10-46 A steam power plant operates on an ideal regenerative Rankine cycle with two open feedwater heaters. The net power output of the power plant and the thermal efficiency of the cycle are to be determined.

**Assumptions**
1. Steady operating conditions exist.
2. Kinetic and potential energy changes are negligible.

**Analysis**

\[ h_1 = h_{f@5 \text{ kPa}} = 137.75 \text{ kJ/kg} \]
\[ v_1 = v_{f@5 \text{ kPa}} = 0.001005 \text{ m}^3/\text{kg} \]
\[ w_{pl,in} = v_1(P_2 - P_1) = (0.001005 \text{ m}^3/\text{kg}) \times (200 - 5) \text{ kPa} \]
\[ h_2 = h_1 + w_{pl,in} = 137.75 + 0.20 = 137.95 \text{ kJ/kg} \]

\[ P_3 = 0.2 \text{ MPa} \]
\[ h_3 = h_{f@0.2 \text{ MPa}} = 504.71 \text{ kJ/kg} \]
\[ v_3 = v_{f@0.2 \text{ MPa}} = 0.001061 \text{ m}^3/\text{kg} \]
\[ w_{pl,III,in} = v_3(P_4 - P_3) = (0.001061 \text{ m}^3/\text{kg}) \times (600 - 200) \text{ kPa} \]
\[ h_4 = h_3 + w_{pl,III,in} = 504.71 + 0.42 = 505.13 \text{ kJ/kg} \]

\[ P_5 = 0.6 \text{ MPa} \]
\[ h_5 = h_{f@0.6 \text{ MPa}} = 670.38 \text{ kJ/kg} \]
\[ v_5 = v_{f@0.6 \text{ MPa}} = 0.001101 \text{ m}^3/\text{kg} \]
\[ w_{pl,in} = v_5(P_6 - P_5) = (0.001101 \text{ m}^3/\text{kg}) \times (10,000 - 600) \text{ kPa} \]
\[ h_6 = h_5 + w_{pl,III,in} = 670.38 + 10.35 = 680.73 \text{ kJ/kg} \]

\[ P_7 = 10 \text{ MPa} \]
\[ h_7 = 3625.8 \text{ kJ/kg} \]
\[ T_7 = 600^\circ \text{C} \]
\[ s_7 = 6.9045 \text{ kJ/kg} \cdot \text{K} \]
\[ P_8 = 0.6 \text{ MPa} \]
\[ s_8 = s_7 \]
\[ x_8 = \frac{s_8 - s_f}{s_{fg}} = \frac{6.9045 - 1.5302}{5.5968} = 0.9602 \]

\[ P_9 = 0.2 \text{ MPa} \]
\[ s_9 = s_7 \]
\[ h_9 = h_f + x_9 h_{fg} = 504.71 + (0.9602)(2201.6) \]
\[ = 2618.7 \text{ kJ/kg} \]
\[ P_{10} = 5 \text{kPa} \quad x_{10} = \frac{s_{10} - s_f}{s_f} = \frac{6.9045 - 0.4762}{7.9176} = 0.8119 \]

\[ s_{10} = s_7 \quad h_{10} = h_f + x_{10} h_{fg} = 137.75 + (0.8119)(2423.0) = 2105.0 \text{ kJ/kg} \]

The fraction of steam extracted is determined from the steady-flow energy balance equation applied to the feedwater heaters. Noting that \( Q \equiv \dot{W} \equiv \Delta ke \equiv \Delta pe \equiv 0 \),

\[
\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system} \Rightarrow (\text{steady}) = 0
\]

FWH-2: \[
\dot{E}_{in} = \dot{E}_{out} \quad \sum \dot{m}_i h_i = \sum \dot{m}_e h_e \quad \dot{m}_s h_8 + \dot{m}_4 h_4 = \dot{m}_5 h_5 \quad y h_8 + (1 - y) h_4 = 1(h_5)
\]

where \( y \) is the fraction of steam extracted from the turbine \((= \dot{m}_s / \dot{m}_s)\). Solving for \( y \),

\[
y = \frac{h_5 - h_4}{h_5 - h_4} = \frac{670.38 - 505.13}{2821.8 - 505.13} = 0.07133
\]

FHW-1: \[
\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \quad \dot{m}_a h_a + \dot{m}_2 h_2 = \dot{m}_3 h_3 \quad z h_9 + (1 - y - z) h_2 = (1 - y) h_3
\]

where \( z \) is the fraction of steam extracted from the turbine \((= \dot{m}_a / \dot{m}_a)\) at the second stage. Solving for \( z \),

\[
z = \frac{h_3 - h_2}{h_3 - h_2} (1 - y) = \frac{504.71 - 137.95}{2618.7 - 137.95} (1 - 0.07136) = 0.1373
\]

Then,

\[
q_{in} = h_7 - h_8 = 3625.8 - 680.73 = 2945.0 \text{ kJ/kg}
\]

\[
q_{out} = (1 - y - z)(h_{10} - h_1) = (1 - 0.07133 - 0.1373)(2105.0 - 137.75) = 1556.8 \text{ kJ/kg}
\]

\[
w_{net} = q_{in} - q_{out} = 2945.0 - 1556.8 = 1388.2 \text{ kJ/kg}
\]

and

\[
\dot{W}_{net} = \dot{m}w_{net} = (22 \text{ kg/s})(1388.2 \text{ kJ/kg}) = 30,540 \text{ kW} \approx 30.5 \text{ MW}
\]

\[
(b) \quad \eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1556.8 \text{ kJ/kg}}{2945.0 \text{ kJ/kg}} = 47.1\%
\]
A steam power plant operates on an ideal regenerative Rankine cycle with two feedwater heaters, one closed and one open. The mass flow rate of steam through the boiler for a net power output of 250 MW and the thermal efficiency of the cycle are to be determined.

**Assumptions**
1. Steady operating conditions exist.
2. Kinetic and potential energy changes are negligible.

**Analysis**

(a) From the steam tables (Tables A-4, A-5, and A-6),

\[ h_1 = h_f@10 \text{ kPa} = 191.81 \text{ kJ/kg} \]
\[ \nu_1 = \nu_f@10 \text{ kPa} = 0.00101 \text{ m}^3/\text{kg} \]
\[ w_{pl,in} = \nu_1 (P_2 - P_1) \]
\[ = (0.00101 \text{ m}^3/\text{kg}) \times 300 \text{ kPa} \times \left( 1 \frac{\text{kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) \]
\[ = 0.29 \text{ kJ/kg} \]
\[ h_2 = h_1 + w_{pl,in} = 191.81 + 0.29 = 192.10 \text{ kJ/kg} \]

\[ P_4 = 0.3 \text{ MPa} \]
\[ h_3 = h_f@0.3 \text{ MPa} = 561.43 \text{ kJ/kg} \]

sat. liquid
\[ \nu_3 = \nu_f@0.3 \text{ MPa} = 0.001073 \text{ m}^3/\text{kg} \]
\[ w_{pl,in} = \nu_3 (P_4 - P_3) \]
\[ = (0.001073 \text{ m}^3/\text{kg}) \times 12.5 \text{ kPa} \times \left( 1 \frac{\text{kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) \]
\[ = 13.09 \text{ kJ/kg} \]
\[ h_4 = h_3 + w_{pl,in} = 561.43 + 13.09 = 574.52 \text{ kJ/kg} \]

\[ P_5 = 0.8 \text{ MPa} \]
\[ h_5 = h_f@0.8 \text{ MPa} = 720.87 \text{ kJ/kg} \]

sat. liquid
\[ \nu_5 = \nu_f@0.8 \text{ MPa} = 0.001115 \text{ m}^3/\text{kg} \]
\[ T_6 = T_{sat}@0.8 \text{ MPa} = 170.4^\circ \text{C} \]

\[ T_6 = T_5, \ P_5 = 12.5 \text{ MPa} \rightarrow h_5 = 727.83 \text{ kJ/kg} \]
\[ P_6 = 12.5 \text{ MPa} \]
\[ h_6 = 3476.5 \text{ kJ/kg} \]
\[ T_6 = 550^\circ \text{C} \]
\[ s_6 = 6.6317 \text{ kJ/kg} \cdot \text{K} \]
\[ P_8 = 0.8 \text{ MPa} \]
\[ x_9 = \frac{s_9 - s_f}{s_{fg}} = \frac{6.6317 - 2.0457}{4.6160} = 0.9935 \]
\[ h_9 = h_f + x_9 h_{fg} = 720.87 + (0.9935)(2047.5) = 2755.0 \text{ kJ/kg} \]

\[ P_{10} = 0.3 \text{ MPa} \]
\[ x_{10} = \frac{s_{10} - s_f}{s_{fg}} = \frac{6.6317 - 1.6717}{5.3200} = 0.9323 \]
\[ h_{10} = h_f + x_{10} h_{fg} = 561.43 + (0.9323)(2163.5) = 2575.8 \text{ kJ/kg} \]

\[ P_1 = 10 \text{ kPa} \]
\[ x_{11} = \frac{s_{11} - s_f}{s_{fg}} = \frac{6.6317 - 0.6492}{7.4996} = 0.7977 \]
\[ h_{11} = h_f + x_{11} h_{fg} = 191.81 + (0.7977)(2392.1) = 2100.0 \text{ kJ/kg} \]

