of ring was derived by examining the influence of the ring length and the penetration depth of the ring based on CFD analysis. The optimum design of sweep angle was also derived based on the sensitivity analysis on the sweep angle of the blade. Fig. 15 shows the numerical results on the efficiency of the proposed turbines. The maximum efficiency is 47.2% for the normal turbine(conventional turbine), 49% for the backward sweep angle turbine, and 51.2% for the ring type turbine[11-12].

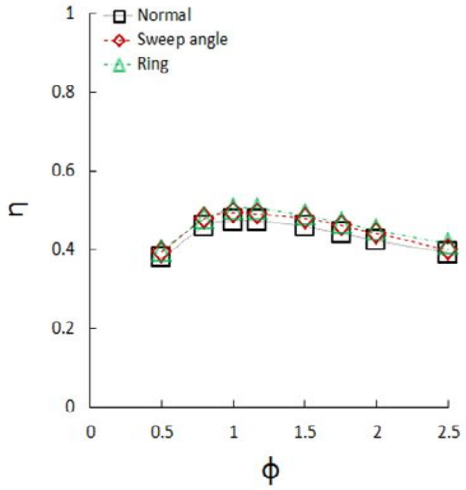


Fig. 15 Efficiency of improved turbine blades based on CFD analysis

A model test was conducted to verify the performance of the designed turbine. A turbine model was installed in a test facility capable of generating an airflow. The flow rate and differential pressure in the duct were measured, as well as the torque and rotational speed acting on the turbine. Fig. 16 shows the test facility and experimental setup.

Fig. 16 Model test for impulse turbine

The efficiency of the turbine designed through the model test is shown in Fig. 17. The maximum efficiency is 45.6% for the normal turbine(conventional turbine), 47.3% for backward sweep angle turbine, and 52.9% for ring type turbine. The results of the experiment are similar to those of the CFD analysis, and the performance of the designed turbine is verified.

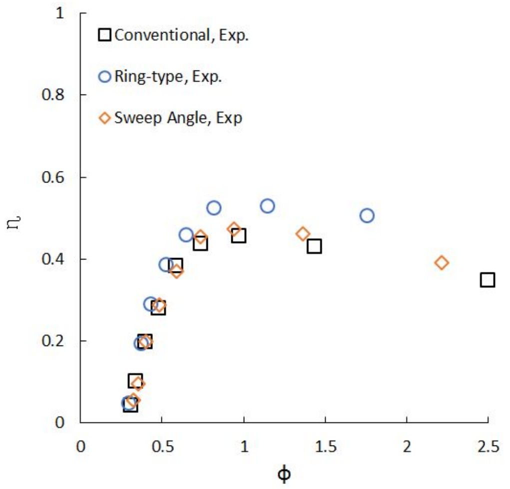


Fig. 17 Efficiency of improved turbine blades based on model test

V. CONCLUSIONS

This study deals with the basic design of small WEC, especially, OWC connected to breakwater and impulse turbine. The design procedure and results of the OWC chamber and impulse turbine are presented. Based on these, the following conclusions are obtained:

- The 2D shape of OWC can be designed from the potential flow based analysis, and its performance can be confirmed by CFD analysis and model test. The interaction of the OWC chamber and the turbine can be considered through the orifice, and an enhanced direct coupled analysis needs to be applied in the future.
- The sloped OWC has good performance compared to the conventional vertical OWC, U-type OWC, and projecting wall OWC. Furthermore, the shape of the breakwater on the Korean island is mostly sloped, so the sloped OWC has the advantage of reducing installation cost.
- The diameter and rated speed of a turbine for wave power generation can be determined by the performance curve of impulse turbine considering the efficiency and target power output. For the basic design of impulse turbine, the effects of various design variables can be analyzed by CFD analysis based on the steady analysis. The performance of turbine needs to be verified by the model test.
- A ring-type and a backward angle type turbines have better efficiency than the conventional turbine. It is necessary to apply the improved turbine considering the fabrication and structural safety.

The design procedure of the breakwater connected WEC proposed in this study can be a guideline for the design of similar WECs. Detailed design based on the basic design will be made in the future, and the performance of the actual wave power generation system can be confirmed through construction and operation of the breakwater-connected small WEC demonstration plant.

ACKNOWLEDGMENT

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