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Feasibility study of a combined Ocean Thermal Energy Conversion method in South Korea

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ABSTRACT

Considering the geographical position of South Korea, the concept of C-OTEC (Combined Ocean Thermal Energy Conversion) is thought to be feasible. C-OTEC uses the latent heat of the steam exhausted into the condenser of a power plant as a heat source, in contrast to the conventional OTEC cycle, which is based on warm surface water. More specifically, the C-OTEC heat source can always be maintained at around 32 °C which is the temperature of saturated steam when it is condensed. This paper describes the selection of the working fluid, thermodynamic analysis, and the impact on the Rankine cycle when providing steam to the C-OTEC process. Based on the analysis, C-OTEC is expected to be beneficial for power plants through increased output and plant efficiency. Especially in the case of old power plants which cannot easily maintain their rated output during the summer, C-OTEC is expected to help to improve the condenser vacuum, reduce the necessary pumping power, and reduce the temperature of the discharge side. Given the current economic scenario situation, the focus is on optimizing the fabrication of the main components which can be done with the design of a prototype C-OTEC. Presently, the KEPCO (Korea Electric Power Corporation) Research Institute is conducting a national research project involving the construction of a prototype C-OTEC for a demonstration. It is expected to be operational by the end of 2014.

1. Introduction

The concept of OTEC (Ocean Thermal Energy Conversion) is based on the principle that the working fluid is evaporated by surface sea water at a high temperature in a cycle and that the evaporated working fluid can generate power through a turbine. This concept was introduced by D'Arsonval in 1881 and research on the subject cycle started in earnest after the first oil shock. The NELHA (National Energy Laboratory of Hawaii) built a closed OTEC facility capable of generating 50 kWe in 1979. This OTEC plant was known as Mini-OTEC, and it generated a net power of 15 kWe [1]. However this cycle requires a minimum temperature difference of 20 °C between the temperatures of the surface sea water and deep sea water [2]. Another OTEC system produced power from very low grade energy and yielded very low efficiency of 3–5% [3]. To overcome this, Straatman et al. [4] proposed a hybrid of OTEC-offshore solar pond (OSP) system to obtain a low LEC (levelized electric cost).

OTEC systems have been conducted in Hawaii and India owing to the feasibility of their tropical locations for this type of research [2,5].

On the other hand, Korea has a mid-latitude location (33°–38°), where high temperatures of surface sea water are very rare except for a few months during the summer season. For this reason, the ocean thermal energy potential around Korea is very low [6]. Alternatively, an idea that utilizes condenser effluent from a nuclear power plant instead of surface sea water has been published [7], considering that considerable amounts of latent heat are wasted during the condensing process. Soto and Vergara [8] proposed a hybrid OTEC system coupled with a thermal power plant intended to enhance the plant's power while also obtaining desalinated water from a location where the surface-to-deep sea water temperature difference would not suffice for a regular OTEC system. In Korea, even waste water from a large plant does not meet the temperature requirements of a heat source for more than half of the year. The temperature variation of the waste water and the difference between the maximum efficiency and the minimum efficiency

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Nomenclature

h	enthalpy, kJ/kg
$\dot{m}$	flow rate, kg/s
p	pressure, kPa
s	entropy, kJ/kg °C
T	temperature, °C
Q	heat duty, kW
W	power, kW
x	quality, –

Acronyms

Sat	saturation
TTD	terminal temperature difference, °C

Greek symbols

η	efficiency, –

Subscripts

cycle	thermodynamic cycle
pmp	pump
tur	turbine
csw	cold sea water
cond	condenser

Superscripts

gross	gross-based (excluding in-plant electricity consumption)
net	net-based (including in-plant electricity consumption)

are other hindrances [7,9]. In order to resolve these problems, we proposed a new concept of C-OTEC (Combined Ocean Thermal Energy Conversion) which uses the latent heat of the condensate steam in the condenser directly. The heat source for the new C-OTEC concept can always be maintained at around 32 °C, which is the temperature of the saturated steam being condensed in a power plant condenser. Therefore, the efficiency of the C-OTEC system is dominated by the temperature of the heat sink (cold deep sea water). The cycles in previous studies [7,8] use warm sea water from the condenser outlet whereas the proposed C-OTEC uses the latent heat of the condensate steam in the condenser directly. In addition, this type of C-OTEC does not need a warm sea water pump, which is necessary for conventional OTEC [1,5] and other combined OTEC systems [7,8].