The fraction of steam extracted is determined from the steady-flow energy balance equation applied to the feedwater heaters. Noting that \( \dot{Q} \equiv \dot{W} \equiv \Delta ke \equiv \Delta pe \equiv 0 \),

\[ \dot{E}_\text{in} - \dot{E}_\text{out} = \Delta E_{\text{system}} \]
\[ \dot{E}_\text{in} = \dot{E}_\text{out} \]
\[ \sum m_i h_i \rightarrow \dot{m}_9 (h_9 - h_6) = \dot{m}_5 (h_5 - h_4) \rightarrow y (h_9 - h_6) = h_5 - h_4 \]
where \( y \) is the fraction of steam extracted from the turbine \((= \dot{m}_10 / \dot{m}_5)\). Solving for \( y \),

\[
y = \frac{h_5 - h_4}{h_5 - h_6} = \frac{727.83 - 574.52}{2755.0 - 720.87} = 0.0753
\]

For the open FWH,

\[
\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system} \quad \text{^{steady}} = 0
\]

\[
\sum \dot{m}_i h_i = \sum \dot{m}_i h_c \quad \rightarrow \quad \dot{m}_1 h_1 + \dot{m}_2 h_2 + \dot{m}_10 h_{10} = \dot{m}_3 h_3 
\]

\[
\rightarrow \quad yh_7 + (1 - y - z)h_2 + zh_{10} = (1)h_3
\]

where \( z \) is the fraction of steam extracted from the turbine \((= \dot{m}_9 / \dot{m}_5)\) at the second stage. Solving for \( z \),

\[
z = \frac{(h_3 - h_5) - y(h_7 - h_2)}{h_{10} - h_2} = \frac{561.43 - 192.10 - (0.0753)(720.87 - 192.10)}{2578.5 - 192.10} = 0.1381
\]

Then,

\[
\dot{q}_{in} = h_8 - h_5 = 3476.5 - 727.36 = 2749.1 \text{ kJ/kg}
\]

\[
\dot{q}_{out} = (1 - y - z)(h_11 - h_1) = (1 - 0.0753 - 0.1381)(2100.0 - 191.81) = 1500.1 \text{ kJ/kg}
\]

\[
\dot{w}_{net} = \dot{q}_{in} - \dot{q}_{out} = 2749.1 - 1500.1 = 1249 \text{ kJ/kg}
\]

and

\[
\dot{m} = \frac{\dot{W}_{net}}{\dot{w}_{net}} = \frac{250,000 \text{ kJ/s}}{1249 \text{ kJ/kg}} = 200.2 \text{ kg/s}
\]

\[
(b) \quad \eta_{th} = 1 - \frac{\dot{q}_{out}}{\dot{q}_{in}} = 1 - \frac{1500.1 \text{ kJ/kg}}{2749.1 \text{ kJ/kg}} = 45.4\
\]
**10-48 EES** Problem 10-47 is reconsidered. The effects of turbine and pump efficiencies on the mass flow rate and thermal efficiency are to be investigated. Also, the $T$-$s$ diagram is to be plotted.

**Analysis** The problem is solved using EES, and the solution is given below.

"Input Data"
\[
\begin{align*}
P[8] &= 12500 \text{ [kPa]} \\
T[8] &= 550 \text{ [C]} \\
P[9] &= 800 \text{ [kPa]} \\
"P\_c\_f\_w\_h=300 \text{ [kPa]}" \\
P[10] &= P\_c\_f\_w\_h \\
P\_c\_\text{ond} &= 10 \text{ [kPa]} \\
P[11] &= P\_c\_\text{ond} \\
W\_\text{dot\_net} &= 250 \text{ [MW]} \text{*Convert(MW, kW)} \\
\text{Eta\_turb} &= 100/100 \text{ "Turbine isentropic efficiency"} \\
\text{Eta\_turb\_hp} &= \text{Eta\_turb} \text{ "Turbine isentropic efficiency for high pressure stages"} \\
\text{Eta\_turb\_ip} &= \text{Eta\_turb} \text{ "Turbine isentropic efficiency for intermediate pressure stages"} \\
\text{Eta\_turb\_lp} &= \text{Eta\_turb} \text{ "Turbine isentropic efficiency for low pressure stages"} \\
\text{Eta\_pump} &= 100/100 \text{ "Pump isentropic efficiency"} \\
\end{align*}
\]

"Condenser exit pump or Pump 1 analysis"
\[
\begin{align*}
\text{Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$} \\
h[1] &= \text{enthalpy(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[1],x=0)} \text{ \{Sat\'d liquid\}} \\
v[1] &= \text{volume(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[1],x=0)} \\
s[1] &= \text{entropy(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[1],x=0)} \\
T[1] &= \text{temperature(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[1],x=0)} \\
w\_\text{pump1\_s} &= v[1]*(P[2]-P[1]) \text{ "SSSF isentropic pump work assuming constant specific volume"} \\
w\_\text{pump1} &= w\_\text{pump1\_s}/\text{Eta\_pump} \text{ "Definition of pump efficiency"} \\
h[1]+w\_\text{pump1} &= h[2] \text{ "Steady-flow conservation of energy"} \\
s[2] &= \text{entropy(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[2],h=h[2])} \\
T[2] &= \text{temperature(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[2],h=h[2])} \\
\end{align*}
\]

"Open Feedwater Heater analysis"
\[
\begin{align*}
h[3] &= \text{enthalpy(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[3],x=0)} \\
T[3] &= \text{temperature(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[3],x=0)} \text{ "Condensate leaves heater as sat. liquid at P[3]"} \\
s[3] &= \text{entropy(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[3],x=0)} \\
\end{align*}
\]

"Boiler condensate pump or Pump 2 analysis"
\[
\begin{align*}
v[3] &= \text{volume(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[3],x=0)} \\
w\_\text{pump2\_s} &= v[3]*(P[4]-P[3]) \text{ "SSSF isentropic pump work assuming constant specific volume"} \\
w\_\text{pump2} &= w\_\text{pump2\_s}/\text{Eta\_pump} \text{ "Definition of pump efficiency"} \\
s[4] &= \text{entropy(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[4],h=h[4])} \\
T[4] &= \text{temperature(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[4],h=h[4])} \\
\end{align*}
\]

"Closed Feedwater Heater analysis"
\[
\begin{align*}
h[5] &= \text{enthalpy(Fluid$\_\"S\_\text{Steam}\_\text{IAPWS}\"$,P=P[6],x=0)} \text{ "h[5] = h(T[5], P[5]) where T[5]=Tsat at P[9]"} \\
\end{align*}
\]

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T[5]=temperature(Fluid$,P=P[5],h=h[5]) "Condensate leaves heater as sat. liquid at P[6]"
s[5]=entropy(Fluid$,P=P[5],h=h[5])
h[6]=enthalpy(Fluid$,P=P[6],x=0)
T[6]=temperature(Fluid$,P=P[6],x=0) "Condensate leaves heater as sat. liquid at P[6]"
s[6]=entropy(Fluid$,P=P[6],x=0)

"Trap analysis"
y*h[6] = y*h[7]. "Steady-flow conservation of energy for the trap operating as a throttle"
T[7]=temperature(Fluid$,P=P[7],h=h[7])
s[7]=entropy(Fluid$,P=P[7],h=h[7])

