Energy and exergy analysis of an Organic Rankine Cycle (ORC) in a biomass-based forest products manufacturing plant

Muharrem EYİDOĞAN¹, Fatma ÇANKA KILIÇ²*, Durmuş KAYA³, Mehmet ÖZKAYMAK⁴, Volkan ÇOBAN¹ and Selman ÇAĞMAN¹

¹Department of Energy and Environmental Technologies, Karabük University, BalıklarKayası Mevkii 78050 Karabük, Turkey. Emails: muharrem_eyidogan@hotmail.com, coban.volkan@yahoo.com.tr, selmancagman@gmail.com

²,*Corresponding Author, Department of Electrical and Energy, Air Conditioning and Refrigeration Technology, Kocaeli Vocational School, Kocaeli University. Mahmutpaşa Mah. Mahmutpaşa Cad. No: 151, 41140 Kollar/Başiskele/Kocaeli, Turkey. E-mail: fatmacanka@hotmail.com, Tel: +90 262 3494351 Fax: +90 262 3493997

³Department of Energy Systems Engineering, Faculty of Technology, Kocaeli University, 41380 Umuttepe, Kocaeli, Turkey. Email: durmuskaya@hotmail.com

⁴Department of Energy Systems Engineering, Faculty of Technology, Karabük University, BalıklarKayası Mevkii 78050 Karabük, Turkey. Email: mozkaymak@gmail.com

Abstract

In this study, an energy and exergy analysis of an Organic Rankine Cycle (ORC) unit was carried out in a biomass-based forest products manufacturing plant. The ORC unit is used for the production of electricity and heat, by using thermal oil as a heat source in the plant. The actual data have been obtained from the ORC unit during the energy production process. The studies have been realized for the energy and exergy analysis of the main components of the ORC unit, which are the evaporator, condenser, turbine and regenerator at two different working conditions. Also, the effect of the condenser pressure on the energy and exergy efficiencies of the system was studied in the context
of this study. At the working conditions of Case-1, the energy and exergy efficiencies were calculated as 12.59% and 33.26 %, respectively. As for Case-2, the energy and exergy efficiencies were calculated as 13.22% and 35.5%. The gradation of the exergy destructions of the components from the greater to the lower one can be listed as; evaporator, condenser, turbine, regenerator and pump.

**Keywords:** Organic Rankine Cycle (ORC), biomass, thermal oil, organic working fluid, energy and exergy analysis

1. **Introduction**

Developing efficient power systems based on renewable energy sources and emitting fewer or no pollutants to the environment are of main concerns of industrial sectors and the governments. The consumption of fossil fuel sources and energy demands are increasing continuously in the world, including Turkey, with the passing of time. The world energy consumption is expected to increase to around 40% between 2006 and 2030 [1]. On the other hand, generating energy from fossil fuel causes some problem to the environment, such as global warming, air pollution, water pollution, soil pollution, acid precipitation, ozone depletion and so on. For this reason, using efficient systems is vital to increase the unit of energy generated per the unit of fuel consumed.

Turkey’s dependence of foreign countries on energy imports especially of oil and non-renewable fossil-originated natural resources (natural gas and hard coal) causes high energy costs. To solve energy problems and prepare for the future developments, many countries and Turkey turn towards renewable energies like biomass, solar, wind and geothermal for the production of clean energy. In addition, power generation from
waste heat recovery is also an important subject for the solution of the energy problems [2-6].

Rankine cycle is one of the most important operating cycles that widely used to convert thermal energy into power in high capacities. Nuclear power plants and coal plants can be given as examples for such applications. In these power plants, water is used as a working fluid, which can cause some technical problems and these problems can be eliminated by using appropriate organic working fluids as a replacement of water in small and medium-scale power cycles [7]. Comparing to water, the organic working fluids have higher molecular weight and lower critical temperatures. They are used in steam cycles, which are called "Organic Rankine Cycles". Organic Rankine Cycles have some advantages over conventional steam cycles that can be listed as [8,9]:

– They require less heat during the evaporation,
– Their evaporation processes can be realized at low pressure and low temperature values,
– Their expansion processes finish in the vapor region, so there is no need to overheat. Thus, the corrosion risk of turbine blades can be almost eliminated.
– Their temperature differences between evaporation and condensation are low; the pressure drops will also be low during the expansion processes. Therefore, simple single stage turbines can be used for the expansion.

