Optimized geothermal binary power cycles

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LOW-BIN project

- ORC power plant for 65-90°C geothermal water
- ORC heat & power cogeneration plant for 120-150°C geo-water and 60/80°C district heating

Industrial partner: TURBODEN

Supported by DG-TREN (FP6)
Isobutane (R600a) and R134a as working fluids

• widely used with excellent results in the heat pumps and cooling/refrigeration industry

• available in the market

• The necessary parts for a Rankine cycle machine are available in the market

• CARRIER, lately developed low cost 200 kWe ORC units using R134a. Two units commenced operation in August-December 2006 in “Chena”, Alaska, USA, utilizing 74°C water
Shell & tubes condenser

Overall heat transfer:

\[
U_o = \frac{1}{A_o \frac{1}{A_i} + \frac{A_o \ln(r_o/r_i)}{2\pi kL} + \frac{1}{h_o}}
\]

Laminar condensation on tubes surface:

\[
h_o = 0.725 \left[ \frac{\rho (\rho - \rho_v) g h_f k_f}{\mu_d (T_g - T_w)} \right]^{0.25}
\]

Turbulent flow in tubes:

\[
h_i = \frac{Nuk}{D}
\]

\[
Nu = 0.023 Re^{0.8} Pr^{0.4}
\]

\[
Re = \frac{u \cdot D \cdot \rho}{\mu}
\]
Plate H.E. as evaporator

One side: Geothermal water
Second side: working fluid
Liquid ⇒ Two Phase ⇒ Vapor

\[ U_{total} = \frac{1}{U_{sp/l}} + \frac{1}{U_{tp}} + \frac{1}{U_{sp/g}} \]

\[ U_{sp/l} = \frac{1}{h_{sp/l} \Delta x + \frac{1}{h_{gw}}} \]
\[ U_{tp} = \frac{1}{h_{tp} \Delta x + \frac{1}{h_{gw}}} \]
\[ U_{sp/g} = \frac{1}{h_{sp/g} \Delta x + \frac{1}{h_{gw}}} \]

Evaporation heat transfer

\[ h_{tp} = C \left( \frac{k_i}{D_e} \right) \left( \frac{\text{Re}_i}{L_p} \right)^{0.4124} \left( \frac{p}{p_{cr}} \right)^{0.12} \left( \frac{65}{\beta} \right)^{0.35} \]

\[ \text{Re} = \frac{u \cdot L \cdot \rho}{\mu} \]
\[ c_f = 0.074 \cdot \frac{\text{Re}^{0.2}}{\text{Re}} - \frac{1050}{\text{Re}} \]
\[ St = c_f \cdot \frac{1}{2} \left( \frac{\text{Pr}}{\text{Pr}_{cr}} \right)^{\frac{3}{2}} \]
\[ Nu = St \cdot \text{Re} \cdot \text{Pr} \]
\[ h_{sp/l,g} = \frac{Nu \cdot k}{L} \]
Rankine cycle optimisation

Objectives:

- Maximize overall net conversion efficiency of the plant

\[
\eta_{\text{cycle}} = \frac{W_{\text{turbine}} - N_{\text{pump}}}{Q_{\text{heatexch}}} = \frac{(h_4 - h_5) \cdot m_{\text{wf}} - N_{\text{pump}}}{(h_3 - h_2) \cdot m_{\text{wf}}}
\]

- Minimize the cost of the plant
  \( \rightarrow \) Minimize both Heat Exchangers surface

Variables:

\( P_2, m_{\text{gr}}, m_{\text{wf}}, \Delta T_H, \Delta T_C \)

Constraints:

Net Power Output

\( 200 \, \text{kW}_e \pm 5\, \text{kW}_e \)

using the EASY software code (Evolutionary Algorithm System) by National Technical University of Athens, ref. http://velos0.ltt.mech.ntua.gr/EASY
ORC machine for 65°C: R134a

optimal solutions - R134a

- Exchangers' surface
- Binary plant's overall efficiency
ORC machine for 65°C: R600a

optimal solutions - isobutan

binary plant's overall efficiency
ORC machine for 65°C: R134a vs Isobutane

Comparison R134a - isobutane

- exchangers' surface
- binary plant's overall efficiency
### ORC machine for 65°C: R134a vs Isobutane