"Boiler analysis"
q_in + h[5]=h[8]"SSSF conservation of energy for the Boiler"
h[8]=enthalpy(Fluid$, T=T[8], P=P[8])
s[8]=entropy(Fluid$, T=T[8], P=P[8])

"Turbine analysis"
ss[9]=s[8]
hs[9]=enthalpy(Fluid$,s=ss[9],P=P[9])
Ts[9]=temperature(Fluid$,s=ss[9],P=P[9])
h[9]=h[8]-Eta_turb_hp*(h[8]-hs[9])"Definition of turbine efficiency for high pressure stages"
T[9]=temperature(Fluid$,P=P[9],h=h[9])
s[9]=entropy(Fluid$,P=P[9],h=h[9])
ss[10]=s[8]
hs[10]=enthalpy(Fluid$,s=ss[10],P=P[10])
Ts[10]=temperature(Fluid$,s=ss[10],P=P[10])
h[10]=h[9]-Eta_turb_hp*(h[9]-hs[9])"Definition of turbine efficiency for Intermediate pressure stages"
T[10]=temperature(Fluid$,P=P[10],h=h[10])
s[10]=entropy(Fluid$,P=P[10],h=h[10])

"Condenser analysis"
(1-y-z)*h[11]=q_out+(1-y-z)*h[1]"SSSF First Law for the Condenser"

"Cycle Statistics"
w_net=w_turb - ((1-y-z)*w_pump1+ w_pump2)
Eta_th=w_net/q_in
W_dot_net = m_dot * w_net
<table>
<thead>
<tr>
<th>η_turb</th>
<th>η_turb</th>
<th>η_th</th>
<th>m [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>0.7</td>
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</tr>
<tr>
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<td>218</td>
</tr>
<tr>
<td>0.85</td>
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<td>0.4267</td>
<td>212.6</td>
</tr>
<tr>
<td>0.9</td>
<td>0.9</td>
<td>0.4363</td>
<td>207.9</td>
</tr>
<tr>
<td>0.95</td>
<td>0.95</td>
<td>0.4452</td>
<td>203.8</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0.4535</td>
<td>200.1</td>
</tr>
</tbody>
</table>

\[ η_{turb} = η_{pump} \]

Steam

\[ s \text{ [kJ/kg-K]} \]

10-36

PROPRIETARY MATERIAL. © 2006 The McGraw-Hill Companies, Inc. Limited distribution permitted only to teachers and educators for course preparation. If you are a student using this Manual, you are using it without permission.
A steam power plant operates on an ideal reheat-regenerative Rankine cycle with an open feedwater heater. The mass flow rate of steam through the boiler and the thermal efficiency of the cycle are to be determined.

**Assumptions**

1. Steady operating conditions exist.
2. Kinetic and potential energy changes are negligible.

**Analysis**

(a) From the steam tables (Tables A-4, A-5, and A-6),

\[ h_1 = h_{fg}(10 \text{ kPa}) = 191.81 \text{ kJ/kg} \]

\[ \nu_1 = \nu_{fg}(10 \text{ kPa}) = 0.00101 \text{ m}^3/\text{kg} \]

\[ w_{pl,in} = \nu_s \left( P_3 - P_4 \right) = \left( 0.00101 \text{ m}^3/\text{kg} \right) \left( 800 - 10 \text{ kPa} \right) \left( \frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) = 0.80 \text{ kJ/kg} \]

\[ h_2 = h_1 + w_{pl,in} = 191.81 + 0.80 = 192.61 \text{ kJ/kg} \]

\[ P_3 = 0.8 \text{ MPa} \quad h_3 = h_{fg}(0.8 \text{ MPa}) = 720.87 \text{ kJ/kg} \]

sat. liquid

\[ \nu_3 = \nu_{fg}(0.8 \text{ MPa}) = 0.001115 \text{ m}^3/\text{kg} \]

\[ w_{pl,in} = \nu_s \left( P_4 - P_3 \right) = \left( 0.001115 \text{ m}^3/\text{kg} \right) \left( 10,000 - 800 \text{ kPa} \right) \left( \frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) = 10.26 \text{ kJ/kg} \]

\[ h_4 = h_3 + w_{pl,in} = 720.87 + 10.26 = 731.12 \text{ kJ/kg} \]

\[ P_3 = 10 \text{ MPa} \quad h_5 = 3502.0 \text{ kJ/kg} \]

\[ T_5 = 550^\circ C \quad s_5 = 6.7585 \text{ kJ/kg} \cdot \text{K} \]

\[ P_6 = 0.8 \text{ MPa} \quad h_6 = 2812.1 \text{ kJ/kg} \]

\[ s_6 = s_5 \]

\[ P_7 = 0.8 \text{ MPa} \quad h_7 = 3481.3 \text{ kJ/kg} \]

\[ T_7 = 500^\circ C \quad s_7 = 7.8692 \text{ kJ/kg} \cdot \text{K} \]

\[ P_8 = 10 \text{ kPa} \quad x_8 = \frac{s_8 - s_f}{s_{fg}} = \frac{7.8692 - 0.6492}{7.4996} = 0.9627 \]

\[ h_8 = h_f + x_8 h_{fg} = 191.81 + (0.9627)(2392.1) = 2494.7 \text{ kJ/kg} \]

The fraction of steam extracted is determined from the steady-flow energy balance equation applied to the feedwater heaters. Noting that \( Q \equiv W \equiv \Delta ke \equiv \Delta pe \equiv 0 \),

\[ E_{in} - E_{out} = \Delta E_{system} \]

\[ \sum m_i h_i = \sum \tilde{m}_i h_{e} \rightarrow \tilde{m}_2 h_2 + y h_6 + (1-y) h_7 = \tilde{m}_3 h_3 \]

where \( y \) is the fraction of steam extracted from the turbine (= \( \tilde{m}_2 / \tilde{m}_3 \)). Solving for \( y \),

\[ y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{720.87 - 192.61}{2812.1 - 192.61} = 0.2017 \]

Then,

\[ q_{in} = (h_5 - h_4) + (1-y)(h_7 - h_6) = (3502.0 - 731.12) + (1 - 0.2017)(3481.3 - 2812.1) = 3305.1 \text{ kJ/kg} \]

\[ q_{out} = (1-y)(h_8 - h_7) = (1 - 0.2017)(2494.7 - 191.81) = 1838.5 \text{ kJ/kg} \]

\[ w_{net} = q_{in} - q_{out} = 3305.1 - 1838.5 = 1466.6 \text{ kJ/kg} \]

and

\[ \dot{m} = \frac{W_{net}}{w_{net}} = \frac{80,000 \text{ kJ/s}}{1466.1 \text{ kJ/kg}} = 54.5 \text{ kg/s} \]

(b) \[ \eta_{th} = \frac{w_{net}}{q_{in}} = \frac{1466.1 \text{ kJ/kg}}{3305.1 \text{ kJ/kg}} = 44.4\% \]
A steam power plant operates on an ideal reheat-regenerative Rankine cycle with a closed feedwater heater. The mass flow rate of steam through the boiler and the thermal efficiency of the cycle are to be determined.

**Assumptions**
1. Steady operating conditions exist.
2. Kinetic and potential energy changes are negligible.

**Analysis**

(a) From the steam tables (Tables A-4, A-5, and A-6),

\[ h_1 = h_f @ 10 \text{kPa} = 191.81 \text{ kJ/kg} \]
\[ \nu_1 = \nu_f @ 10 \text{kPa} = 0.00101 \text{ m}^3/\text{kg} \]
\[ w_{pf, in} = \nu_1 (P_2 - P_1) = \left(0.00101 \text{ m}^3/\text{kg}\right) \left(10,000 - 10 \text{kPa}\right) \left(\frac{1 \text{ kJ}}{1 \text{kPa} \cdot \text{m}^3}\right) \]
\[ = 10.09 \text{ kJ/kg} \]
\[ h_2 = h_1 + w_{pf, in} = 191.81 + 10.09 = 201.90 \text{ kJ/kg} \]
\[ P_3 = 0.8 \text{ MPa} \]
\[ h_3 = h_f @ 0.8 \text{ MPa} = 720.87 \text{ kJ/kg} \]
\[ \text{sat. liquid} \]
\[ \nu_3 = \nu_f @ 0.8 \text{ MPa} = 0.001115 \text{ m}^3/\text{kg} \]
\[ w_{pf, in} = \nu_3 (P_4 - P_3) = \left(0.001115 \text{ m}^3/\text{kg}\right) \left(10,000 - 800 \text{kPa}\right) \left(\frac{1 \text{ kJ}}{1 \text{kPa} \cdot \text{m}^3}\right) \]
\[ = 10.26 \text{ kJ/kg} \]
\[ h_4 = h_3 + w_{pf, in} = 720.87 + 10.26 = 731.13 \text{ kJ/kg} \]