Although ORC systems studies and researches have started since the 1880s, it has not become widespread until today. It is inevitable to the use of low-temperature heat sources for the power generation when considering the future of energy, decreasing fossil fuels reserves and increasing environmental concerns. ORC systems give the opportunity to work at low temperatures, which makes possible to generate electricity
from various energy sources like solar energy, geothermal energy, biomass and waste heat [10-23].

There are many academic studies [1,14,24-50] on energy and exergy analysis of ORCs, published in the scientific literature. For example, Al-Sulaiman [26] was carried out a study about detailed exergy analysis of selected thermal power systems driven by parabolic trough solar collectors (PTSCs). In the study, seven refrigerants for the ORC were examined: R134a, R152a, R290, R407c, R600, R600a, and ammonia. Key exergetic parameters were examined: exergetic efficiency, exergy destruction rate, fuel depletion ratio, irreversibility ratio, and improvement potential. The study revealed that there was an exergetic improvement potential of 75% in the systems considered. Also, Al-Sulaiman et al. [28] conducted a study about greenhouse gas emission and exergy assessments of an integrated organic Rankine cycle with a biomass combustor for combined cooling, heating and power production. In the study, the results showed that when the trigeneration case was used, the exergy efficiency increases significantly to 27% as compared with the exergy efficiency of the electrical power case, which was around 11%. It was also found that the main two sources of exergy destruction were the biomass combustor and ORC evaporator. Also, the study showed that the emissions of CO₂ in kg/MWh were significantly high for the electrical power case while for the trigeneration case, the emissions per MWh of trigeneration dropped significantly to relatively low level. El-Emam and Dincer [30] realized a study about exergy and exergoeconomic analyses and optimization of geothermal organic Rankine cycle. In the study, an optimization study was performed based on the heat exchangers total surface area parameter. Parametric studies were performed to investigate the effect of operating parameters, and their effects on the system energetic and exergetic efficiencies and
economic parameters were also investigated. Feng et al. [31] carried out a study on
comparison between regenerative organic Rankine cycle (RORC) and basic organic
Rankine cycle (BORC) based on thermoeconomic multi-objective optimization
considering exergy efficiency and leveled energy cost (LEC). The study demonstrated
that there was a negative correlation between thermodynamic performance and
economic factors. The optimum exergy efficiency and LEC for the Pareto-optimal
solution of the RORC are 55.97% and 0.142 $/kW h, respectively, which are 8.1%
higher exergy efficiency and 21.1% more LEC than that of the BORC under the
considered condition. Li [37] conducted a study on Organic Rankine Cycle performance
evaluation and thermo-economic assessment with various applications and also made
energy and exergy performance evaluation. In the study, working fluid candidates for
various ORC applications based on the heat source temperature domains were
investigated for the thermal efficiency, exergy destruction rate and mass flow rate under
different ORC configurations. Nafey and Sharaf [41] examined, a combined organic
Rankine cycle (solar collector, turbine, recuperator, condenser, and pump), and reverse
osmosis unit (RO) for seawater desalination. Exergy and cost analysis were performed
for saturation and super-heated operating conditions. Exergy efficiency, total exergy
destruction, thermal efficiency, and specific capital cost are evaluated for direct vapor
generation (DVG) process. Toluene and water achieved minimum results for total solar
collector area, specific total cost and the rate of exergy destruction. Tchanche et al. [44]
realized a study about exergy analysis of micro-organic Rankine power cycles for a
small scale solar driven reverse osmosis desalination system. The study showed an
increase of 7% in the energy efficiency of an ORC integrated with a reverse osmosis
desalination system when a regenerator is used.
In this study, an energy and exergy analysis of an ORC unit was carried out in a biomass-based forest products manufacturing plant. The ORC unit is used for the production of electricity and heat in the biomass-based energy production plant by using thermal oil as a heat source for the process. Hexamethyldisiloxane is used as an organic working fluid in the ORC unit. When studies are examined in the literature [51-66], it has not been encountered any energy and exergy analysis of an ORC unit that used hexamethyldisiloxane as an organic working fluid so far. In this article, the energy and exergy analysis of an ORC unit were performed under two different operating conditions. In addition, the effect of condenser pressure on energy and exergy efficiencies of the ORC unit have been investigated experimentally.

