Conceptual Design of MW-scale Combined Ocean Thermal Energy Conversion in Nuclear Power Plants

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1. Introduction

There has been a lot of research on Organic Rankin Cycles (ORCs) using waste heat from power plants. The ORC can generate electric power from relatively low-temperature heat sources, so the working fluids of the ORC have generally low boiling points and latent heat, which can have good performance even at low temperatures. [1,2]. They have also less specific volume than water, so it is more economical for plant construction. As an application of the ORC, C-OTEC (Combined-Ocean Thermal Energy Conversion) succeeded in developing 10 kW power generation in the past and is planning to install 200 kW in the current Yeongdong Thermal power plant. [3]

This study analyzed the conceptual design and safety implications of the C-OTEC applied herein to nuclear power plants. The C-OTEC for nuclear power plants were designed as 1MWe because of their large capacity, and the idea of heating feed refrigerant was introduced to optimize the design.

In the conventional ORC cycle, the working fluid at the discharge part of the turbine is in the superheated state, which can be further reduced in term of temperature. A heat exchanger was installed at the discharge side of the turbine using this characteristic. The design of the flow path for deep water intake was considered for the cooling of the C-OTEC cycle.

2. Methods and Results

2.1 Introduction to C-OTEC

If the temperature difference between the surface water and the deep water differs by 20 °C, the ORC can be used to devise an Ocean Thermally Energy Conversion (OTEC). As a result of the survey on the East Sea of Korea, the temperature difference is more than 20 °C in summer, but it is difficult to maintain in other periods. This is why the concept of C-OTEC was developed, which uses the steam from the condenser of a power plant as a heat source.

Since the steam from power plant condensers is discharged at a constant temperature, C-OTEC is sufficiently effective in generating electricity regardless of season. It should be noted that the temperature of the deep water on the East Sea is constantly 4 ~ 6 °C.

2.2 Analysis of Feed Refrigerant Heating.

In previous studies, R134a was selected as a working fluid. For R134a, referring to Fig.1 and Fig.2, even if the temperature drops through the turbine, the working fluid is in superheated vapor, which can increase the cycle efficiency.

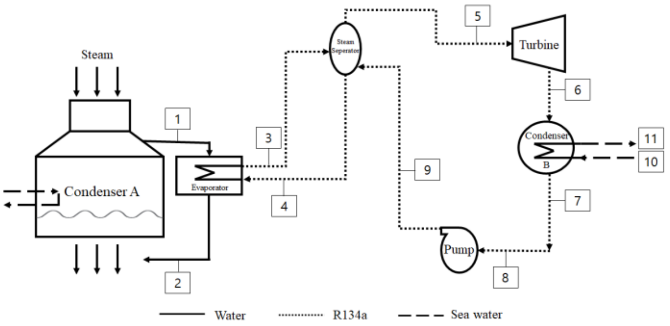

Fig. 1. Summary of original C-OTEC model.

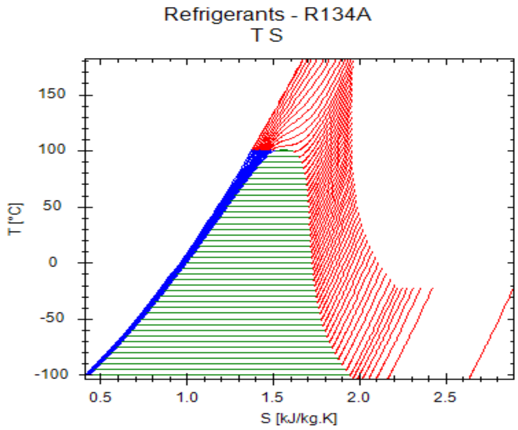

Fig. 2. R134a T-s diagram

By installing a heat exchanger at the end of the turbine in the original cycle, the temperature and quality of the working fluid can be higher. Such a kind of heat regenerative process can reduce entire system. Before passing the feed pump and entering the C-OTEC evaporator, another heat exchanger is used to increase the quality of the vapor working fluid.

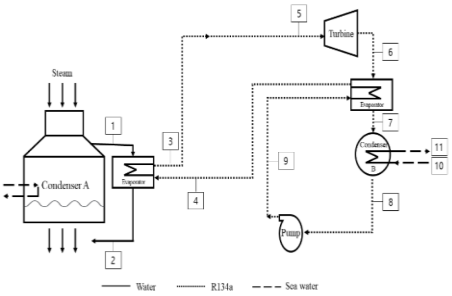

Fig. 3. Summary of C-OTEC with heat exchanger model

Assuming that C-OTEC will be installed in a nuclear power plant, the heat balance analysis of 1 MW C-OTEC was carried out.

The same component specifications given in the existing 200 kW C-OTEC were used. To compare the original model with the modified model with heat exchanger installed, Table 1 and Table 2 are provided.