Also, \( h_4 = h_9 = h_{10} = 731.12 \text{ kJ/kg} \) since the two fluid streams that are being mixed have the same enthalpy.

\[ P_9 = 10 \text{ MPa} \]
\[ h_9 = 3502.0 \text{ kJ/kg} \]
\[ T_9 = 550^\circ \text{C} \]
\[ s_9 = 6.7585 \text{ kJ/kg} \cdot \text{K} \]
\[ P_8 = 0.8 \text{ MPa} \]
\[ h_8 = 2812.7 \text{ kJ/kg} \]
\[ s_9 = s_9 \]
\[ P_7 = 0.8 \text{ MPa} \]
\[ h_7 = 3481.3 \text{ kJ/kg} \]
\[ T_7 = 500^\circ \text{C} \]
\[ s_7 = 7.8692 \text{ kJ/kg} \cdot \text{K} \]
\[ P_6 = 10 \text{ kPa} \]
\[ x_8 = \frac{s_8 - s_f}{s_{fg}} = \frac{7.8692 - 0.6492}{7.4996} = 0.9627 \]
\[ s_8 = s_7 \]
\[ h_8 = h_f + x_8 h_f = 191.81 + (0.9627)(2392.1) = 2494.7 \text{ kJ/kg} \]
The fraction of steam extracted is determined from the steady-flow energy balance equation applied to the feedwater heaters. Noting that $Q \equiv \dot{W} \equiv \Delta ke \equiv \Delta p e \equiv 0$,

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta \dot{E}_{\text{system}}^{(\text{steady})} = 0$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\sum m_i h_i = \sum \dot{m}_i h_c \rightarrow \dot{m}_2 (h_9 - h_2) = \dot{m}_3 (h_6 - h_3) \rightarrow (1 - y)(h_9 - h_2) = y(h_6 - h_3)$$

where $y$ is the fraction of steam extracted from the turbine ($= \dot{m}_3 / \dot{m}_4$). Solving for $y$,

$$y = \frac{h_6 - h_3}{(h_6 - h_3) + (h_9 - h_2)} = \frac{731.13 - 201.90}{2812.7 - 720.87 + 731.13 - 201.90} = 0.2019$$

Then,

$$q_{\text{in}} = (h_5 - h_4) + (1 - y)(h_7 - h_6) = (3502.0 - 731.13) + (1 - 0.2019)(3481.3 - 2812.7) = 3304.5 \text{ kJ/kg}$$

$$q_{\text{out}} = (1 - y)(h_8 - h_1) = (1 - 0.2019)(2494.7 - 191.81) = 1837.9 \text{ kJ/kg}$$

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 3304.5 - 1837.8 = 1466.6 \text{ kJ/kg}$$

and

$$\dot{m} = \frac{W_{\text{net}}}{w_{\text{net}}} = \frac{80,000 \text{ kJ/s}}{1467.1 \text{ kJ/kg}} = 54.5 \text{ kg/s}$$

(b) $\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1837.8 \text{ kJ/kg}}{3304.5 \text{ kJ/kg}} = 44.4\%$
A steam power plant operates on an ideal reheat-regenerative Rankine cycle with one reheater and two open feedwater heaters. The mass flow rate of steam through the boiler, the net power output of the plant, and the thermal efficiency of the cycle are to be determined.

**Assumptions**
1. Steady operating conditions exist.
2. Kinetic and potential energy changes are negligible.

**Analysis**

(a) From the steam tables (Tables A-4E, A-5E, and A-6E),

\[ h_1 = h_{f@1\text{ psia}} = 69.72 \text{ Btu/lbm} \]
\[ \nu_1 = \nu_{f@1\text{ psia}} = 0.01614 \text{ ft}^3/\text{lbm} \]
\[ w_{plf,in} = \nu_1 (P_2 - P_1) \]
\[ = (0.01614 \text{ ft}^3/\text{lbm}) (40 - 1 \text{ psia}) \left( \frac{1 \text{ Btu}}{5.4039 \text{ psia} \cdot \text{ft}^3} \right) \]
\[ = 0.12 \text{ Btu/lbm} \]
\[ h_2 = h_1 + w_{plf,in} = 69.72 + 0.12 = 69.84 \text{ Btu/lbm} \]

\[ P_3 = 40 \text{ psia} \]
\[ h_3 = h_{f@40\text{ psia}} = 236.14 \text{ Btu/lbm} \]

sat. liquid
\[ \nu_3 = \nu_{f@40\text{ psia}} = 0.01715 \text{ ft}^3/\text{lbm} \]
\[ w_{plII,in} = \nu_3 (P_4 - P_3) \]
\[ = (0.01715 \text{ ft}^3/\text{lbm}) (250 - 40 \text{ psia}) \left( \frac{1 \text{ Btu}}{5.4039 \text{ psia} \cdot \text{ft}^3} \right) \]
\[ = 0.67 \text{ Btu/lbm} \]
\[ h_4 = h_3 + w_{plII,in} = 236.14 + 0.67 = 236.81 \text{ Btu/lbm} \]

\[ P_5 = 250 \text{ psia} \]
\[ h_5 = h_{f@250\text{ psia}} = 376.09 \text{ Btu/lbm} \]

sat. liquid
\[ \nu_5 = \nu_{f@250\text{ psia}} = 0.01865 \text{ ft}^3/\text{lbm} \]
\[ w_{plII,in} = \nu_5 (P_6 - P_5) \]
\[ = (0.01865 \text{ ft}^3/\text{lbm}) (1500 - 250 \text{ psia}) \left( \frac{1 \text{ Btu}}{5.4039 \text{ psia} \cdot \text{ft}^3} \right) \]
\[ = 4.31 \text{ Btu/lbm} \]
\[ h_6 = h_5 + w_{plII,in} = 376.09 + 4.31 = 380.41 \text{ Btu/lbm} \]

\[ P_7 = 1500 \text{ psia} \]
\[ h_7 = h_{f@1500\text{ psia}} = 1550.5 \text{ Btu/lbm} \]

\[ T_7 = 1100^\circ \text{F} \]
\[ s_7 = 1.6402 \text{ Btu/lbm} \cdot \text{R} \]

\[ P_8 = 250 \text{ psia} \]
\[ s_8 = s_7 \]
\[ h_8 = 1308.5 \text{ Btu/lbm} \]
\begin{align*}
P_9 &= 140 \text{ psia} \quad\Rightarrow\quad h_9 = 1248.8 \text{ Btu/lbm} \\
s_9 &= s_7 \\
P_{10} &= 140 \text{ psia} \quad\Rightarrow\quad h_{10} = 1531.3 \text{ Btu/lbm} \\
T_{10} &= 1000^\circ\text{F} \quad\Rightarrow\quad s_{10} = 1.8832 \text{ Btu/lbm} \cdot \text{R} \\
P_{11} &= 40 \text{ psia} \quad\Rightarrow\quad h_{11} = 1356.0 \text{ Btu/lbm} \\
s_{11} &= s_{10} \\
x_{12} &= \frac{s_{12} - s_f}{s_{fg}} = \frac{1.8832 - 0.13262}{1.84495} = 0.9488 \\
P_{12} &= 1 \text{ psia} \quad\Rightarrow\quad h_{12} = h_f + x_{12}h_{fg} = 69.72 + (0.9488)(1035.7) = 1052.4 \text{ Btu/lbm}
\end{align*}

The fraction of steam extracted is determined from the steady-flow energy balance equation applied to the feedwater heaters. Noting that \( Q \equiv \dot{W} \equiv \Delta k_e \equiv \Delta p_e \equiv 0 \),

\[ \dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta \dot{E}_{\text{system}} \]

