Geo-Ocean Thermal Energy Conversion (GeOTEC) power cycle/plant

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A B S T R A C T

A new Rankine power cycle utilising a combination of ocean thermal energy and geothermal waste energy is proposed and thus called a GeOTEC (Geo-Ocean Thermal Energy Conversion) power cycle/plant. The potential geothermal waste heat, which exists in the form of raw hot natural gas is continuously pumped from a shallow water Malaysia-Thailand Joint Authority (MTJA) gas production platform, and the supply data is estimated based on the output of the platform. A thermodynamic model derived from an energy balance calculation is used to simulate the proposed GeOTEC cycle with Matlab. A capital cost estimation is performed for the proposed GeOTEC based on the commercially available components and manufacturing practices. With higher superheated ammonia temperature, GeOTEC power plant efficiency increases, while the net power output decreases. A maximum net power produced by the proposed GeOTEC is 32.593 MW with estimated capital cost of USD 4,489/kW.

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1. Introduction

Closed cycle systems can be divided into organic Rankine cycle (ORC) and absorption power cycle [1]. A research work by Wei et al. showed that ORC operates best in higher grade heat source of heating temperatures between 280 °C and 300 °C [2]. For a lower grade heat source, an ammonia-water absorption cycle exhibits a higher thermal efficiency compared to that of ORC [3]. However, the most efficient solution to improve the thermal efficiency of Rankine power generation cycle is by increasing the temperature of the heat source. Therefore, any efforts to increase the temperature difference between the hot source and cold sink would lead to a better plant performance and a higher cycle efficiency.

OTEC technology generates electricity by harnessing natural thermal energy found within the ocean [4]. OTEC power cycle uses the temperature difference between warmer surface seawater and cold deep seawater to produce electricity. Surface sea water between 100 and 200 meters depth have a temperature range between 30 to 25°C. Cooler deep sea water found beyond 600 m depth ranges between 3 to 5°C, which yield a temperature difference of 10 to 25°C with higher differences occur in tropical and equatorial waters [5–10].

J. D’Arsenoval, a French scientist, developed OTEC technology in 1881 [11]. In 1930, his student, G. Claude was the first to build a simple experimental OTEC power plant of 22 kW in Cuba [12]. From this significant effort, scientists began to show interests in OTEC, and some designs of OTEC power plants were developed and run experimentally.

In the 1900s, a small plant of 100 kW net power output was operating successfully for six years in Hawaii. In 2002, a floating 1 MW OTEC plant known as Sagr Shakthi was built by the National Institute of Ocean Technology in corporation with Saga University Japan in India [11,13]. Lockheed Martin’s has been working on 10 MW OTEC pilot plant in Hawaii, and the system would be a prospect for sizing up into a commercial plant in the future [13]. This evidence shows the world interest in evaluating OTEC implementation as a sustainable energy source, and extensive studies and effort are focused on OTEC development.

Several studies on OTEC components which was done by Uehara et al. showed R717 or ammonia is the suitable working fluid for a closed-cycle OTEC plant [5,14,15]. Nevertheless, the small-temperature difference between warm surface sea water and cold deep sea water resulted in a low performance of a closed Rankine cycle OTEC plant. A reversible efficiency for a perfect cycle of an OTEC system amounts only about 8% which implies that almost 92% of the ocean thermal energy source is rejected to the cold deep sea water during the power generation process.

In 1985, A. Kalina [11] proposed an absorption cycle for OTEC power plant, by using a mixture of ammonia and water as its working fluid. This process required a separator and a regenerator.
This so-called Kalina cycle was applied to a wide range of low-temperature OTEC systems, and the thermal efficiency theoretically increased. However, the performance of the evaporator and condenser fell due to the use of the binary fluid [16]. About a decade later, a new OTEC cycle was developed by H. Uehara which provided an improvement to that of Kalina cycle with an even higher theoretical efficiency [11]. Uehara cycle used a liquid-vapour separator to separate dry vapour and liquid in the wet vapour mixture, ensuring exclusive entry of dry vapour into the turbine and consequently reduces the load of the condenser [17].

Another alternative and innovative way to improve the efficiency has been proposed by Yamada et al. and Kim et al., by using an external heat source to increase the temperature difference. Yamada et al. proposed an addition of solar collector into the OTEC cycle [18]; a system called SOTEC, whereas Kim et al. used the waste heat from nuclear power plant condenser effluent to replace the seawater heat in OTEC system [19]. Kim et al. [19] studies showed an improvement in OTEC system efficiency by 2% by using condenser effluent. They also suggested that superheated vapour produced by an evaporator should prevent cavity, but cause little impact on system efficiency. Yamada et al. [18] concluded that the addition of external heat source by solar collector enhanced OTEC thermal efficiency by 2.7 times higher compared to that of conventional OTEC operation.