Table. 1. Properties for the original model of 1MW C-OTEC

No. (Fig.1)	T (℃)	P (kPa)	x	$\dot{m}$ (kg/s)	Fluid
1	32.87	5	0.85	12.43	Steam
2	32.87	5	0.00	12.43	Steam
3	30.37	757.54	1.01	143.84	R134a
4	14.63	772.54	0.10	143.84	R134a
8	14.40	484.19	0.00	143.84	R134a
9	14.63	772.54	-0.13	143.84	R134a
10	10	151.3	-0.19	1,761.68	Sea
11	13.9	101.3	-0.16	1,761.68	Sea

Table. 2. Properties for the modified model with exchanger for feed refrigerant heating

No. (Fig.3)	T (℃)	P (kPa)	x	$\dot{m}$ (kg/s)	Fluid
1	32.87	5	0.85	10.95	Steam
2	32.87	5	0.00	10.95	Steam
4	14.63	772.54	0.10	143.84	R134a
7	15.03	484.19	0.8	143.84	R134a
8	14.40	484.19	0.00	143.84	R134a
9	14.63	772.54	-0.13	143.84	R134a
10	10	151.3	-0.19	1400.30	Sea
11	13.9	101.3	-0.16	1400.30	Sea

Table.3. Thermal performance metrics of the original model.

Q_in (kW)	28,124.70
Q_out (kW)	27,124.14
W_pump (kW)	52.07
Power output (Turbine)(kW)	1,052.63
Power output (Gen)(kW)	1,000.00
Gross Efficiency (%)	3.56

Table. 4. Thermal performance metrics for the modified model

Q_in (kW)	22,561.54
Q_out (kW)	21,560.12
W_pump (kW)	51.21
Power output (Turbine)(kW)	1,052.63
Power output (Gen)(kW)	1,000.00
Gross Efficiency (%)	4.43

Tables 3 and 4 show the performance metrics for both designs.

In the case of C-OTEC with feed refrigerant heating, the flow rate of the heat source required for the same output and the seawater flow rate required for the C-OTEC condenser are reduced. The efficiency of the two models differs by about 1% point, which is quite large considering the absolute value.

2.3 Long-Range Sea Water Transport

In order to intake seawater to the C-OTEC condenser, it is necessary to extend piping from the seawater passage of the power plant to the condenser of the C-OTEC. Since this is comparatively long, it should be checked whether additional power consumption is affordable. The material used in the calculation was assumed to be smooth concrete, and then roughness was used as the material property built into the Flownex^{TM} program. The seawater flow required for the condenser was fixed at 1761.68 kg/s based on Table 1. The efficiency of the pump was assumed to be 65%, and the calculation of the flow rate and pump power consumption according to the pipe diameter was carried out through the EES program. The length of the pipe was fixed at 500 m. This is because Hanul site was selected as a hypothetical site fir the C-OTEC where the deep seawater can be taken most easily. This distance may be adjusted depending on in-depth geographical study.

Fig. 4. Distance from Hanul nuclear power plant to Sea

Table. 5. Pumping power according to pipe diameter

D(m)	V(m/s)	ΔP(kPa)	W(kW)
0.5	8.975	177.4	480.8
0.6	6.232	68.4	185.4
0.7	4.579	30.61	83
0.8	3.506	15.28	41.42

The larger the pipe diameter, the less the power consumption and flow velocity of the pump that draws the seawater. However, since broadening the diameter of the pump would require a high construction cost, cost-benefit analysis is further required.

2.4 Safety Issue in Nuclear Power Plants

When the C-OTEC is applied to a nuclear power plant, the impact of the accident should be evaluated. In this study, the safety issue was mentioned from the PSA(Probabilistic Safety Assessment) point of view.

We assumed the impact of the C-OTEC can affect the LOCV(Loss of Condenser Vacuum). In order the quantify the additional impact of the C-OTEC, we guessed the increased frequency of the LOCV.

In order to operate the C-OTEC, additional pipes should be installed in the condenser, considering that the pipe may be damaged and cause a LOCV. In a conventional PSA, the frequency of the LOCV occurred about 0.04 times a year, and its effect on the total CDF(Core Damage Frequency) is 0.5%.

The frequency of LLOCA(Large Loss of Coolant Accident), MLOCA(Medium Loss of Coolant Accident), SLOCA(Small Loss of Coolant Accident), and SGTR(Steam Generator Tube Rupture), which are the pipe breakage accidents that can occur at nuclear power plants, is added together to the LOCV frequency when conservatively considered as the frequency of damage that can occur due to the installation of the C-OTEC. The consequential LOCV value is about 0.008 different from the existing frequency.

Even if the pipe break affects the frequency of the LOCV due to the installation of C-OTEC pipe, it can be expected that there will be no significant difference from the existing CDF.

3. Conclusions

The OTEC, which uses the temperature difference of sea water, can be used in summer in the East Sea, but the efficiency decreases due to the decrease in temperature difference in winter. However, if the waste heat from the condenser of a power plant is utilized, it can be seen that the efficiency can be stably maintained. In addition, by installing C-OTEC in the power plant, it is possible to reduce the marine environmental pollution caused by the warm water discharged from the power plant condenser and to generate additional power.

In the previous model, the C-OTEC with feed refrigerant heating not only increases the efficiency of the power plant, but also reduces the power consumption of the pump that draws seawater by reducing the flow rate required for each seawater and evaporator. The warm drainage discharged by reduced seawater flow will benefit the marine environment.

In the case of a large C-OTEC, the waste heat of the power plant itself is also required in a large amount, so this study examined the applicability to nuclear power plants, and in particular, briefly examined the effects of C-OTEC installation from a PSA perspective.

ACKNOWLEDEMENT

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