FWH-2:

\[ \dot{E}_{\text{in}} = \dot{E}_{\text{out}} \sum \dot{m}_i h_i = \sum \dot{m}_c h_c \quad \Rightarrow \quad \dot{m}_5 h_5 + \dot{m}_4 h_4 = \dot{m}_5 h_5 \quad\Rightarrow\quad y h_5 + (1 - y) h_4 \quad(1) \]

where \( y \) is the fraction of steam extracted from the turbine \(= \dot{m}_5 / \dot{m}_5 \). Solving for \( y \),

\[ y = \frac{h_5 - h_4}{h_5 - h_4} = \frac{376.09 - 236.81}{1308.5 - 236.81} = 0.1300 \]

\[ \dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta \dot{E}_{\text{system}} \]

FWH-1:

\[ \dot{E}_{\text{in}} = \dot{E}_{\text{out}} \sum \dot{m}_i h_i = \sum \dot{m}_c h_c \quad \Rightarrow \quad \dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \quad\Rightarrow\quad z h_1 + (1 - y - z) h_2 = (1 - y) h_3 \]

where \( z \) is the fraction of steam extracted from the turbine \(= \dot{m}_5 / \dot{m}_5 \) at the second stage. Solving for \( z \),

\[ z = \frac{h_3 - h_2}{h_1 - h_2}(1 - y) = \frac{236.14 - 69.84}{1356.0 - 60.84}(1 - 0.1300) = 0.1125 \]

Then,

\[ q_{\text{in}} = h_7 - h_6 + (1 - y)(h_{10} - h_9) = 1550.5 - 380.41 + (1 - 0.1300)(1531.3 - 1248.8) = 1415.8 \text{ Btu/lbm} \]
\[ q_{\text{out}} = (1 - y - z)(h_{12} - h_1) = (1 - 0.1300 - 0.1125)(1052.4 - 69.72) = 744.4 \text{ Btu/lbm} \]
\[ w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 1415.8 - 744.4 = 671.4 \text{ Btu/lbm} \]

and

\[ \dot{m} = \frac{\dot{Q}_\text{in}}{q_{\text{in}}} = \frac{4 \times 10^5 \text{ Btu/s}}{1415.8 \text{ Btu/lbm}} = 282.5 \text{ lbm/s} \]

(b) \[ \dot{W}_{\text{net}} = \dot{m}w_{\text{net}} = (282.5 \text{ lbm/s})(671.4 \text{ Btu/lbm}) \left(\frac{1.055 \text{ kJ}}{1 \text{ Btu}}\right) = 200.1 \text{ MW} \]

(c) \[ \eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{744.4 \text{ Btu/lbm}}{1415.8 \text{ Btu/lbm}} = 47.4\% \]
A steam power plant that operates on an ideal regenerative Rankine cycle with a closed feedwater heater is considered. The temperature of the steam at the inlet of the closed feedwater heater, the mass flow rate of the steam extracted from the turbine for the closed feedwater heater, the net power output, and the thermal efficiency are to be determined.

Assumptions
1. Steady operating conditions exist.
2. Kinetic and potential energy changes are negligible.

Analysis
(a) From the steam tables (Tables A-4, A-5, and A-6),

\[
\begin{align*}
   h_1 &= h_{f@20 \text{ kPa}} = 251.42 \text{ kJ/kg} \\
   \nu_1 &= \nu_{f@20 \text{ kPa}} = 0.001017 \text{ m}^3/\text{kg} \\
   w_{\text{pf,in}} &= \nu_1 \left( P_2 - P_1 \right) / \eta_p \\
                &= (0.001017 \text{ m}^3/\text{kg})(12,500 - 20 \text{ kPa}) / 0.88 \\
                &= 14.43 \text{ kJ/kg} \\
   h_2 &= h_1 + w_{\text{pf,in}} = 251.42 + 14.43 = 265.85 \text{ kJ/kg} \\
   P_3 &= 1 \text{ MPa} \quad \{ h_3 = h_{f@1 \text{ MPa}} = 762.51 \text{ kJ/kg} \\
        &\text{sat. liquid} \quad \{ \nu_3 = \nu_{f@1 \text{ MPa}} = 0.001127 \text{ m}^3/\text{kg} \\
   w_{\text{pIf,in}} &= \nu_3 \left( P_1 - P_3 \right) / \eta_p \\
                &= (0.001127 \text{ m}^3/\text{kg})(12,500 - 1000 \text{ kPa}) / 0.88 \\
                &= 14.73 \text{ kJ/kg} \\
   h_{11} &= h_3 + w_{\text{pIf,in}} = 762.51 + 14.73 = 777.25 \text{ kJ/kg} \\
\end{align*}
\]

Also, \( h_4 = h_{10} = h_{11} = 777.25 \text{ kJ/kg} \) since the two fluid streams which are being mixed have the same enthalpy.

\[
\begin{align*}
   P_5 &= 12.5 \text{ MPa} \quad \{ h_5 = 3476.5 \text{ kJ/kg} \\
   T_5 &= 550^\circ \text{C} \quad \{ s_5 = 6.6317 \text{ kJ/kg} \cdot \text{K} \\
   P_6 &= 5 \text{ MPa} \quad \{ h_{6s} = 3185.6 \text{ kJ/kg} \\
       s_6 &= s_5 \\
   \eta_T &= \frac{h_5 - h_6}{h_5 - h_{6s}} \quad \rightarrow \quad h_6 = h_5 - \eta_T(h_5 - h_{6s}) \\
       &= 3476.5 - \left(0.88 \times (3476.5 - 3185.6)\right) = 3220.5 \text{ kJ/kg} \\
   P_7 &= 5 \text{ MPa} \quad \{ h_7 = 3550.9 \text{ kJ/kg} \\
       T_7 &= 550^\circ \text{C} \quad \{ s_7 = 7.1238 \text{ kJ/kg} \cdot \text{K} \\
   P_8 &= 1 \text{ MPa} \quad \{ h_{8s} = 3051.1 \text{ kJ/kg} \\
       s_8 &= s_7 \\
   \eta_T &= \frac{h_7 - h_8}{h_7 - h_{8s}} \quad \rightarrow \quad h_8 = h_7 - \eta_T(h_7 - h_{8s}) \\
       &= 3550.9 - \left(0.88 \times (3550.9 - 3051.1)\right) = 3111.1 \text{ kJ/kg} \\
   P_8 &= 1 \text{ MPa} \quad \{ h_8 = 3111.1 \text{ kJ/kg} \\
       T_8 &= 328^\circ \text{C}
\end{align*}
\]
The fraction of steam extracted from the low pressure turbine for closed feedwater heater is determined from the steady-flow energy balance equation applied to the feedwater heater. Noting that \( \dot{Q} \simeq \dot{W} \simeq \Delta ke \simeq \Delta pe \simeq 0 \),
\[
(1 - y)(h_{10} - h_2) = y(h_8 - h_3)
\]
\[
(1 - y)(777.25 - 265.85) = y(3111.1 - 762.51) \rightarrow y = 0.1788
\]
The corresponding mass flow rate is
\[
\dot{m}_8 = y\dot{m}_s = (0.1788)(24 \text{ kg/s}) = 4.29 \text{ kg/s}
\]
(c) Then,
\[
q_{\text{in}} = h_5 - h_4 + h_7 - h_6 = 3476.5 - 777.25 + 3550.9 - 3220.5 = 3029.7 \text{ kJ/kg}
\]
\[
q_{\text{out}} = (1 - y)(h_0 - h_1) = (1 - 0.1788)(2492.2 - 251.42) = 1840.1 \text{ kJ/kg}
\]
and
\[
\dot{W}_{\text{net}} = \dot{m}(q_{\text{in}} - q_{\text{out}}) = (24 \text{ kg/s})(3029.7 - 1840.1)\text{kJ/kg} = 28,550 \text{ kW}
\]
(b) The thermal efficiency is determined from
\[
\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1840.1 \text{ kJ/kg}}{3029.7 \text{ kJ/kg}} = 0.393 = 39.3\%
\]
Second-Law Analysis of Vapor Power Cycles

10-53C In the simple ideal Rankine cycle, irreversibilities occur during heat addition and heat rejection processes in the boiler and the condenser, respectively, and both are due to temperature difference. Therefore, the irreversibilities can be decreased and thus the 2nd law efficiency can be increased by minimizing the temperature differences during heat transfer in the boiler and the condenser. One way of doing that is regeneration.

10-54 The exergy destructions associated with each of the processes of the Rankine cycle described in Prob. 10-15 are to be determined for the specified source and sink temperatures.

