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Performance simulation of solar-boosted ocean thermal energy conversion plant

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ABSTRACT

Ocean thermal energy conversion (OTEC) is a power generation method that utilizes small temperature difference between the warm surface water and cold deep water of the ocean. This paper describes the performance simulation results of an OTEC plant that utilizes not only ocean thermal energy but also solar thermal energy as a heat source. This power generation system was termed SOTEC (solar-boosted ocean thermal energy conversion). In SOTEC, the temperature of warm sea water was boosted by using a typical low-cost solar thermal collector. In order to estimate the potential thermal efficiency and required effective area of a solar collector for a 100-kWe SOTEC plant, first-order modeling and simulation were carried out under the ambient conditions at Kumejima Island in southern part of Japan. The results show that the proposed SOTEC plant can potentially enhance the annual mean net thermal efficiency up to a value that is approximately 1.5 times higher than that of the conventional OTEC plant if a single-glazed flat-plate solar collector of 5000-m^2 effective area is installed to boost the temperature of warm sea water by 20 K.

1. Introduction

Ocean thermal energy conversion (OTEC) is a power generation method wherein the heat energy associated with the temperature difference between the warm surface water and cold deep water of the ocean is converted into electricity [1–4]. Considerable research effort has been directed to the development of OTEC. Uehara [5–8] conducted numerous theoretical and experimental studies on the major components of an OTEC plant. The results of these studies revealed that ammonia is one of the suitable working fluids for a closed-Rankine-cycle OTEC plant. However, due to a small temperature difference (approximately 15–25 K) between the surface water and deep water of the ocean, the Rankine-cycle efficiency is limited to be only 3–5%. This results in a high cost of the electricity generated by an OTEC plant. In order to improve the cycle efficiency, other thermodynamic cycles such as Kalina cycle and Uehara cycle that use an ammonia–water mixture as the working fluid have been developed and reported to have better thermal efficiency than the Rankine cycle at the same temperature difference. However, it is evident that increasing the temperature difference between the hot and cold heat sources is the most effective solution to improve the thermal efficiency of a thermodynamic power generation cycle. Saitoh and Yamada [9] have described a conceptual design of the multiple Rankine-cycle system using both solar-thermal energy and ocean thermal energy in order to improve the cycle efficiency. This concept is quite reasonable because good seasonal solar radiation would be expected at many OTEC candidate sites. Further, in order to reduce material cost and attain low electricity cost, Straatman and Van Sark [10] have reported the conceptual description of a unique OTEC system combined with an offshore solar pond called the OTEC-OSP hybrid system. We consider that the combination of OTEC and typical low-cost solar collectors could be another possible way to improve the cycle efficiency and to attain low-electricity cost.

In this study, we describe a first-order simulation model of the OTEC system that utilizes not only ocean thermal energy but also solar-thermal energy; the latter is used as a secondary heat source. A solar collector used in a residential application is simply installed to the conventional OTEC component. This power generation system is termed as SOTEC (Solar-boosted Ocean Thermal Energy Conversion). The performance simulation of a 100-kWe SOTEC plant with three typical low-cost solar-thermal collectors, which

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increase the turbine inlet temperature of the working fluid, is carried out under the actual weather and sea-water conditions at Kumejima Island in the southern part of Japan. The simulation results of the SOTEC plant are discussed and compared with that of the conventional OTEC plant.

2. Simulation model of SOTEC plant

Figs. 1 and 2 show schematics of the conventional closed-Rankine-cycle OTEC operation and the proposed SOTEC operation, respectively; these figures show the general arrangement of the heat exchangers, pumps, piping, turbine generator, and solar collector. In SOTEC, we present two probable ways to install solar collector into the cycle, as shown in Fig. 2(a) and (b). In Fig. 2(a), the warm sea water is pumped from the ocean surface and is heated by a solar collector; then, the working fluid is indirectly heated and evaporated through the evaporator. On the other hand, in Fig. 2(b), the working fluid is directly heated and evaporated by a solar collector after the working fluid is pre-heated by the warm sea water through the heat exchanger. In this study, the former ‘indirect’ SOTEC in Fig. 2(a) was selected for the performance simulation because of some advantages in feasibility over the latter ‘direct’ SOTEC shown in Fig. 2(b). The solar collector in Fig. 2(b) must be prepared to have corrosion resistance and high-pressure tightness to directly heat the ammonia, the working fluid. A large amount of ammonia would be necessary to fill up the entire solar-collector piping in operation. This might increase the operational cost. Moreover, in the case of this direct SOTEC plant, there are safety and security concerns: due care must be exercised in order to prevent the ammonia from leaking into the environment during long-term operation. In addition, for faithful simulation of this plant, we must know the characteristics of the solar collector when it functions as an evaporator and/or a superheating device. For these reasons, in this study, we modeled and simulated the indirect SOTEC. Further, the OTEC of this SOTEC plant is selectively operated in night-time, i.e. in the absence of solar radiation, and even in those times during a day when the solar radiation is insufficient for the SOTEC operation.