2. System description

In this paper, an energy and exergy analysis of an ORC unit has been performed in an integrated forest products manufacturing plant, which has been operated to manufacture wood products, such as laminate flooring with wood, door-skin, wood panels, MDF (Medium Density Fiberboard) and chipboard in Turkey. During the production, waste like wood chips, shavings and sawdust, etc. is burned in a fluidized bed biomass boiler to get thermal oil, which is used to meet the need for heat in the power production process. The temperature of the thermal oil ranges between 280 °C and 300 °C. A portion of the thermal oil is used in the process and the rest is used in the ORC unit for the production of power and heat.

The ORC (Organic Rankine Cycle) unit comprises of preheater (thermal oil/working fluid), evaporator (thermal oil/working fluid), regenerator (working fluid liquid/working fluid vapor), condenser (working fluid/hot water), working fluid feed pump, low voltage
asynchronous electric generator, turbine with pertinent ancillary equipment, turbo
generator auxiliaries (lubricating system, vacuum pump, etc.) and switch-gear. A
scheme of the concept is given in Figure 1., which explains the connections of the turbo
generator to the thermal oil and cooling water loops [67].

**Figure 1.** Main connections of the ORC unit to thermal oil and cooling water circuits.

The turbo generator uses the thermal oil to pre-heat and vaporize a proper organic
working fluid in the evaporator. The organic working fluid vapor actuates the turbine,
which is straight coupled to the electric generator through an elastic coupling. The
exhaust vapor flows through the regenerator where heats the organic working fluid. The
vapor is then condensed in the condenser. The organic working fluid liquid is eventually
pumped to the regenerator and then to the evaporator therefore, finalizing the sequence
of operations in the closed-loop circuit.

The mass flow rate of the thermal oil has been measured by an orifice plate
flowmeter. Thermal oil temperature measurements have been carried out by a
thermocouple at the inlet and outlet of the evaporator. Condenser water flow rate has
been determined by an ultrasonic flow meter (Panametrics PT D 878). The flow rate of
the organic working fluid has been determined by the electromagnetic flow-meter at a
point between the pump and the regenerator. The temperature of organic working fluid
has been measured by a thermocouple at the inlet and outlet of the each unit in the
cycle. The pressure values of the organic working fluid have been determined by a
pressure gauge at the outlet of the evaporator and the condenser. Also, the pressure
values of thermal oil and water have been read at the inlet of the evaporator and the condenser, respectively.

3. Energy and exergy analysis

After leaving the condenser, the organic working fluid (Hexamethyldisiloxane) enters the main pump (organic working fluid pump), where its pressure is increased and then directed to the regenerator. In the regenerator, the organic working fluid gains the heat that comes from the other side of the stream’s recovered heat (of the organic working fluid, which is in the vapor phase) and exits the regenerator in the liquid phase. Then the organic working fluid enters the preheater, in which thermal oil’s heat is transferred to the organic working fluid. The temperature of the organic working fluid is increased to its bubble point. After the preheater, the organic working fluid enters the evaporator, where the organic working fluid is vaporized by drawing heat from the thermal oil. When the organic working fluid is to reach a superheated state, it is send to the turbine; the vapor is expanded through the turbine, the temperature and pressure of the vapor are both decreased, this produce mechanical work, which is converted to power. In the state of vapor, the organic working fluid is sent to the regenerator and rejects its heat to the other side of the organic working fluid in the regenerator. After the regenerator, the organic working fluid is sent directly to the condenser, where it is cooled by rejecting its heat to water and turns into the liquid phase (it condenses). Therefore, the hot water is obtained for the purpose of heating in the process. Leaving the condenser in the liquid phase, the organic working fluid enters the main pump, where its pressure is increased and the cycle continues. A water cooled condenser is used in the cycle. In the
calculations, the pressure drops in the evaporator, condenser and the regenerator have been neglected.

