

Exergy analysis of R717 high-efficiency OTEC power cycle for the efficiency and pressure drop in main components

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Abstract : In this paper, an analysis on exergy efficiency of high-efficiency R717 OTEC power system for the efficiency and pressure drop in main components were investigated theoretically in order to optimize the design for the operating parameters of this system. The operating parameters considered in this study include turbine and pump efficiency, and pressure drop in a condenser and evaporator, respectively. As the turbine efficiency of R717 OTEC power system increases, the exergy efficiency of this system increases. But pressure drop in the evaporator of R717 OTEC power system increases, the exergy efficiency of this system decreases, respectively. And, in case of exergy efficiency of this OTEC system, the turbine efficiency and pressure drop in a condenser on R717 OTEC power system is the largest and the lowest among operation parameters, respectively.

Key Words : R717, High-Efficiency, Ocean Thermal Energy Conversion(OTEC) Power Cycle, Exergy Analysis, Pressure drop

1. Introduction

For environmental issues such as global warming and ozone depletion, interest has been focused on the development of technologies that take advantage of renewable energy, such as ocean energy. Especially, in spite of the low efficiency

of ocean thermal energy conversion (following OTEC), the OTEC has some advantages such as the ability to be used as a clean energy source, obtained directly from the ocean surface water and deep water. In a situation, the research related to the OTEC is being done in various worldwide.

The OTEC uses the temperature difference between cooler deep and warmer shallow or surface ocean waters to run a heat engine and produce useful work, usually in the form of electricity. Our country has progressed diversified research with an interest in the development of OTEC power generation systems to industry-university joint research from 2010.¹⁻²⁾

Many researchers³⁻⁶⁾ have been much effort for the development of high-efficiency OTEC power

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system. Uehara et al.⁵⁾ such as the Kalina et al.⁶⁾ used the ammonia-water mixture as a working fluid, applied multi-stage turbine, reheater, separators and other devices to OTEC power cycle. This cycle represents a similar efficiency of OTEC power cycle with reheater. But, the cycle is required precise optimal control in order to highly efficient operation.

In this study, as shown in Figure 1, high-efficiency OTEC power cycle with cooler, reheater, expansion valve and gas-liquid separator is developed. The cycle reduces the dissipation heat of condenser by adopting the gas-liquid separator and cooler, and the absorption heat of evaporator by using the reheater, and increases the power output and efficiency by applying two-stage turbine.

Therefore, the high-efficiency OTEC power cycle to grasp its exergy characteristics using HYSYS⁷⁾ software. And, the exergy effects on each variable of the OTEC power cycle are analyzed. Accordingly, it is intended to provide a basis design data of highly efficient OTEC power cycle proposed in this study.

2. Performance analysis

2.1 Schematic diagram

Fig. 1 shows the schematic of the high-efficiency R717 OTEC power cycle proposed in this study. As shown in Fig. 1, this OTEC cycle consists of two turbines, one pump, four heat exchangers, one gas-liquid separator and one expansion valve. R717(ammonia) as a working fluid is used. Furthermore, the high-temperature surface seawater and the low-temperature deep seawater are used for the evaporation and condensation of the working fluid that circulates inside the evaporator and the condenser, respectively.

To examine the flow of the working fluid that circulates inside this OTEC power cycle, the working fluid with a high temperature and pressure that evaporated from the evaporator enters the high-stage turbine and produces stored work around it by expanding to the medium pressure before cooling while passing through the regenerator and the cooler.

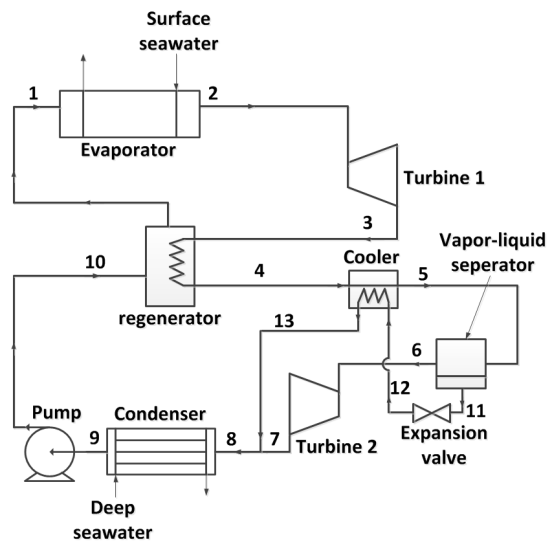


Fig. 1 Schematic of high-efficiency R717 OTEC power cycle proposed in this study²⁾

As stated, the OTEC power cycle that is proposed in this study reduces the discharged heat in the condenser by adopting a cooler and a gas-liquid separator, decreases the absorbed heat using a regenerator and increases the output work and the system efficiency through a two-stage turbine with high and low stages.

