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Thermodynamic and Thermo-Economic Analysis of the Absorption Heat Transformer, Organic Rankine Cycle, and Reverse Osmosis Desalination Combined System

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ABSTRACT: In this study, the thermodynamic and thermo-economic analysis of an absorption heat transformer, organic Rankine cycle and reverse osmosis desalination combined system was performed aiming at generation the electricity and fresh water from low-temperature heat sources. All analyses are based on the thermodynamic and thermo-economic laws. The results have shown that the absorption heat transformer with the coefficient of performance of 0.4372 produces 494.7 kW of thermal energy at a temperature of 105°C in the absorber. By applying the absorption heat transformer produced thermal energy, it is possible to produce 63.18 kW of electricity in the organic Rankine cycle. By using this amount of electricity in the reverse osmosis system, 216.2m3/day of freshwater is produced at the cost of 2.217$/m3. Also, in thermo-economic analysis, the unit cost of the exergy for all points of the system and the unit cost of the electricity and fresh water were calculated. The levelized cost of electricity at different heat rates was determined and it was shown that the levelized cost of electricity is reduced when the heat rate is increased. Also, the effects of the capital cost of each system and real interest rate changes on the unit cost of the fresh water were studied.

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1- INTRODUCTION

The decreasing of the average total annual rainfall and over-consuming underground water resources especially in the dry, hot and desert regions has resulted in water shortage and scarcity in the country. Seawater desalination is one way to solve this problem using thermal and electrical energy [1]. On the other hand, a portion of energy in various industries, which has low quality and temperature ranges between 60 °C and 90°C, is wasted to the environment. The Absorption Heat Transformer (AHT) system is capable of increasing the wasted energy temperature with the heat loss recovery of about 50 % [2]. Also, the Organic Rankine Cycle (ORC) is capable of producing electricity from these upgraded sources [3]. Reverse Osmosis (RO) is a technology for producing freshwater that uses electricity [4]. In AHT, ORC and RO combined system, by applying the ORC electricity in the RO system it is possible to produce fresh water. Based on the bibliographic review, many studies have been carried out on the thermodynamic and thermoeconomic analysis of each system, but it is clear that there are not theoretical works on thermoeconomic evaluation of the AHT/ORC/RO combined system. This study aimed to investigate the production of freshwater using the low temperatures heat sources from the thermoeconomic point of views.

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2- METHODOLOGY

Fig.1 shows the schematic of absorption heat transformer, organic Rankine cycle and reverse osmosis combined system. The low-temperature heat source is applied to AHT to upgrade its temperature. Then, the upgraded heat supplied to the ORC in order to generate the electricity in the ORC turbine. Eventually, the fresh water is produced by consuming the generated electricity in the RO system.

3- GOVERNING EQUATIONS

The following assumptions are made for simplification: a) the analysis is carried out under steady-state conditions, b) heat losses and pressure drops in the tubing and the components are considered negligible and c) the pressure and temperature of the reference environment for the analyses are 1 atm and 20 °C, respectively. The first and second laws of thermodynamics, which are made in terms of mass, energy, and exergy balances, are used in the present study [5, 6].

$$\sum(\dot{m}_{in})_k - \sum(\dot{m}_{out})_k = 0 \quad (1)$$

$$\sum \dot{m}_{in}\dot{X}_{in} = \sum \dot{m}_{out}\dot{X}_{out} \quad (2)$$

$$\sum \dot{Q}_k - \sum \dot{W}_k + \sum(\dot{m}h)_{out,k} - \sum(\dot{m}h)_{in,k} = 0 \quad (3)$$

$$EX_D = (\sum E\dot{x}_{in})_k - (\sum E\dot{x}_{out})_k - \dot{W}_k + \dot{Q}_k(1-\frac{T_0}{T_k}) \quad (4)$$

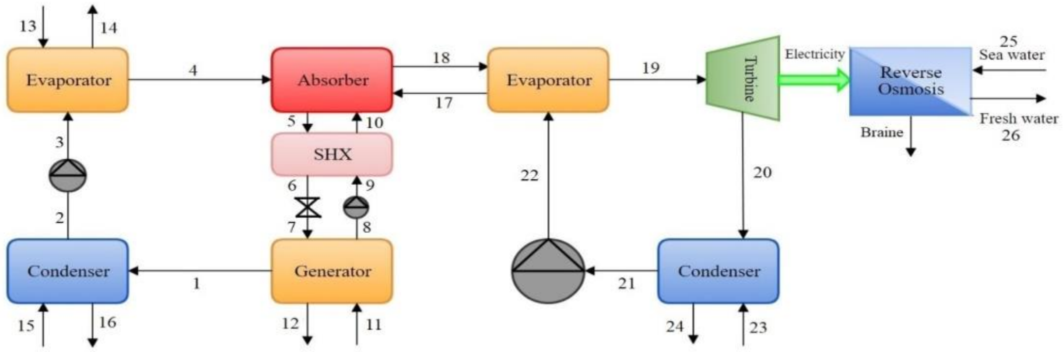

Fig. 1. Schematic of the absorption heat transformer, organic Rankine cycle and reverse osmosis combined system