The ORC systems consist of several steady state control volumes. General expressions of mass, energy, and exergy balances of any steady state control volume, by neglecting the potential and kinetic energy changes, can be expressed, respectively, as:

\[ \sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}} \]  
\[ \dot{Q} + \dot{W} = \sum \dot{m}_{\text{out}} h_{\text{out}} - \sum \dot{m}_{\text{in}} h_{\text{in}} \]  
\[ \dot{E}_{\text{heat}} + \dot{W} = \sum \dot{E}_{\text{out}} - \sum \dot{E}_{\text{in}} + \dot{I} \]

Where, subscripts in and out represent the inlet and exit states, \( \dot{Q} \) and \( \dot{W} \) are the net heat and work inputs, \( \dot{E} \) is the exergy rate and \( \dot{I} \) is the irreversibility rate.

The thermal efficiency of the ORC may be expressed as:

\[ \eta_{\text{th}} = \frac{\dot{W}_{\text{net,out}}}{\dot{Q}_{\text{in}}} = \frac{\dot{W}_{\text{net,out}}}{\dot{m}_{\text{in}}(h_{\text{in}} - h_{\text{out}})} \]

\[ \dot{W}_{\text{net,out}} = \dot{W}_{\text{turb}} - \dot{W}_{\text{pump}} \]

Where;

\( \eta_{\text{th}} \): The thermal efficiency of the system

\( \dot{W}_{\text{turb}} \): Turbine’s work

3.1. Exergy of the system

\[ E = (E - U_0) + P_0(V - V_0) - T_0(S - S_0) \]
1 \[ E = U + KE + PE \]  

(7)

Where;

4 \[ E: \] Exergy of the system,

5 \[ E: \] Energy of the system,

6 \[ V: \] The volume of the system,

7 \[ S: \] Entropy of the system.

8

Exergy efficiency of the turbine demonstrates how well the actual turbine output is achieved from the stream exergy. The overall exergy efficiency of the entire cycle can be expressed as;

\[ \eta_{\text{ex,cyc}} = \frac{\dot{W}_{\text{net,out}}}{E_{\text{in}}} = \frac{\dot{W}_{\text{net,out}}}{m_{\text{oil}}[h_{1} - h_{2} - T_{0}(s_{1} - s_{2})]} \]  

(8)

4. Results and discussion

In this study, an energy and exergy analysis of an Organic Rankine Cycle (ORC) unit was realized in a biomass-based forest products manufacturing plant. The ORC unit is used to produce electricity and hot water by using the thermal oil as a heat source. The required heat for this thermal oil is obtained from biomass, which is burned in a fluidized bed biomass boiler. Hexamethyldisiloxane is used as the organic working fluid in the ORC unit. In this article, the real data have been obtained from the ORC unit during the energy production process. The studies named as Case-1 and Case-2 and they have been carried out at two different operating conditions for the energy and exergy
analysis of the main components of the ORC unit, which are evaporator, condenser, turbine and regenerator. Also, the effect of condenser pressure on the energy and exergy efficiencies of the system was examined. The results of these studies have been presented and commented.

In the first study (Case-1), 6831 kW heat was transferred from the thermal oil to the ORC unit and 947.36 kWe gross power was generated. To circulate the organic working fluid in the cycle, the power that drawn by the pump was about 87.3 kW. Hot water was obtained from the condenser at the temperature of 93.1 °C, with the thermal capacity of 5483 kW. The net power generation of the ORC unit was 860.06 kW and electrical energy efficiency was calculated as 12.59%.

The highest exergy destruction has occurred in the evaporator during heat exchange process. Exergy destruction rate in the evaporator was 3920.81 kW. This was the 60.25% of exergy input of 6507.05 kW. Condenser, turbine, regenerator and pump followed the evaporator, respectively, in relation to the exergy destruction rate. The reason for high exergy loss in the evaporator is high outlet temperature of the thermal oil (at the temperature of 217.1 °C). The thermal oil that is already leaving the evaporator is sent back to the biomass boiler to raise its temperature to 280 °C. The properties at various states for Case-1 are given in Table 1.