2.2 Performance analysis

The balance equations of the irreversibility and exergy destruction factor (EDF) for each component of the OTEC power cycle are as follows.

Evaporator :

Table 1: Analysis range of high-efficiency R717 OTEC power cycle proposed in this study

Refrigerant	R717(NH ₃)
Evaporation pressure drop, ΔP_e , [kPa]	5*, 15, 25, 35, 45
Condensation pressure drop, ΔP_c , [kPa]	5*, 15, 25, 35
Regenerator pressure drop, ΔP_{HX1} , [kPa]	5*
Mass flow rate, m , [kg/h]	1350, ($W = 20$ kW)
Turbine efficiency, η_t , [/]	0.55, 0.65, 0.75, 0.85*, 0.95
Pump efficiency, η_p , [/]	0.55, 0.65, 0.75, 0.85*, 0.95
Surface seawater outlet temperature, $T_{ss,out}$, [°C]	22*
Deep seawater outlet temperature, $T_{ds,out}$, [°C]	6*
Surface seawater mass flow rate, m_{ss} , [kg/h]	134,000
Deep seawater mass flow rate, m_{ds} , [kg/h]	192,200
Condenser outlet vapor quality, $x_{c,out}$, [/]	$x = 0$
High turbine outlet pressure, $P_{HT,out}$, [kPa]	630*
Condenser inlet pressure, $P_{c,in}$, [kPa]	535*
Evaporator outlet pressure, $P_{e,in}$, [kPa]	915*
Cooler outlet vapor quality, $x_{co,out}$, [/]	0.95*
* Reference value	

$$\Delta ex_{loss,e} = m(ex_1 - ex_2) + Q_e(1 - T_o/T_H) \quad (1) \quad EDF_p = \Delta ex_{loss,p}/W \quad (10)$$

$$EDF_e = \Delta ex_{loss,e}/W \quad (2)$$

Condenser :

$$\Delta ex_{loss,c} = m(ex_1 - ex_2) - Q_c(1 - T_o/T_L) \quad (3)$$

$$EDF_c = \Delta ex_{loss,c}/W \quad (4)$$

Heat exchanger :

$$\Delta ex_{loss,HX} = \sum_{i=1}^n m_i(ex_{i,in} - ex_{i,out}) \quad (5)$$

$$EDF_{HX} = \Delta ex_{loss,HX}/W \quad (6)$$

Turbine :

$$\Delta ex_{loss,t} = m(ex_1 - ex_2) - W_t \quad (7)$$

$$EDF_t = \Delta ex_{loss,t}/W \quad (8)$$

Pump :

$$\Delta ex_{loss,p} = m(ex_1 - ex_2) + W_p \quad (9)$$

Tank :

$$\Delta ex_{loss,ta} = m_1ex_1 - m_2ex_2 - m_3ex_3 \quad (11)$$

$$EDF_{ta} = \Delta ex_{loss,ta}/W \quad (12)$$

mixer :

$$\Delta ex_{loss,mx} = m_1ex_1 + m_2ex_2 - m_3ex_3 \quad (13)$$

$$EDF_{mx} = \Delta ex_{loss,mx}/W \quad (14)$$

Expansion valve :

$$\Delta ex_{loss,exp} = m(ex_1 - ex_2) \quad (15)$$

$$EDF_{exp} = \Delta ex_{loss,exp}/W \quad (16)$$

For the same conditions, the second law efficiency of the OTEC power cycle, η_{II} , is a function of a ratio of real efficiency, η_{real} , to maximum reversible efficiency, $\eta_{th,rev}$.

$$\eta_{II} = \frac{\eta_{real}}{\eta_{th,rev}} = \frac{\eta_{OTEC}}{1 - T_o/T_H} \quad (17)$$

Where, T_H is 25°C as a heat source temperature, T_o is 30°C as an ambient temperature of OTEC power cycle using R717. Thus, the second law efficiency is a negative value, because of T_o/T_H in Eq. (17) is higher than one. In this case, the second law efficiency can be expressed from an EDF (exergy destruction factor) and defined as Eq. (18).⁸⁾

$$\eta_{II} = \frac{1}{1 + EDF_{total}} \quad (18)$$

Where, EDF_{total} is the sum of the EDFs for four main components in the subcritical OTEC power cycle.