In this study, the selection of the working fluid, a thermodynamic analysis of the C-OTEC cycle, and a performance assessment on existing power plants are done. This study was undertaken in as effort to design C-OTEC demonstration experiment as part of a national project in South Korea.

2. Concept of C-OTEC

The proposed C-OTEC would be installed at the Yeongdong power plant in South Korea for the demonstration. The conditions and scenario related to this site were considered in a feasibility analysis.

2.1. Configuration

Yeongdong power plant Unit 1 has a capacity of 125,000 kWe and consumes either crude oil or coal. The construction started in 1968 and the plant has operated since 1973. The thermodynamic conditions of the main steam at this plant are 12.55 MPa, at 539 °C with flow of 372 tons/h. The first two values for reheated steam are 2.77 MPa and, 538 °C. The designed condenser pressure is 5 kPa. The steam flow rate when entering the condenser is 262 tons/h with steam quality of 0.92. This plant has the configuration of a typical large Rankine cycle as shown in Fig. 1. The efficiency of the plant is 40.8% and the heat rate is 8817 kJ/kWh in the designed condition. In this paper, the Rankine cycle of the Yeongdong power plant is referred to as the 'PRC (Primary Rankine Cycle)' in order to distinguish it from the C-OTEC ('Secondary Rankine Cycle') side. Yeh et al. [11] determined the optimal ratio of warm-to-cold sea water flow but in the C-OTEC design, the heat source (condensate steam) is too large, limiting the scale of the C-OTEC system according to the scale of the heat sink (the secondary condenser and the cold sea water flow).

One particular condition of the Yeongdong power plant is that the plant cannot operate at 100% capacity during the summer season because the condenser back pressure increases due to the increase in the sea water temperature at that time. The original heat balance of the Yeongdong power plant was designed according to a sea water temperature of 15 °C, which is no longer achievable. It has not achieved its designed back pressure because it is located in an area of rising sea water temperatures despite the use of available vacuum maintenance functions. C-OTEC can resolve such a problem as well because it uses deep, cold sea water as the heat sink. The PRC condenser is the evaporator in the C-OTEC system. Fig. 2 shows the configuration of the C-OTEC system. In this figure, the working fluid inside the tube is evaporated by the steam in condenser as the steam is condensed. Moisture carried over is separated from the saturated vapor in a drum and re-circulates. The saturated vapor passes through a turbine and is condensed into a saturated liquid in the secondary condenser. The saturated liquid passes through a feed pump and flows into the drum.

For a large-scale thermal power plant, the pressure of the condenser is maintained at 5 kPa (about 1.5 inches of Hg), at this pressure, the temperature of the saturated steam is 32.9 °C. Therefore the working fluid in the C-OTEC system should be vaporized at a temperature slightly lower than 32.9 °C and liquefied at a temperature slightly higher than 10 °C assuming that a deep sea water temperature range of 4 °C–10 °C can be maintained.

2.2. Selection of the working fluid

The determination of the working fluid temperature is an important design parameter of the ORC (Organic Rankine Cycle) which is applied in the C-OTEC system. In particular, in this study, the feasibility of the proposed facility should be verified. It was necessary to determine the working fluid by taking into account technical factors, regulatory factors, and certain economic aspects. Hung et al. [12] studied ORC efficiency variations due to the working fluid from low grade energy sources. Odum [13] showed that the land based OTEC is not likely to be feasible due to what he termed low 'EMergy' yield ratio and the large investment. Zhang et al. [14] studied efficiency variations and, optimization methods and conducted an exergy analysis of the subcritical ORC and transcritical power cycle for low temperature geothermal power generation. Kuo et al. [15] analyzed the thermal efficiency of a 50 kW ORC subject to various condensing and evaporation temperatures. Wang et al. [16] determined the optimal selection of the working fluid corresponding to the heat source temperature and Mirko et al. [17] investigated the relationship between the working fluid and the economic criteria.

In Section 2.1, we derived two pre-conditions. The first prerequisite was that the working fluid of the C-OTEC cycle should be evaporated at a temperature slightly lower than 32.9 °C, and the second prerequisite was that the working fluid of C-OTEC cycle