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

Cuneyt Uysal, Hasan Ozcan, Hakan Caliskan, Ho-Young Kwak, Huseyin Kurt, Hiki Hong

대한설비공학회 학술발표대회논문집, 2017.6, 507-510 (4 pages)

URL
http://www.dbpia.co.kr/Article/NODE07224225

Copyright Information
Copyright of all literary works provided by DBpia belongs to the copyright holder(s) and Nurimedia does not guarantee contents of the literary work or assume responsibility for the same. In addition, the literary works provided by DBpia may only be used by the users affiliated to the institutions which executed a subscription agreement with DBpia or the individual purchasers of the literary works for non-commercial purposes. Therefore, any person who illegally uses the literary works provided by DBpia by means of reproduction or transmission shall assume civil and criminal responsibility according to applicable laws and regulations.

경희대학교 국제캠퍼스
163.***.131.189
2019/03/04 17:34 (KST)
The Effect of Evaporator Effectiveness on Unit Exergy Cost of Electricity Generated by an Organic Rankine Cycle

Cuneyt Uysal1†, Hasan Ozcan2, Hakan Caliskan3,4, Ho-Young Kwak5, Huseyin Kurt2, and Hiki Hong4
1Automotive Technologies Program, TOBB Vocational School of Technical Sciences, Karabuk University, 78050, Karabuk, Turkey.
2Mechanical Engineering Department, Faculty of Engineering, Karabuk University, 78050, Karabuk, Turkey.
3Mechanical Engineering Department, Faculty of Engineering, Usak University, 64200, Usak, Turkey.
4Mechanical Engineering Department, Faculty of Engineering, Kyung Hee University, Yongin 449-701, Republic of Korea.
5Mechanical Engineering Department, Faculty of Engineering, Chung-Ang University, Seoul 156-756, Seoul, Republic of Korea.

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 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 $\varepsilon =0.5$, while it is 41.64 $/kJ$ for $\varepsilon =0.95$.

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

† Corresponding author, E-mail: cuneytuysal@karabuk.edu.tr

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](image)

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 °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:**

\[
\dot{W}_p = \frac{\dot{m}_p \Delta P}{\rho \eta_p} \\
\eta_p = \frac{h_{2,a} - h_{1}}{h_{2,s} - h_{1}} \tag{1}
\]

**Evaporator:**

\[
\dot{Q} = \dot{m}_p ( h_{1} - h_{2} ) = \dot{m}_{evap} ( h_{s} - h_{i} ) \tag{3}
\]

\[
\varepsilon = \frac{T_j - T_2}{T_j - T_2} = \frac{( \dot{m}C_p )_{evap} ( T_j - T_2 )}{( \dot{m}C_p )_{evap} ( T_j - T_2 )} = \frac{(\dot{m}C_p)_{evap} ( T_j - T_2 )}{(\dot{m}C_p)_{evap} ( T_j - T_2 )} \tag{4}
\]

\[
A_{EVA} = \frac{\dot{Q}_{EVA}}{U_{EVA}F_{EVA}LMTD_{EVA}} \tag{5}
\]

**Turbine:**

\[
\dot{W}_T = \dot{m}_p ( h_{2} - h_{3} ) \tag{6}
\]

\[
\eta_T = \frac{h_{3} - h_{2s}}{h_{3} - h_{2s}} \tag{7}
\]

**Condenser**

\[
\dot{Q} = \dot{m}_p ( h_{4} - h_{5} ) = \dot{m}_{evap} ( h_{b} - h_{4} ) \tag{8}
\]
\[ \varepsilon = \frac{T_d - T_f}{T_s - T_f} = \frac{(mC_p)_s (T_s - T_f)}{(mC_p)_f (T_d - T_f)} \] (9)

\[ A_{\text{COND}} = \frac{\dot{Q}_{\text{COND}}}{U_{\text{COND}} F_{\text{COND}} \Delta T_{\text{LMTD,COND}}} \] (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 (10):

- **Heat exchanger:**
  \[ Z_{\text{HE}} = 8500 + 406(A_{\text{HE}})^{0.85} \] (11)

- **Turbine:**
  \[ Z_T = W_T \left( 1118.5 - 98.328 \ln(W_T) \right) \] (12)

- **Pump:**
  \[ Z_{\text{pump}} = 705.48W_{\text{pump}}^{0.71} \left( 1 + \frac{0.2}{1 - \eta_{\text{pump}}} \right) \] (13)

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

\[ Z_c = \frac{Z_c \times CRF \times \phi}{N \times 3600} \] (14)

where \( N, \phi \) and \( CRF \) are annual operating hours of system, maintenance factor and capital recovery factor, respectively.

Capital recovery factor (CRF) is written as follows:

\[ CRF = \frac{i(1 + i^n)}{(1 + i^n)^n - 1} \] (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) thermoeconomic method. The general cost balance equation for SPECO is written as follows:

\[ \sum (c_{m,i} \tilde{E}_{m,i}) + c_{w,i} \tilde{W}_i = \sum (c_{m,o} \tilde{E}_{m,o}) + c_{w,o} \tilde{E}_{w,o} + \tilde{Z}_d \] (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>
<thead>
<tr>
<th>( \varepsilon )</th>
<th>Evaporator</th>
<th>Condenser</th>
<th>Turbine</th>
<th>Pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,5</td>
<td>6,92</td>
<td>22,36</td>
<td>49,14</td>
<td>0,92</td>
</tr>
<tr>
<td>0,75</td>
<td>13,28</td>
<td>22,39</td>
<td>53,17</td>
<td>0,92</td>
</tr>
<tr>
<td>0,95</td>
<td>27,97</td>
<td>22,40</td>
<td>56,31</td>
<td>0,92</td>
</tr>
</tbody>
</table>
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.

![Graph showing the variation of unit exergy cost of electricity with evaporator effectiveness.](image)

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 $\varepsilon=0.5$. Whereas, it is 37.42 $/kJ and 41.64 $/kJ for $\varepsilon=0.75$ and $\varepsilon=0.95$, 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.

References