Table 1. The properties at various states for Case-1.

T-S diagram of Organic Rankine Cycle for Case-1 can be seen in Figure 2.
Representative exergy and energy performance data for Case-1 can be seen in Table 2.

Table 2. Representative exergy and energy performance data for Case-1.

Exergy losses diagram for Case-1 is given in Figure 3.

Figure 3. Exergy losses diagram for Case-1 (given as the percentages of exergy input).

In the second study (Case-2), 6746 kW heat was transferred from the thermal oil to the ORC unit and 977.21 kWe gross power was generated. The net power generation of the ORC unit was 891.76 kW and electrical energy efficiency was calculated as 13.22%. The thermal capacity of hot water which was obtained from the condenser was 5376.46 kW and its temperature was 85.6 °C. In the second study, the effect of condenser pressure on the performance of the ORC unit was investigated by reducing condenser pressure to 1.6 bar. When condenser pressure was reduced from 2.1 bar to 1.6 bar, the cycle efficiency (net power production rate) increased from 12.59% to 13.22%. When condenser pressure was reduced, the water temperature at the outlet of the condenser was lowered, too. If the water that exiting from the condenser, is used for the heating purposes in the process, the water temperature at the condenser outlet should be checked out to meet the need of heating in the process. Water that coming from the condenser was used to preheat the air (which was taken from the atmosphere) during the studies and it was also used for the purpose of space heating. In this process, the temperature of
the water was decreased from 93.1 °C to 85.6 °C. This does not affect the production process. To cool organic working fluid in the condenser efficiently, the flow rate of condenser cooling water was raised from 64.42 kg/s to 120.33 kg/h. Therefore, the energy consumption of condenser cooling water circulation pump was increased.

The properties at various states for Case-2 are given in Table 3.

Table 3. The properties at various states for Case-2.

T-S diagram of Organic Rankine Cycle for Case-2 can be seen in Figure 4.

Figure 4. T-S diagram of Organic Rankine Cycle for Case-2.

Representative exergy and energy performance data for Case-2 can be seen in Table 4.

Table 4. Representative exergy and energy performance data for Case-2.

In the second study, the highest exergy loss took place in the evaporator just as in the first study. The evaporator was followed by condenser, turbine, regenerator and pump, respectively, in relation to the exergy destruction rate. While the energy and exergy efficiency were calculated as 12.59% and 33.26% in the first experiment, the values of the energy and exergy efficiency in the second experiment were calculated as 13.22% and 35.5%, respectively. Reducing the condenser pressure has affected the energy and exergy efficiency, significantly. When condenser pressure was reduced, the energy and
Exergy efficiency of the ORC has increased. The main reason for this situation is the decrease of the transferred energy amount to the cooling water of the condenser. If the energy that transferred to the condenser is used as a heat source in the process, the condenser operating pressure should be preferred in accordance with the required temperature at the point that the heat source is used. If the heat that obtained from the condenser is not used in the process and rejected to the atmosphere by the cooling tower, it is necessary to prefer the lowest pressure for the condenser to increase the energy and exergy efficiencies, considering atmospheric conditions.

Exergy losses diagram for Case-2 can be seen in Figure 5.

**Figure 5.** Exergy losses diagram for Case-2.

5. Conclusions

In this academic work, an energy and exergy analysis of an Organic Rankine Cycle (ORC) unit was implemented in a biomass-based forest products manufacturing plant. The ORC unit is used for the production of electricity and heat in the plant by using thermal oil as a heat source for the process. The genuine data have been attained from the ORC unit during the energy production process. The studies have been realized at two different working conditions to analyze the energy and exergy situations of the main components of the ORC unit. The results were compared. The followings can be concluded from the context of these studies:

- In the first study, the evaporator pressure was set at 12.9 bar and the condenser pressure was set at 2.1 bar. Under these conditions, 6831 kW heat was transferred from
thermal oil to the ORC unit and 860.06 kW net electricity production was realized. In these circumstances, the energy and exergy efficiencies were calculated as 12.59% and 33.26%, respectively. Hot water was obtained from the condenser at the temperature of 93.1 °C and with the thermal capacity of 5483 kW.