Using the results of the calculation of the analysis conditions in Table 1. such factors as the turbine and pump efficiency, the pressure drop of the evaporator and condenser, which affect the exergy efficiency of the proposed R717 OTEC power cycle, were examined.

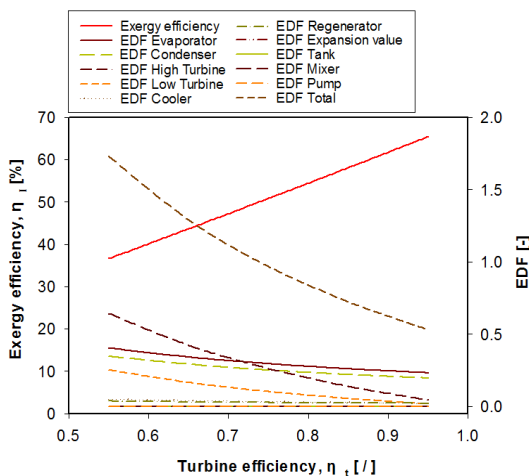


Fig. 2 Exergy efficiency and EDF of R717 OTEC power cycle with turbine efficiencies

3. Results and discussion

To find the medium pressure (the high-stage turbine outlet pressure) at which the efficiency of the proposed high-efficiency OTEC power cycle peaks, the changes in the evaporation heat capacity, the condensation heat capacity and the total work were examined while the outlet pressure of the high-stage turbine were examined. Therefore, the existence of a turbine outlet pressure that shows the highest efficiency was confirmed. That is, the high-efficiency OTEC power cycle has the highest efficiency of 4.25% at the high-stage turbine outlet pressure of 630 kPa. So, the exergy efficiency of the proposed OTEC power cycle was analyzed using the turbine outlet pressure of 630 kPa.

Fig. 2 shows the exergy efficiency(η_{II}) and exergy destruction factor(EDF) with respect to the variation of high- and low-stage turbine efficiency (η_t) of R717 OTEC power cycle under conditions. From Fig. 2, the exergy efficiency increases about 79% with the turbine efficiency due to the increasing net working power of high-and low-stage turbine. And, the EDFs of high- and low-stage turbine, condenser and evaporator decrease with the increasing turbine efficiency, respectively. This is the irreversibility of high- and low-stage turbine, condenser and evaporator. Therefore, the exergy efficiency of OTEC power cycle increases because of the decrease in their EDFs and EDF_{total} .

Fig. 3 presents the exergy efficiency and EDF of R717 OTEC power cycle according to the change of pump efficiency(η_p) under the analysis conditions. In Fig. 3, the exergy efficiency of R717 OTEC power cycle increases with the pump efficiency. The reason is because of only 0.27 kW compared to the net turbine power of 20 kW. From the above results, the EDF_p of pump is

smaller than that of other devices. So, the exergy efficiency of OTEC power cycle has no effect on the variation of pump efficiency. And, EDF_{total} does not change due to the constant EDF of other devices except for refrigerant pump.