**Assumptions** 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.

**Analysis** From Problem 10-15,

\[ s_1 = s_2 = s_f @ 50 \text{ kPa} = 1.0912 \text{ kJ/kg} \cdot \text{K} \]
\[ s_3 = s_4 = 6.5412 \text{ kJ/kg} \cdot \text{K} \]
\[ q_m = 2650.72 \text{ kJ/kg} \]
\[ q_{out} = 1931.8 \text{ kJ/kg} \]

Processes 1-2 and 3-4 are isentropic. Thus, \( i_{12} = 0 \) and \( i_{34} = 0 \). Also,

\[ x_{\text{destroyed,23}} = T_0 \left( s_3 - s_2 + \frac{q_{R,23}}{T_R} \right) = (290 \text{ K}) \left( 6.5412 - 1.0912 + \frac{-2650.8 \text{ kJ/kg}}{1500 \text{ K}} \right) = 1068 \text{ kJ/kg} \]
\[ x_{\text{destroyed,41}} = T_0 \left( s_1 - s_4 + \frac{q_{R,41}}{T_R} \right) = (290 \text{ K}) \left( 1.0912 - 6.5412 + \frac{1931.8 \text{ kJ/kg}}{290 \text{ K}} \right) = 351.3 \text{ kJ/kg} \]

10-55 The exergy destructions associated with each of the processes of the Rankine cycle described in Prob. 10-16 are to be determined for the specified source and sink temperatures.

**Assumptions** 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.

**Analysis** From Problem 10-16,

\[ s_1 = s_2 = s_f @ 10 \text{ kPa} = 0.6492 \text{ kJ/kg} \cdot \text{K} \]
\[ s_3 = s_4 = 6.5995 \text{ kJ/kg} \cdot \text{K} \]
\[ q_m = 3173.2 \text{ kJ/kg} \]
\[ q_{out} = 1897.9 \text{ kJ/kg} \]

Processes 1-2 and 3-4 are isentropic. Thus, \( i_{12} = 0 \) and \( i_{34} = 0 \). Also,

\[ x_{\text{destroyed,23}} = T_0 \left( s_3 - s_2 + \frac{q_{R,23}}{T_R} \right) = (290 \text{ K}) \left( 6.5995 - 0.6492 + \frac{-3173.2 \text{ kJ/kg}}{1500 \text{ K}} \right) = 1112.1 \text{ kJ/kg} \]
\[ x_{\text{destroyed,41}} = T_0 \left( s_1 - s_4 + \frac{q_{R,41}}{T_R} \right) = (290 \text{ K}) \left( 0.6492 - 6.5995 + \frac{1897.9 \text{ kJ/kg}}{290 \text{ K}} \right) = 172.3 \text{ kJ/kg} \]
10-56 The exergy destruction associated with the heat rejection process in Prob. 10-22 is to be determined for the specified source and sink temperatures. The exergy of the steam at the boiler exit is also to be determined.

**Assumptions** 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.

**Analysis** From Problem 10-22,

\[ s_1 = s_2 = s_f @ 100 \text{kPa} = 0.6492 \text{kJ/kg} \cdot \text{K} \]
\[ s_3 = s_4 = 6.8000 \text{kJ/kg} \cdot \text{K} \]
\[ h_3 = 3411.4 \text{kJ/kg} \]
\[ q_{\text{out}} = 1961.8 \text{kJ/kg} \]

The exergy destruction associated with the heat rejection process is

\[ x_{\text{destroyed,41}} = T_0 \left( s_1 - s_4 + \frac{q_{R,41}}{T_R} \right) = (290 \text{K}) \left( 0.6492 - 6.8000 + \frac{1961.8 \text{kJ/kg}}{290 \text{K}} \right) = 178.0 \text{kJ/kg} \]

The exergy of the steam at the boiler exit is simply the flow exergy,

\[ \psi_3 = \left( h_3 - h_0 \right) - T_0 \left( s_3 - s_0 \right) + \frac{V^2}{2} - q_3 \phi_0 \]
\[ = \left( h_3 - h_0 \right) - T_0 \left( s_3 - s_0 \right) \]

where
\[ h_0 = h_{\text{i}} (290 \text{K}, 100 \text{kPa}) \equiv h_f @ 290 \text{K} = 71.95 \text{kJ/kg} \]
\[ s_0 = s_{\text{i}} (290 \text{K}, 100 \text{kPa}) \equiv s_f @ 290 \text{K} = 0.2533 \text{kJ/kg} \cdot \text{K} \]

Thus,
\[ \psi_3 = (3411.4 - 71.95) \text{kJ/kg} - (290 \text{K})(6.8000 - 0.2532) \text{kJ/kg} \cdot \text{K} = 1440.9 \text{kJ/kg} \]

10-57 The exergy destructions associated with each of the processes of the reheat Rankine cycle described in Prob. 10-32 are to be determined for the specified source and sink temperatures.

**Assumptions** 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.

**Analysis** From Problem 10-32,

\[ s_1 = s_2 = s_f @ 20 \text{kPa} = 0.8320 \text{kJ/kg} \cdot \text{K} \]
\[ s_3 = s_4 = 6.7266 \text{kJ/kg} \cdot \text{K} \]
\[ s_5 = s_6 = 7.2359 \text{kJ/kg} \cdot \text{K} \]
\[ q_{23, \text{i}} = 3399.5 - 259.54 = 3140.0 \text{kJ/kg} \]
\[ q_{45, \text{i}} = 3457.2 - 3105.1 = 352.1 \text{kJ/kg} \]
\[ q_{\text{out}} = h_6 - h_0 = 2385.2 - 251.42 = 2133.8 \text{kJ/kg} \]

Processes 1-2, 3-4, and 5-6 are isentropic. Thus, \( i_{12} = i_{34} = i_{56} = 0 \). Also,

\[ x_{\text{destroyed,23}} = T_0 \left( s_3 - s_2 + \frac{q_{R,23}}{T_R} \right) = (300 \text{K}) \left( 6.7266 - 0.8320 + \frac{3140.0 \text{kJ/kg}}{1800 \text{K}} \right) = 1245.0 \text{kJ/kg} \]
\[ x_{\text{destroyed,45}} = T_0 \left( s_5 - s_4 + \frac{q_{R,45}}{T_R} \right) = (300 \text{K}) \left( 7.2359 - 6.7266 + \frac{352.5 \text{kJ/kg}}{1800 \text{K}} \right) = 94.1 \text{kJ/kg} \]
\[ x_{\text{destroyed,61}} = T_0 \left( s_1 - s_6 + \frac{q_{R,61}}{T_R} \right) = (300 \text{K}) \left( 0.8320 - 7.2359 + \frac{2133.8 \text{kJ/kg}}{300 \text{K}} \right) = 212.6 \text{kJ/kg} \]
Problem 10-57 is reconsidered. The problem is to be solved by the diagram window data entry feature of EES by including the effects of the turbine and pump efficiencies. Also, the $T$-$s$ diagram is to be plotted.

Analysis

The problem is solved using EES, and the solution is given below.

```plaintext
function x6$(x6) "this function returns a string to indicate the state of steam at point 6"
    x6$=""
    if (x6>1) then x6$=('superheated')
    if (x6<0) then x6$=('subcooled')
end

"Input Data - from diagram window"

{P[6] = 20 [kPa]
P[3] = 8000 [kPa]
T[3] = 500 [C]
P[4] = 3000 [kPa]
T[5] = 500 [C]
Eta_t = 100/100 "Turbine isentropic efficiency"
Eta_p = 100/100 "Pump isentropic efficiency"

"Data for the irreversibility calculations:"

T_o = 300 [K]
T_R_L = 300 [K]
T_R_H = 1800 [K]

"Pump analysis"
Fluid$='Steam_IAPWS'
x[1]=0 "Sat'd liquid"
h[1]=enthalpy(Fluid$,P=P[1],x=x[1])
v[1]=volume(Fluid$,P=P[1],x=x[1])
s[1]=entropy(Fluid$,P=P[1],x=x[1])
T[1]=temperature(Fluid$,P=P[1],x=x[1])
W_p_s=v[1]*(P[2]-P[1]) "SSSF isentropic pump work assuming constant specific volume"
W_p=W_p_s/Eta_p
v[2]=volume(Fluid$,P=P[2],h=h[2])
s[2]=entropy(Fluid$,P=P[2],h=h[2])
T[2]=temperature(Fluid$,P=P[2],h=h[2])

"High Pressure Turbine analysis"
h[3]=enthalpy(Fluid$,T=T[3],P=P[3])
s[3]=entropy(Fluid$,T=T[3],P=P[3])
v[3]=volume(Fluid$,T=T[3],P=P[3])
s_s[4]=s[3]
h[4]=enthalpy(Fluid$,s=s_s[4],P=P[4])
T_s[4]=temperature(Fluid$,s=s_s[4],P=P[4])
Eta_t=(h[3]-h[4])/(h[3]-h[4]) "Definition of turbine efficiency"
T[4]=temperature(Fluid$,P=P[4],h=h[4])
s[4]=entropy(Fluid$,T=T[4],P=P[4])
v[4]=volume(Fluid$,s=s_s[4],P=P[4])

"Low Pressure Turbine analysis"
s[5]=entropy(Fluid$,T=T[5],P=P[5])
h[5]=enthalpy(Fluid$,T=T[5],P=P[5])
h[6]=enthalpy(Fluid$,s=s_s[6],P=P[6])
T_s[6]=temperature(Fluid$,s=s_s[6],P=P[6])
v[6]=volume(Fluid$,s=s_s[6],P=P[6])
Eta_t=(h[5]-h[6])/(h[5]-h[6]) "Definition of turbine efficiency"
x[6]=QUALITY(Fluid$,h=h[6],P=P[6])
```