Table 1. the AHT and ORC specifications

AHT					
COP	COP_{ex}	Q_{ab} (kW)	Q_{gen} (kW)	Q_{ev} (kW)	Q_{con} (kW)
0.43	0.51	494.7	523.9	609.4	606.9

ORC			
η_{orc} (%)	Q_{ev} (kW)	Q_{con} (kW)	W_{tur} (kW)
12.6	494	428	63.18

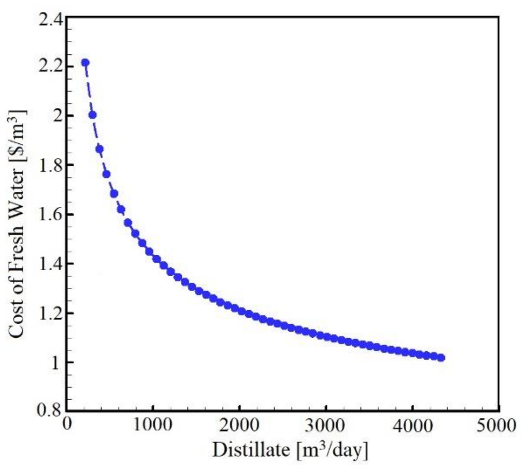

Fig. 2. Variations of fresh water amount based on the variation of waste heat rate

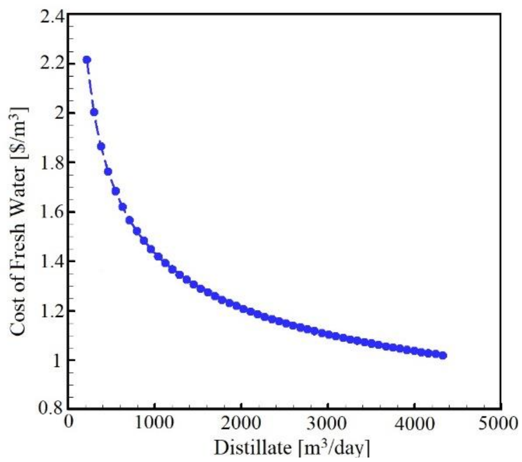

Fig. 3. Variations cost of fresh water according to distillate amount

For each inlet or outlet streams, the thermo-economic equation can be rewritten as follows [7]:

$$\sum_{in} \dot{C}_{in,k} + \dot{C}_{Q,k} + \dot{Z}_k = \sum_{out} \dot{C}_{out,k} + \dot{C}_{W,k} \quad (5)$$

$$\dot{C} = c\dot{Ex} \quad (6)$$

Using the above formulations, each component of the system is analyzed and finally the amount of generated electricity and produced fresh water, as well as their unit costs, are achieved.

4- RESULTS AND DISCUSSION

At first, for the AHT system, the heat rates of each component and the unit exergy cost of each stream are obtained as it is shown in Table.1. As can be seen in Table.1, the Coefficient of performance (COP) and COP_{ex} of the AHT are obtained as 0.43 and 0.51, respectively. Finally, by applying the absorber thermal energy in the ORC boiler, the amount of electricity generated by the ORC is determined. The variation of the fresh water production versus the waste heat rate is shown in Fig.2. According to Fig.2, the amount of produced fresh water is increased when the waste heat rate applied to AHT system is increased. As a consequence, with increasing the amounts of fresh water, the levelized cost of fresh water is reduced as can be seen in Fig.3.

A sensitivity analysis is also performed to investigate the effect of each cost parameters on the unit cost of the fresh water (Fig.4). Based on the results shown in Fig.4, the unit cost of fresh water is most sensitive to the real interest rate.

Also, the ORC, AHT and RO capital costs are respectively, the second, third and fourth cost parameters that affect the unit cost of the fresh water.

5- CONCLUSIONS

Main conclusions of the present study are as follows:

-The AHT system produced 494.4 kW heat with 105°C by achieving a COP of 0.4372.

-The ORC system generated 63.18 kW electricity with the levelized cost of electricity of 0.2843$/kWh.

-The RO system produces 216.2 m^3/day fresh water with unit cost of 2.217 $/$m^3$.

-With increment waste heat rate, the electricity generation rate and consequently the amount of fresh water are increased.

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