<table>
<thead>
<tr>
<th>Variable</th>
<th>Isobutane</th>
<th>R134a</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_2$ (bar)</td>
<td>6.19</td>
<td>11.99</td>
</tr>
<tr>
<td>$m_{\text{geothermal water}}$ (kg/sec)</td>
<td>46</td>
<td>51.2</td>
</tr>
<tr>
<td>$m_{\text{working fluid}}$ (kg/sec)</td>
<td>10.2</td>
<td>17.5</td>
</tr>
<tr>
<td>$\Delta T_H$ ($^\circ$C)</td>
<td>21.8</td>
<td>18.6</td>
</tr>
<tr>
<td>$\Delta T_C$ ($^\circ$C)</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>pump power (kW)</td>
<td>3.9</td>
<td>13.4</td>
</tr>
<tr>
<td>cooling water flow (kg/sec)</td>
<td>119</td>
<td>116</td>
</tr>
<tr>
<td>surface of the condenser (m$^2$)</td>
<td>7.0</td>
<td>5.5</td>
</tr>
<tr>
<td>surface of the heat exchanger (m$^2$)</td>
<td>5.7</td>
<td>4.0</td>
</tr>
<tr>
<td>total H.E. surface (m$^2$)</td>
<td>12.7</td>
<td>9.5</td>
</tr>
<tr>
<td>net conversion efficiency</td>
<td>7.04</td>
<td>7.16</td>
</tr>
</tbody>
</table>
ORC heat & power cogeneration
source: 120°C, cooling: 60/80°C

optimal solutions - R134a

exchangers' surface

binary plant's overall efficiency
R134a ORC plants

R134a - temperature threshold at 65, 100, 120

- Cogeneration 120°C-60/80°C
- Low temperature 65°C
- Standard 100°C

surface of the exchangers

overall efficiency of the binary plant
# R134a ORC plants

<table>
<thead>
<tr>
<th>Variable</th>
<th>Heat &amp; power cogeneration 120°C</th>
<th>Power generation 65°C</th>
<th>Standard binary power plant, 100°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_2$ (bar)</td>
<td>34.99</td>
<td>11.99</td>
<td>15.52</td>
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<tr>
<td>$m_{\text{geothermal}}$ (kg/sec)</td>
<td>52</td>
<td>51.2</td>
<td>45</td>
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<tr>
<td>$m_{R134a}$ (kg/sec)</td>
<td>35</td>
<td>17.5</td>
<td>17.8</td>
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<tr>
<td>$\Delta T_H$ (°C)</td>
<td>26</td>
<td>18.6</td>
<td>20.0</td>
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<tr>
<td>$\Delta T_C$ (°C)</td>
<td>20</td>
<td>7.5</td>
<td>7.5</td>
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<tr>
<td>Cooling Temp (°C)</td>
<td>60</td>
<td>10</td>
<td>10</td>
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<tr>
<td>Condensing Temp (°C)</td>
<td>80</td>
<td>30</td>
<td>27</td>
</tr>
<tr>
<td>R134a pump power (kW)</td>
<td>58</td>
<td>13.4</td>
<td>18.5</td>
</tr>
<tr>
<td>Cooling water flow (kg/sec)</td>
<td>66</td>
<td>116</td>
<td>110</td>
</tr>
<tr>
<td>Condenser surface (m²)</td>
<td>22.0</td>
<td>5.5</td>
<td>4.6</td>
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<tr>
<td>Surface of the PHE (m²)</td>
<td>2.0</td>
<td>4.0</td>
<td>5.4</td>
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<tr>
<td>Total H.E. surface (m²)</td>
<td>24.0</td>
<td>9.5</td>
<td>10</td>
</tr>
<tr>
<td><strong>Net conversion efficiency</strong></td>
<td><strong>5.93</strong></td>
<td><strong>7.16</strong></td>
<td><strong>7.7</strong></td>
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<tr>
<td>Net electrical Power (kW)</td>
<td>207</td>
<td>202</td>
<td>204</td>
</tr>
</tbody>
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