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"Boiler analysis"

"Condenser analysis"
\[ h[6]=Q_{out}+h[1]\] "SSSF First Law for the Condenser"

\[ T[6]=\text{temperature}(\text{Fluid}, h=h[6], P=P[6]) \]
\[ s[6]=\text{entropy}(\text{Fluid}, h=h[6], P=P[6]) \]
\[ x[6]=x[6](x[6]) \]

"Cycle Statistics"
\[ W_{net}=W_{t\_hp}+W_{t\_lp}-W_p \]
\[ \text{Eff}=\frac{W_{net}}{Q_{in}} \]

"The irreversibilities (or exergy destruction) for each of the processes are:"
\[ q_{R\_23} = - (h[3] - h[2]) \] "Heat transfer for the high temperature reservoir to process 2-3"
\[ i_{23} = T_o(s[3]-s[2]) + \frac{q_{R\_23}}{T_R_H} \]
\[ q_{R\_45} = - (h[5] - h[4]) \] "Heat transfer for the high temperature reservoir to process 4-5"
\[ i_{45} = T_o(s[5]-s[4]) + \frac{q_{R\_45}}{T_R_H} \]
\[ q_{R\_61} = (h[6] - h[1]) \] "Heat transfer to the low temperature reservoir in process 6-1"
\[ i_{61} = T_o(s[1]-s[6]) + \frac{q_{R\_61}}{T_R_L} \]
\[ i_{34} = T_o(s[4]-s[3]) \]
\[ i_{56} = T_o(s[6]-s[5]) \]
\[ i_{12} = T_o(s[2]-s[1]) \]

**SOLUTION**

\[ \text{Eff}=0.389 \]
\[ \text{Eta}_p=1 \]
\[ \text{Eta}_t=1 \]
\[ \text{Fluid}='\text{Steam\_IAPWS}' \]
\[ h[1]=251.4 \text{ [kJ/kg]} \]
\[ h[2]=259.5 \text{ [kJ/kg]} \]
\[ h[3]=3400 \text{ [kJ/kg]} \]
\[ h[4]=3105 \text{ [kJ/kg]} \]
\[ h[5]=3457 \text{ [kJ/kg]} \]
\[ h[6]=2385 \text{ [kJ/kg]} \]
\[ h[3]=3400 \text{ [kJ/kg]} \]
\[ h[4]=3105 \text{ [kJ/kg]} \]
\[ h[5]=3457 \text{ [kJ/kg]} \]
\[ h[6]=2385 \text{ [kJ/kg]} \]
\[ i_{12}=0.012 \text{ [kJ/kg]} \]
\[ i_{23}=1245.038 \text{ [kJ/kg]} \]
\[ i_{34}=0.000 \text{ [kJ/kg]} \]
\[ i_{45}=94.028 \text{ [kJ/kg]} \]
\[ i_{56}=0.000 \text{ [kJ/kg]} \]
\[ i_{61}=212.659 \text{ [kJ/kg]} \]
\[ P[1]=20 \text{ [kPa]} \]
\[ P[2]=8000 \text{ [kPa]} \]
\[ Q_{in}=3493 \text{ [kJ/kg]} \]
\[ Q_{out}=2134 \text{ [kJ/kg]} \]
\[ q_{R\_23}=-3140 \text{ [kJ/kg]} \]
\[ q_{R\_45}=-352.5 \text{ [kJ/kg]} \]
\[ q_{R\_61}=2134 \text{ [kJ/kg]} \]
\[ s[1]=0.832 \text{ [kJ/kg-K]} \]
\[ s[2]=0.8321 \text{ [kJ/kg-K]} \]
\[ s[3]=6.727 \text{ [kJ/kg-K]} \]
\[ s[4]=6.727 \text{ [kJ/kg-K]} \]
\[ s[5]=6.727 \text{ [kJ/kg-K]} \]
\[ s[6]=6.727 \text{ [kJ/kg-K]} \]
\[ s[8]=x[8](x[8]) \]
\[ P[3]=8000 \text{ [kPa]} \]
\[ P[4]=3000 \text{ [kPa]} \]
\[ P[5]=3000 \text{ [kPa]} \]
\[ T[4]=345.2 \text{ [C]} \]
\[ T[5]=500 \text{ [C]} \]
\[ T[6]=60.06 \text{ [C]} \]
\[ T_s[4]=345.2 \text{ [C]} \]
\[ T_s[6]=60.60 \text{ [C]} \]
\[ v[1]=0.001017 \text{ [m^3/kg]} \]
\[ v[2]=0.001014 \text{ [m^3/kg]} \]
\[ v[3]=0.04177 \text{ [m^3/kg]} \]
\[ v[4]=0.08968 \text{ [m^3/kg]} \]
\[ v[8]=6.922 \text{ [m^3/kg]} \]
\[ W_{net}=1359 \text{ [kJ/kg]} \]
\[ W_p=8.117 \text{ [kJ/kg]} \]
\[ W_p_s=8.117 \text{ [kJ/kg]} \]
\[ W_{t\_hp}=294.8 \text{ [kJ/kg]} \]
\[ W_{t\_lp}=1072 \text{ [kJ/kg]} \]
\[ x[6]=0 \]
\[ T[1]=60.06 \text{ [C]} \]
\[ T[2]=60.4 \text{ [C]} \]
\[ x[6]=x[6](x[6]) \]
\[ T_o=300 \text{ [K]} \]
\[ T_R_H=1800 \text{ [K]} \]
\[ T_R_L=300 \text{ [K]} \]
\[ v[1]=0.001017 \text{ [m^3/kg]} \]
\[ v[2]=0.001014 \text{ [m^3/kg]} \]
\[ v[3]=0.04177 \text{ [m^3/kg]} \]
\[ v[4]=0.08968 \text{ [m^3/kg]} \]
\[ v[8]=6.922 \text{ [m^3/kg]} \]
\[ W_{net}=1359 \text{ [kJ/kg]} \]
\[ W_p=8.117 \text{ [kJ/kg]} \]
\[ W_p_s=8.117 \text{ [kJ/kg]} \]
\[ W_{t\_hp}=294.8 \text{ [kJ/kg]} \]
\[ W_{t\_lp}=1072 \text{ [kJ/kg]} \]
\[ x[6]=x[6](x[6]) \]
\[ T[1]=60.06 \text{ [C]} \]
\[ T[2]=60.4 \text{ [C]} \]
\[ x[6]=x[6](x[6]) \]
\[ T[3]=500 \text{ [C]} \]
\[ x[1]=0 \]
x[6]=0.9051
The exergy destruction associated with the heat addition process and the expansion process in Prob. 10-34 are to be determined for the specified source and sink temperatures. The exergy of the steam at the boiler exit is also to be determined.