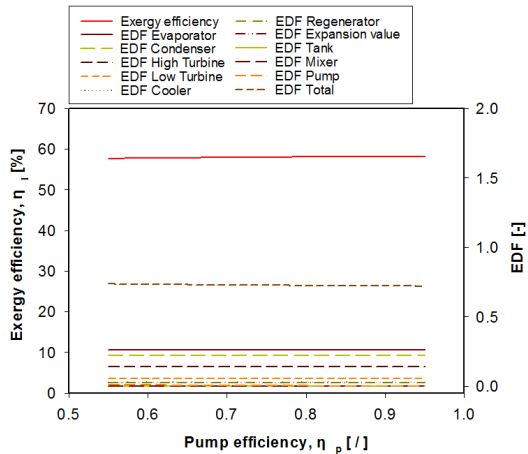


Fig. 3 Exergy efficiency and EDF of R717 OTEC power cycle with pump efficiencies

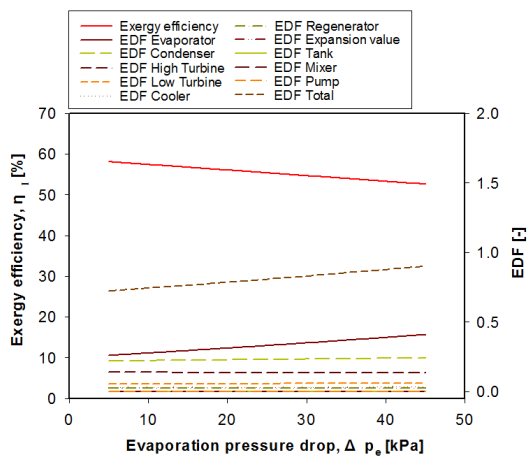


Fig. 4 Exergy efficiency and EDF of R717 OTEC power cycle with pressure drops in evaporator

Fig. 4 depicts the exergy efficiency and EDF of R717 OTEC power cycle according to the change of refrigerant pressure drop in the evaporator (ΔP_e) under the analysis conditions. As shown in Fig. 4,

the exergy efficiency of OTEC power cycle decreases with the increase of pressure drop in the evaporator. This is because the inlet pressure of high-stage turbine decreases with the increasing pressure drop, resulting in decreasing the power of high-stage turbine. The exergy efficiency of OTEC power cycle decreases with the increasing pressure drop in the evaporator, due to the increase of evaporator EDF, as shown in Eq. (18).

Fig. 5 displays the exergy efficiency (η_{II}) and EDF of R717 OTEC power cycle according to the variation of refrigerant pressure drop in the condenser (ΔP_c) under the analysis conditions. From Fig. 5, the exergy efficiency has a constant value with the pressure drop in the condenser. The outlet pressure of condenser (also inlet pressure of refrigerant pump) decreases as the pressure drop increases. From the above results, the EDF and power of pump increase, respectively. At the time, the EDF of pump has not an effect on the exergy efficiency of OTEC power cycle. And the total EDF has a constant value due to the constant EDF of other devices. Therefore, the exergy efficiency of OTEC power cycle has a constant value.

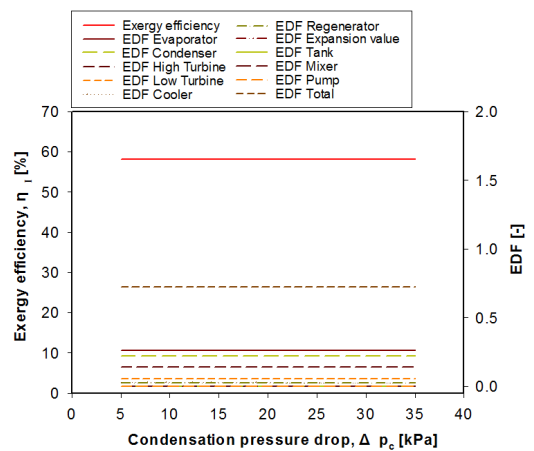


Fig. 5 Exergy efficiency and EDF of R717 OTEC power cycle with pressure drops in condenser

4. Conclusions

So far, the exergy efficiency and EDF of the proposed R717 OTEC power cycle with respect to the variation of turbine efficiency(η_t), pump efficiency(η_p) and pressure drop in the evaporator and condenser are investigated theoretically using HYSYS software under analysis conditions. The findings can be summarized as follows.

The exergy efficiency of R717 OTEC power cycle increases with turbine efficiency, but decrease with the pressure drop in the evaporator. Therefore, the exergy efficiency has a more effect on turbine efficiency compared to the pressure drop in the heat exchanger. From the above results, it is an important to develop the high-efficiency turbine in order to enhance the exergy efficiency of the proposed R717 OTEC power cycle. And, the exergy efficiency of the system should be identified by grasping the exergy loss of each component. The exergy loss of the R717 OTEC power cycle should be minimized to indicate its maximum exergy efficiency.

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