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The Effect of Evaporator Effectiveness on Unit Exergy Cost of Electricity Generated by an Organic Rankine Cycle

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Abstract An Organic Rankine Cycle is theoretically modelled and thermoeconomically investigated for different evaporator effectiveness. In thermoeconomic analysis, the Specific Exergy Costing (SPECO) method is used and the effect of evaporator effectiveness on unit exergy cost of electricity generated by the system is investigated. Exergy value of electricity generated by the system increases with increase in evaporator effectiveness. On the other hand, increase in evaporator effectiveness causes to an increase in hourly capital cost of system components and overall system. The results showed that the unit exergy cost of electricity generated by the system is 36.72 \$/kJ for evaporator effectiveness of ε =0.5, while it is 41.64 \$/kJ for ε =0.95.

Key words Organic Rankine Cycle, SPECO, Thermoeconomic, Evaporator Effectiveness.

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1. Introduction

Energy utilization is increasing day after day, while fossil fuels reserves are not enough to meet the necessary energy demand. So, an efficient use of low-grade energy sources becomes very important (1).Also, electricity demand and cost are increasing and more greenhouse gas emissions are releasing to the atmosphere. Organic Rankine Cycle (ORC) plays important role to generate electrical energy considering to reduce fossil fuel consumption and emissions (2). ORC may be considered similar to the steam cycle considering its working principles. In ORC, water is replaced with a high molecular mass fluid with lower degree of boiling temperature in comparison with water. Fluid characteristics make ORC favorable for applications of low temperature heat recovery (3).

Effectiveness of the energy systems such as ORC can be understood better if first and second laws of thermodynamics are taken into account. So, exergy, also known as available energy, is a useful tool to assess the ORC systems by using both laws of thermodynamics. Nowadays, most of the energy systems are analyzed and designed under consideration of the combine of thermodynamics and cost accounting (economic) disciplines (4). Also, numerical and mathematical optimization techniques are not sufficient to achieve the optimization of the systems. Because only these techniques are not practical or possible for every promising design configuration of the systems due to incomplete models, plant complexity, or generic difficulties in the mathematical treatments. So, systems are considered with cost accounting analysis such as exergy cost analysis (5).

In this paper, the effect of evaporator effectiveness on unit exergy cost of electricity generated by an ORC is investigated. In the definition of unit exergy cost of electricity generated by ORC, SPECO thermoeconomic method is used.

2. System Description

An Organic Rankine Cycle consists of four main components: turbine, pump, condenser and evaporator. The schematic diagram of an Organic Rankine Cycle is illustrated in Figure 1.

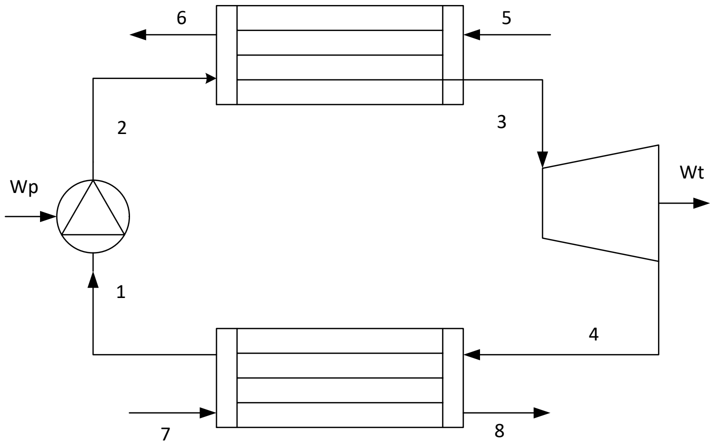

Fig. 1 The schematic diagram of an Organic Rankine Cycle

An organic working fluid is pressurized with circulating pump and enters to evaporator. In evaporator, the working fluid is superheated with heat gained from external low temperature heat source such as wasting heat, geothermal energy etc. The superheated working fluid leaving from evaporator enters to turbine and its energy is converted to work. Then, the working fluid is condensed in the condenser.

In this study, butane is selected as working fluid. It is assumed that the Organic Rankine Cycle uses a geothermal energy of 130 $^{\circ}C$ as a heat source.

3. Mathematical Modeling

The thermodynamics relations for equipment required in the mathematical modeling of Organic Rankine Cycle are given in below (6):

Pump:

$$\dot{W}_P = \frac{\dot{m}_{rf}\Delta P}{\rho_{rf}\eta_p} \tag{1}$$

$$\eta_P = \frac{h_{2,s} - h_1}{h_{2,a} - h_1} \tag{2}$$

Evaporator:

$$\dot{Q} = \dot{m}_{rf}(h_3 - h_2) = \dot{m}_{geo}(h_5 - h_6) \tag{3}$$

$$\varepsilon = \frac{T_3 - T_2}{T_3 - T_2} = \frac{(\dot{m}C_p)_{geo}\left(T_7 - T_6\right)}{(\dot{m}C_p)_{rf}\left(T_3 - T_2\right)} \tag{4}$$

$$A_{EVA} = \frac{\dot{Q}_{EVA}}{U_{EVA}F_{EVA}\Delta T_{LMTD,EVA}} \tag{5}$$

Turbine:

$$\dot{W}_T = \dot{m}_{rf}(h_3 - h_4) \tag{6}$$

$$\eta_T = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} \tag{7}$$

Condenser

$$\dot{Q} = \dot{m}_{rf}(h_4 - h_1) = \dot{m}_{cw}(h_8 - h_7) \tag{8}$$

$$\varepsilon = \frac{T_4 - T_1}{T_4 - T_7} = \frac{(\dot{m}C_p)_{cw}(T_8 - T_7)}{(\dot{m}C_p)_{rf}(T_4 - T_7)} \tag{9}$$

$$A_{COND} = \frac{\dot{Q}_{COND}}{U_{COND}F_{COND}\Delta T_{LMTD,COND}} \tag{10}$$

For this study, the isentropic efficiencies of pump and turbine is assumed to be 0.8. Mass flow rate of geothermal brine is 200 kg/s and its temperature is 130 $°C$. The condenser effectiveness is fixed as 0.95.

The cost functions of equipment used in Organic Rankine Cycle are given in below (6):

Heat exchanger: $$Z_{HE} = 8500 + 406(A_{HE})^{0.85} \tag{11}$$

Turbine: $$Z_T = \dot{W}_T\left[1318.5 - 98.328\ln(\dot{W}_T)\right] \tag{12}$$

Pump: $$Z_{pump} = 705.48\dot{W}_{pump}^{0.71}\left(1 + \frac{0.2}{1 - \eta_{pump}}\right) \tag{13}$$

The capital cost can be converted into the cost per unit time by using following equation:

$$\dot{Z}_k = \frac{Z_k \times CRF \times \phi}{N \times 3600} \tag{14}$$

where N, ϕ and CRF are annual operating hours of system, maintenance factor and capital recovery factor, respectively.

Capital recovery factor (CRF) is written as follows:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{15}$$

where i and n are the interest rate and the system lifetime, respectively.

The unit exergy cost of electricity generated by Organic Rankine Cycle is calculated by Specific Exergy Costing (SPECO) (7) thermoeconomic method. The general cost balance equation for SPECO is written as follows:

$$\sum\left(c_{in}\dot{Ex}_{in}\right)_k + c_{W,k}\dot{W}_k = \sum\left(c_{out}\dot{Ex}_{out}\right)_k + c_{q,k}\dot{Ex}_{q,k} + \dot{Z}_k \tag{16}$$

3. Result

An Organic Rankine Cycle is theoretically modelled for different evaporator effectiveness. The specific exergy cost of electricity generated by the system is calculated by Specific Exergy Costing (SPECO) thermoeconomic method.

The results obtained by economic analysis for different evaporator effectiveness are shown in Table 1.

Table 1 Capital cost values of system components

ε	Evaporator	Condenser	Turbine	Pump
0,5	6,92	22,36	49,14	0,92
0,75	13,28	22,39	53,17	0,92
0,95	27,97	22,40	56,31	0,92

As can be seen from Table 1, the hourly capital cost values of the system components increases with increase in evaporator effectiveness. For evaporator, increase in evaporator requires higher heat transfer surface area. Therefore, purchased equipment cost of evaporator increases. Moreover, increasing evaporator effectiveness cause to an increase in the amount of electricity generated by the system. By this way, the purchased equipment cost of turbine increases with increasing evaporator effectiveness.

Figure 2 shows the variation of unit exergy cost of electricity generated by the system with evaporator effectiveness.

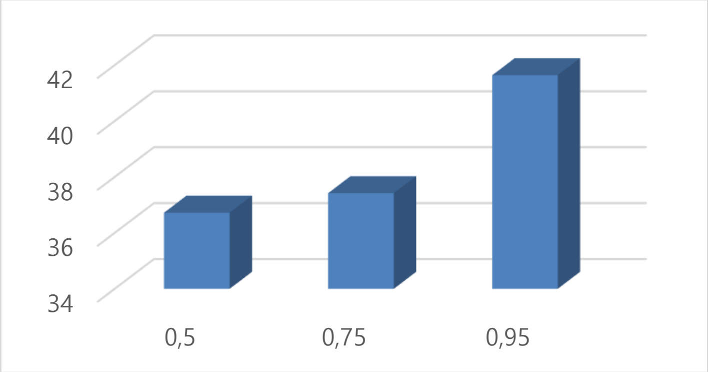

Fig. 2 The variation of unit exergy cost of electricity with evaporator effectiveness.

The unit exergy cost of electricity generated by the system increases with increase in evaporator effectiveness. The unit exergy cost of electricity is obtained to be 36.72 \$/kJ for evaporator effectiveness of ε =0.5. Whereas, it is 37.42 \$/kJ and 41.64 \$/kJ for ε =0.75 and ε =0.95, respectively. This situation shows that increment ratio in purchased equipment cost of system components is higher compared to that of the amount of electricity generated by the system.

4. Conclusion

Increase in evaporator effectiveness cause to increase in thermodynamic performance; however, at the same time, increase in capital investment cost of system components. The obtained results showed that the capital investment cost is affected higher than thermodynamic performance by evaporator effectiveness.

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