– In the second study, evaporator pressure was set at 12.8 bar and condenser pressure was set at 1.6 bar. In these circumstances, 6746 kW heat was transferred from thermal oil to the ORC unit and 977.21 kW gross electricity generation was realized. Energy and exergy efficiency of the system were calculated as 13.43% and 35.5%, respectively.

– When condenser pressure was reduced from 2.1 bar to 1.6 bar, the efficiency of the cycle (net power production rate) increased from 12.59% to 13.22% and also, the exergy efficiency increased from 33.26% to 35.5%. When the condenser pressure was lowered, the temperature of the water that leaving the condenser decreased from 93.1 °C to 85.6 °C.

– In both studies, the gradation of the exergy destructions of the components from the greater one to the lower one can be listed as evaporator, condenser, turbine, regenerator and pump. The reason for high exergy loss in the evaporator is high outlet temperature of the thermal oil (at the temperature of 217.1 °C) that exiting from the evaporator.

References


[40] Mohammadhkani F, Shokati N, Mahmoudi SMS, Yari M, Rosen MA. Exergoeconomic assessment and parametric study of a Gas Turbine-Modular


Table 1. The properties at various states for Case-1.

<table>
<thead>
<tr>
<th>State No</th>
<th>T (°C)</th>
<th>Fluid</th>
<th>Phase</th>
<th>P (bar)</th>
<th>h (kJ/kg)</th>
<th>s (kJ/kg·K⁻¹)</th>
<th>m (kg/s)</th>
<th>E (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>25.00</td>
<td>Water</td>
<td>Dead state</td>
<td>1.0</td>
<td>104.89</td>
<td>0.3674</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0'</td>
<td>25.00</td>
<td>HMDSO</td>
<td>Dead state</td>
<td>1.0</td>
<td>-150.54</td>
<td>-0.4494</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0''</td>
<td>25.00</td>
<td>Thermal oil</td>
<td>Dead state</td>
<td>1.0</td>
<td>61.88</td>
<td>0.7200</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>276.50</td>
<td>Thermal oil</td>
<td>Liquid</td>
<td>2.5</td>
<td>573.20</td>
<td>1.0306</td>
<td>49.73</td>
<td>20,821.22</td>
</tr>
<tr>
<td>2</td>
<td>217.30</td>
<td>Thermal oil</td>
<td>Liquid</td>
<td>2.5</td>
<td>431.58</td>
<td>0.9945</td>
<td>49.73</td>
<td>14,314.16</td>
</tr>
<tr>
<td>3</td>
<td>219.46</td>
<td>HMDSO</td>