In a study by Saitoh and Yamada [20] multiple Rankine cycle systems have been proposed to improve the cycle efficiency. The cycle used both solar thermal and ocean thermal energies. Strata- man and Van Sark [21] described a conceptual design of a combined OTEC system and an offshore solar pond known as OTEC-OSP hybrid. In the other hand, Soto and Vergara [22] proposed a hybrid OTEC cycle where the flow that enters the evaporator is pumped from a thermal power plant discharge. Their effort contributes to extending OTEC potential to colder water areas. Furthermore, the simulation demonstrated the combination of OTEC plant to Punta Alcalde coal-fired power station, where the power plant efficiency improved by 1.3%. Recent work by Aydin et al. [23] simulates the addition of solar collector as a pre-heater or superheater into OTEC system. Both the preheating and superheating enhance OTEC power production by 20–25%, with superheating requires less collector area compared to the pre-heating system. The addition of solar superheater improved the efficiency of the existing system by 60%, signifying the superheating method is a better approach in OTEC [23]. All these efforts to increase the temperature of the heat source improves OTEC overall efficiency. Several of these studies also aim to achieve a low electricity cost, but the results emphasised more on the efficiency improvements rather than a quantitative cost analysis.

In this study, we proposed a new concept of combining OTEC and offshore geothermal waste energy to increase the temperature difference between the hot and cold heat sources. However, the potential waste energy is estimated and limited to 27.49 MW. The temperature of the heat source is manipulated to determine the maximum potential output and system efficiency. Capital cost estimation is performed to evaluate the feasibility of the proposed system.

2. GeOTEC power system description

The proposed GeOTEC power cycle utilises both energy sources from warm seawater and raw natural gas from offshore gas production platform. Warm seawater is pumped into the evaporator to evaporate ammonia as the working fluid into a saturated vapour. The geothermal waste energy is used in GeOTEC cycle to superheat the saturated ammonia vapour before it enters the turbine to generate electricity. The turbine exhaust gases enter the condenser to be cooled by cold deep seawater and condensed back into liquid ammonia. The schematic of GeOTEC power cycle which includes geothermal water heating system (GWHS), heat exchanger, geothermal superheater, evaporator, turbine, condenser, and pumps is shown in Fig. 1. The T-s diagram in Fig. 2 shows all the state points in the GeOTEC closed cycle, where Tsh is the superheating temperature, Te is the evaporating temperature, Tc is the condensing temperature, Pc is the evaporating pressure, and Pe is the condensing pressure.

2.1. Geothermal base data of hot raw natural gas

Table 1 lists the geothermal data used in the sizing exercise for the proposed GeOTEC power plant. As shown in Fig. 3, the potential of geothermal waste energy generation was estimated from the operating Malaysia Thailand Joint Authority (MTJA) offshore gas production platform. However, the actual potential of geothermal waste energy is more anticipated in deep sea oil and gas (O&G) platform operations.

Data of raw natural gas obtained from the MTJA platform and the calculated potential waste heat are shown in Table 1, whereas the specific heat capacity of raw natural gas was calculated based on chemical composition obtained from the Terengganu’s Bergadung platform and shown in Table 2 using the following equation:

\[
\begin{align*}
C_p &= \sum (n_i \cdot CP_i) \\
\Delta H &= H_2 - H_1 \\
\end{align*}
\]

where \( CP \) signify the specific heat capacity for crude natural gas and its compositions, and \( n \) is the percentage of chemical composition, each specified by the subscript. The potential geothermal waste energy from the MTJA platform, \( Q_{out\ gas} \) is estimated using the equation below:

\[ Q_{out\ gas} = \dot{m}_{raw\ gas} \cdot C_p \cdot \Delta T \cdot \eta_{HE} \cdot \eta_{SH} \]

where \( \dot{m}_{raw\ gas} \) is the mass flow rate of raw natural gas given in Table 1, \( \Delta T \) is the temperature difference of raw natural gas, \( \eta_{HE} \) is GWHS heat exchanger efficiency and, \( \eta_{SH} \) is geothermal superheater efficiency. The temperature difference of raw natural gas is given as:

\[ \Delta T = T_{out\ (raw\ gas)} - T_{in\ (raw\ gas)} \]

where \( T_{out\ (raw\ gas)} \) is the temperature of raw natural gas entering the cooler and, \( T_{out\ (raw\ gas)} \) is the temperature of raw natural gas leaving the cooler.

3. Thermodynamic design of GeOTEC

In the GeOTEC analysis, ammonia has been established to be the best working fluid, justified by the reductions in heat exchanger size and piping cost [25,26].

The T-s diagram in Fig. 3 shows that constant pressure is assumed during evaporation and superheating, \( P_2 = P_3 = P_4 \). This is also assumed during heat extraction in the condenser, \( P_1 = P_3 = P_4 \).

3.1. Geothermal Water Heating System (GWHS)

GWHS is proposed to be used to capture the geothermal waste energy of the hot raw natural gas from a gas production platform into the GeOTEC power cycle. The waste energy is transferred from geothermal through GWHS which uses water as the heat carrier.
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