In the simulation, an ideal saturated Rankine cycle was assumed in order to determine the theoretical thermal efficiency of the Rankine-cycle η_{th}. Fig. 3 shows the corresponding temperature–entropy (T–s) diagram. Here, T_E, T_C, and T_{SCO} are the evaporation temperature, condensation temperature, and the outlet temperature of the solar collector, respectively; T_{WSI} and T_{WSO}, the inlet and outlet temperatures of the warm sea water, respectively; T_{CSI} and T_{CSO}, the inlet and outlet temperatures of the cold sea water, respectively; and Q_E and Q_C, the heat-flow rate at the evaporator and condenser, respectively.

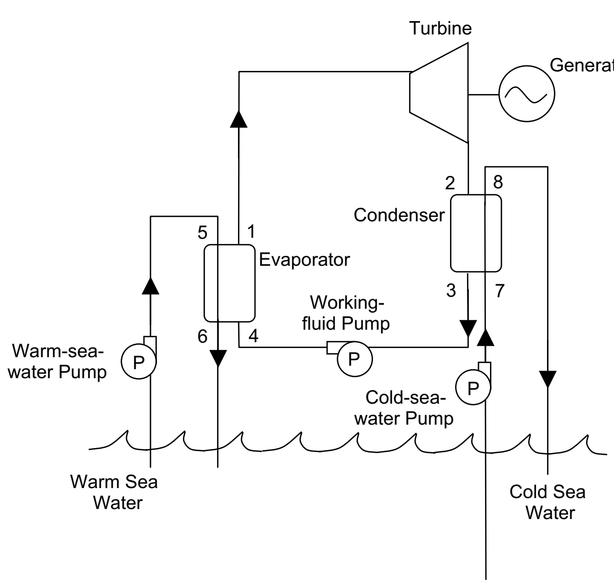

Fig. 1. Schematics of conventional closed-Rankine-cycle OTEC operation.

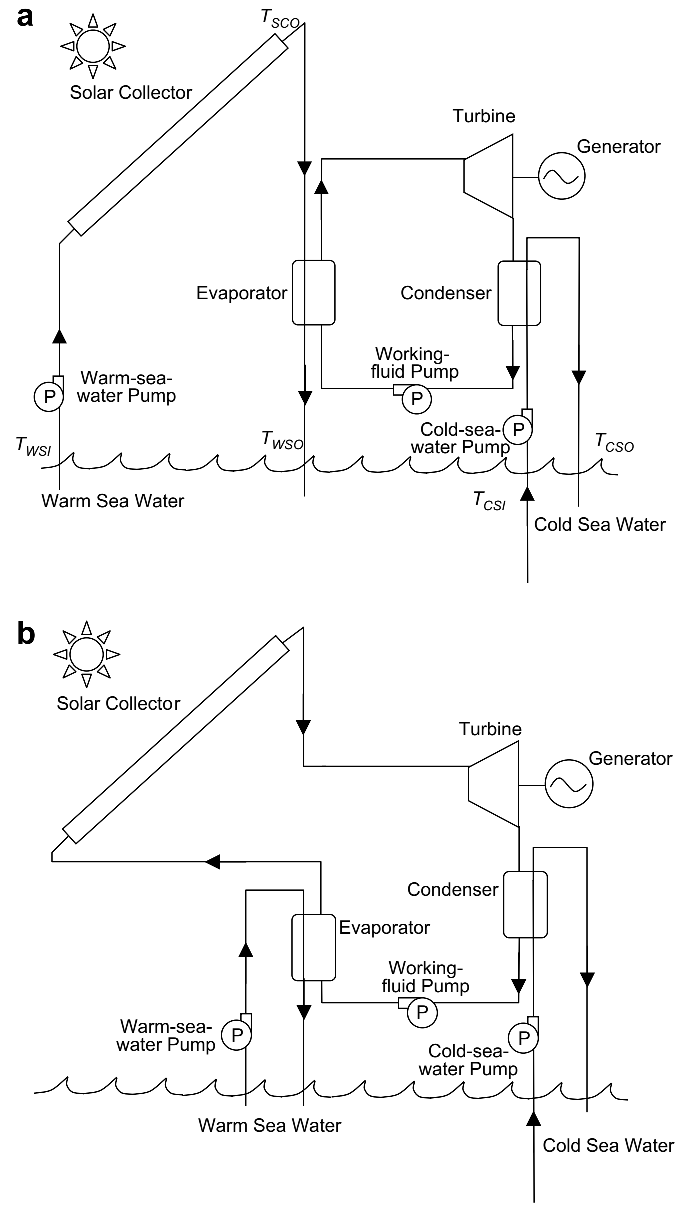

Fig. 2. Schematics of SOTEC operation: (a) Solar collector installed in warm-sea-water line (b) Solar collector installed in working-fluid line.

Fig. 4 shows the relationship between the theoretical thermal efficiency of the Rankine-cycle η_{th} and the temperature difference $\Delta T = T_E - T_C$. The conventional OTEC has ΔT between 15 K and 25 K; as a result, the maximum theoretical thermal efficiency is approximately $\eta_{th} = 8\%$. If a solar collector can additionally boost T_E by 20 K, the theoretical thermal efficiency of the SOTEC can be improved up to $\eta_{th} = 13\%$. Pumping power was not considered in the calculation of η_{th}. According to Rafferty [11] and Vega [12], ΔT is the key factor that determines the cost of a solar-thermal energy (STE) plant in the range of low ΔT values due to a logarithmic