<td>Sat. vapor</td>
<td>12.9</td>
<td>374.95</td>
<td>0.8348</td>
<td>30.64</td>
<td></td>
</tr>
<tr>
<td>3'</td>
<td>221.80</td>
<td>HMDSO</td>
<td>Sup. vapor</td>
<td>12.9</td>
<td>381.48</td>
<td>0.8480</td>
<td>30.64</td>
<td>4,448.64</td>
</tr>
<tr>
<td>4</td>
<td>185.10</td>
<td>HMDSO</td>
<td>Sup. vapor</td>
<td>2.1</td>
<td>346.09</td>
<td>0.8507</td>
<td>30.64</td>
<td>3,339.89</td>
</tr>
<tr>
<td>5</td>
<td>129.60</td>
<td>HMDSO</td>
<td>Sup. vapor</td>
<td>2.1</td>
<td>240.36</td>
<td>0.6049</td>
<td>30.64</td>
<td>2,345.91</td>
</tr>
<tr>
<td>6</td>
<td>126.10</td>
<td>HMDSO</td>
<td>Comp. liquid</td>
<td>2.1</td>
<td>55.41</td>
<td>0.1430</td>
<td>30.64</td>
<td>898.23</td>
</tr>
<tr>
<td>7</td>
<td>72.80</td>
<td>Water</td>
<td>Comp. liquid</td>
<td>3.0</td>
<td>304.75</td>
<td>0.9888</td>
<td>64.42</td>
<td>939.89</td>
</tr>
<tr>
<td>8</td>
<td>93.10</td>
<td>Water</td>
<td>Comp. liquid</td>
<td>3.0</td>
<td>390.02</td>
<td>1.2282</td>
<td>64.42</td>
<td>1,835.60</td>
</tr>
<tr>
<td>9</td>
<td>126.80</td>
<td>HMDSO</td>
<td>Comp. liquid</td>
<td>12.9</td>
<td>57.33</td>
<td>0.1437</td>
<td>30.64</td>
<td>950.95</td>
</tr>
<tr>
<td>10</td>
<td>171.80</td>
<td>HMDSO</td>
<td>Comp. liquid</td>
<td>12.9</td>
<td>158.51</td>
<td>0.3833</td>
<td>30.64</td>
<td>1,862.39</td>
</tr>
<tr>
<td>11</td>
<td>214.70</td>
<td>HMDSO</td>
<td>Comp. liquid</td>
<td>12.9</td>
<td>264.05</td>
<td>0.6095</td>
<td>30.64</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Representative exergy and energy performance data for Case-1.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Exergy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_r$ (ev, kW)</td>
<td>6,831.00 $\eta_{\text{evap}}$ (%) 39.75</td>
</tr>
<tr>
<td>$Q_r$ (con, kW)</td>
<td>5,666.27 $\eta_{\text{con}}$ (%) 61.87</td>
</tr>
<tr>
<td>$W$ (tur, kW)</td>
<td>947.36 $\eta_{\text{tur}}$ (%) 85.44</td>
</tr>
<tr>
<td>$W$ (pump, kW)</td>
<td>87.30 $\eta_{\text{reg}}$ (%) 91.70</td>
</tr>
<tr>
<td>$W$ (rev, pump, kW)</td>
<td>58.75 $\eta_{\text{exc, cyc}}$ (%) 33.26</td>
</tr>
<tr>
<td>$Q_w$ (con, kW)</td>
<td>5,493.00 - -</td>
</tr>
<tr>
<td>$\eta$ (pump, %)</td>
<td>67.30 - -</td>
</tr>
<tr>
<td>$\eta$ (cycle, %)</td>
<td>12.59</td>
</tr>
</tbody>
</table>

Table 3. The properties at various states for Case-2.

<table>
<thead>
<tr>
<th>State No</th>
<th>T (°C)</th>
<th>Fluid</th>
<th>Phase</th>
<th>P (bar)</th>
<th>$h$ (kJ/kg)</th>
<th>$s$ (kJ/kg-K)</th>
<th>$m$ (kg/s)</th>
<th>$E$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>25.00</td>
<td>Water</td>
<td>Dead state</td>
<td>1.0</td>
<td>104.89</td>
<td>0.3674</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0'</td>
<td>25.00</td>
<td>HMDSO</td>
<td>Dead state</td>
<td>1.0</td>
<td>-150.54</td>
<td>-0.4494</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0''</td>
<td>25.00</td>
<td>Thermal oil</td>
<td>Dead state</td>
<td>1.0</td>
<td>61.88</td>
<td>0.7200</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>281.60</td>
<td>Thermal</td>
<td>Liquid</td>
<td>2.6</td>
<td>586.00</td>
<td>1.0334</td>
<td>47.88</td>
<td>20,620.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>-----</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>221.30</td>
<td>Thermal</td>
<td>Liquid</td>
<td>2.6</td>
<td>440.74</td>
<td>0.9972</td>
<td>47.88</td>
<td>14,182.73</td>
</tr>
<tr>
<td>3</td>
<td>218.97</td>
<td>HMDSO</td>
<td>Sat. vapor</td>
<td>12.8</td>
<td>374.36</td>
<td>0.8338</td>
<td>27.93</td>
<td></td>
</tr>
<tr>
<td>3'</td>
<td>219.40</td>
<td>HMDSO</td>
<td>Sup. vapor</td>
<td>12.8</td>
<td>375.56</td>
<td>0.8362</td>
<td>27.93</td>
<td>3,987.93</td>
</tr>
<tr>
<td>4</td>
<td>178.90</td>
<td>HMDSO</td>
<td>Sup. vapor</td>
<td>1.6</td>
<td>335.51</td>
<td>0.8406</td>
<td>27.93</td>
<td>2,833.00</td>
</tr>
<tr>
<td>5</td>
<td>122.10</td>
<td>HMDSO</td>
<td>Sup. vapor</td>
<td>1.6</td>
<td>229.08</td>
<td>0.5892</td>
<td>27.93</td>
<td>1,954.18</td>
</tr>
<tr>
<td>6</td>
<td>115.40</td>
<td>HMDSO</td>
<td>Comp. liquid</td>
<td>1.6</td>
<td>32.22</td>
<td>0.0844</td>
<td>27.93</td>
<td>659.86</td>
</tr>
<tr>
<td>7</td>
<td>74.90</td>
<td>Water</td>
<td>Comp. liquid</td>
<td>3.1</td>
<td>313.74</td>
<td>1.0155</td>
<td>120.33</td>
<td>1,879.37</td>
</tr>
<tr>
<td>8</td>
<td>85.60</td>
<td>Water</td>
<td>Comp. liquid</td>
<td>3.1</td>
<td>358.42</td>
<td>1.1413</td>
<td>120.33</td>
<td>2,743.30</td>
</tr>
<tr>
<td>9</td>
<td>116.03</td>
<td>HMDSO</td>
<td>Comp. liquid</td>
<td>12.8</td>
<td>34.09</td>
<td>0.0848</td>
<td>27.93</td>
<td>708.03</td>
</tr>
<tr>
<td>10</td>
<td>161.20</td>
<td>HMDSO</td>
<td>Comp. liquid</td>
<td>12.8</td>
<td>134.02</td>
<td>0.3276</td>
<td>27.93</td>
<td>1,477.31</td>
</tr>
<tr>
<td>11</td>
<td>213.90</td>
<td>HMDSO</td>
<td>Comp. liquid</td>
<td>12.8</td>
<td>261.96</td>
<td>0.6053</td>
<td>27.93</td>
<td>-</td>
</tr>
<tr>
<td>11'</td>
<td>219.00</td>
<td>HMDSO</td>
<td>Sat. liquid</td>
<td>12.8</td>
<td>275.70</td>
<td>0.6333</td>
<td>27.93</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>116.67</td>
<td>HMDSO</td>
<td>Sat. vapor</td>
<td>1.6</td>
<td>219.25</td>
<td>0.5641</td>
<td>27.93</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 4.** Representative exergy and energy performance data for Case-2.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Exergy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_r$ (ev, kW)</td>
<td>6,746.00 $\eta_{evap}$ (%) 39.0</td>
</tr>
<tr>
<td>$Q_r$ (con, kW)</td>
<td>5,498.08 $\eta_{con}$ (%) 66.7</td>
</tr>
<tr>
<td>$W$ (tur, kW)</td>
<td>977.21 $\eta_{tur}$ (%) 84.6</td>
</tr>
<tr>
<td>$W$ (pump, kW)</td>
<td>85.45 $\eta_{reg}$ (%) 87.5</td>
</tr>
<tr>
<td>$W$ (rev, pump, kW)</td>
<td>52.12 $\eta_{exc. cyc}$ (%) 35.5</td>
</tr>
<tr>
<td>$Q_w$ (con, kW)</td>
<td>5,376.46 - -</td>
</tr>
<tr>
<td>$\eta$ (pump, %)</td>
<td>61.00 - -</td>
</tr>
</tbody>
</table>
η (cycle, %)  13.22 - -

Figure 1. Main connections of the ORC unit to thermal oil and cooling water circuits.
Figure 2. T-S diagram of Organic Rankine Cycle for Case-1.

Figure 3. Exergy losses diagram for Case-1 (given as the percentages of exergy input).

Figure 4. T-S diagram of Organic Rankine Cycle for Case-2.
Figure 5. Exergy losses diagram for Case-2.