**Assumptions**
1. Steady operating conditions exist.
2. Kinetic and potential energy changes are negligible.

**Analysis**
From Problem 10-34,

\[
s_1 = s_2 = s_f @ 10 \text{ kPa} = 0.6492 \text{ kJ/kg} \cdot \text{K}
\]

\[
s_3 = 6.5995 \text{ kJ/kg} \cdot \text{K}
\]

\[
s_4 = 6.8464 \text{ kJ/kg} \cdot \text{K} \quad (P_4 = 1 \text{ MPa}, \ h_4 = 2902.0 \text{ kJ/kg})
\]

\[
s_5 = 7.7642 \text{ kJ/kg} \cdot \text{K}
\]

\[
s_6 = 8.3870 \text{ kJ/kg} \cdot \text{K} \quad (P_6 = 10 \text{ kPa}, \ h_6 = 2664.8 \text{ kJ/kg})
\]

\[
h_3 = 3375.1 \text{ kJ/kg}
\]

\[
q_{in} = 3749.8 \text{ kJ/kg}
\]

The exergy destruction associated with the combined pumping and the heat addition processes is

\[
x_{\text{destroyed}} = T_0 \left( s_3 - s_1 + s_5 - s_4 + \frac{q_{R,15}}{T_R} \right)
\]

\[
= \left( 285 \text{ K} \right) \left[ 6.5995 - 0.6492 + 7.7642 - 6.8464 + \frac{-3749.8 \text{ kJ/kg}}{1600 \text{ K}} \right] = 1289.5 \text{ kJ/kg}
\]

The exergy destruction associated with the pumping process is

\[
x_{\text{destroyed,12}} = \dot{w}_{p,a} - \dot{w}_{p,s} = \dot{w}_{p,a} - v\Delta P = 10.62 - 10.09 = 0.53 \text{ kJ/kg}
\]

Thus,

\[
x_{\text{destroyed,heating}} = x_{\text{destroyed}} - x_{\text{destroyed,12}} = 1289.5 - 0.5 = \boxed{1289 \text{ kJ/kg}}
\]

The exergy destruction associated with the expansion process is

\[
x_{\text{destroyed,34}} = T_0 \left( s_4 - s_3 + (s_6 - s_5) + \frac{q_{R,36}}{T_R} \phi_0 \right)
\]

\[
= \left( 285 \text{ K} \right) \left[ 6.8464 - 6.5995 + 8.3870 - 7.7642 \right] \text{kJ/kg} \cdot \text{K} = \boxed{247.9 \text{ kJ/kg}}
\]

The exergy of the steam at the boiler exit is determined from

\[
\psi_3 = (h_3 - h_0) - T_0 (s_3 - s_0) + \frac{V^2}{2} \phi_0 + qz_3 \phi_0
\]

where

\[
h_0 = h @ (285 \text{ K}, 100 \text{ kPa}) \equiv h_f @ 285 \text{ K} = 50.51 \text{ kJ/kg}
\]

\[
s_0 = s @ (285 \text{ K}, 100 \text{ kPa}) \equiv s_f @ 285 \text{ K} = 0.1806 \text{ kJ/kg} \cdot \text{K}
\]

Thus,

\[
\psi_3 = (3375.1 - 50.51) \text{ kJ/kg} - (285 \text{ K})(6.5995 - 0.1806) \text{ kJ/kg} \cdot \text{K} = \boxed{1495 \text{ kJ/kg}}
\]
The exergy destruction associated with the regenerative cycle described in Prob. 10-44 is to be determined for the specified source and sink temperatures.

**Assumptions**
1. Steady operating conditions exist.
2. Kinetic and potential energy changes are negligible.

**Analysis**
From Problem 10-44, \( q_{\text{in}} = 2692.2 \text{ kJ/kg} \) and \( q_{\text{out}} = 1675.7 \text{ kJ/kg} \). Then the exergy destruction associated with this regenerative cycle is

\[
x_{\text{destroyed,cycle}} = T_0 \left( \frac{q_{\text{out}}}{T_L} - \frac{q_{\text{in}}}{T_H} \right) = \left( 290 \text{ K} \right) \left( \frac{1675.7 \text{ kJ/kg}}{290 \text{ K}} - \frac{2692.2 \text{ kJ/kg}}{1500 \text{ K}} \right) = 1155 \text{ kJ/kg}
\]

The exergy destruction associated with the reheating and regeneration processes described in Prob. 10-49 are to be determined for the specified source and sink temperatures.

**Assumptions**
1. Steady operating conditions exist.
2. Kinetic and potential energy changes are negligible.

**Analysis**
From Problem 10-49 and the steam tables,

\[
y = 0.2016
\]

\[
s_3 = s_{f@0.8\text{MPa}} = 2.0457 \text{ kJ/kg} \cdot \text{K}
\]

\[
s_5 = s_6 = 6.7585 \text{ kJ/kg} \cdot \text{K}
\]

\[
s_7 = 7.8692 \text{ kJ/kg} \cdot \text{K}
\]

\[
s_1 = s_2 = s_{f@10\text{kPa}} = 0.6492 \text{ kJ/kg} \cdot \text{K}
\]

\[
q_{\text{reheat}} = h_7 - h_6 = 3481.3 - 2812.7 = 668.6 \text{ kJ/kg}
\]

Then the exergy destruction associated with reheating and regeneration processes are

\[
x_{\text{destroyed, reheat}} = T_0 \left( s_7 - s_6 + \frac{q_{\text{reheat}}}{T_R} \right)
\]

\[
= \left( 290 \text{ K} \right) \left( 7.8692 - 6.7585 + \frac{-668.6 \text{ kJ/kg}}{1800 \text{ K}} \right) = 214.3 \text{ kJ/kg}
\]

\[
x_{\text{destroyed, regen}} = T_0 s_{\text{gen}} = T_0 \left( \sum m_i s_i - \sum m_i s_i + \frac{q_{\text{surr}}}{T_0} \right) = T_0 \left( s_3 - y s_6 - (1-y) s_2 \right)
\]

\[
= \left( 290 \text{ K} \right) \left[ 2.0457 - (0.2016) \left( 6.7585 \right) - (1-0.2016) \left( 0.6492 \right) \right] = 47.8 \text{ kJ/kg}
\]
A single-flash geothermal power plant uses hot geothermal water at 230°C as the heat source. The power output from the turbine, the thermal efficiency of the plant, the exergy of the geothermal liquid at the exit of the flash chamber, and the exergy destructions and exergy efficiencies for the flash chamber, the turbine, and the entire plant are to be determined.

**Assumptions**
1. Steady operating conditions exist.
2. Kinetic and potential energy changes are negligible.

**Analysis**

(a) We use properties of water for geothermal water (Tables A-4, A-5, and A-6)

\[ T_1 = 230°C \quad h_1 = 990.14 \text{ kJ/kg} \]
\[ x_1 = 0 \quad s_1 = 2.6100 \text{ kJ/kg.K} \]
\[ P_2 = 500 \text{ kPa} \quad x_2 = 0.1661 \]
\[ h_2 = h_1 = 990.14 \text{ kJ/kg} \quad s_2 = 2.6841 \text{ kJ/kg.K} \]
\[ \dot{m}_3 = x_2 \dot{m}_1 = (0.1661)(230 \text{ kg/s}) = 38.19 \text{ kg/s} \]
\[ P_3 = 500 \text{ kPa} \quad h_3 = 2748.1 \text{ kJ/kg} \]
\[ x_3 = 1 \quad s_3 = 6.8207 \text{ kJ/kg.K} \]
\[ P_4 = 10 \text{ kPa} \quad h_4 = 2464.3 \text{ kJ/kg} \]
\[ x_4 = 0.95 \quad s_4 = 7.7739 \text{ kJ/kg.K} \]
\[ P_6 = 500 \text{ kPa} \quad h_6 = 640.09 \text{ kJ/kg} \]
\[ x_6 = 0 \quad s_6 = 1.8604 \text{ kJ/kg.K} \]
\[ \dot{m}_6 = \dot{m}_1 - \dot{m}_3 = 230 - 38.19 = 191.81 \text{ kg/s} \]

The power output from the turbine is
\[ W_T = \dot{m}_3 (h_3 - h_4) = (38.19 \text{ kJ/kg})(2748.1 - 2464.3) \text{ kJ/kg} = 10,842 \text{ kW} \]

We use saturated liquid state at the standard temperature for dead state properties
\[ T_0 = 25°C \quad h_0 = 104.83 \text{ kJ/kg} \]
\[ x_0 = 0 \quad s_0 = 0.3672 \text{ kJ/kg.K} \]
\[ \dot{W}_{in} = \dot{m}_1 (h_1 - h_0) = (230 \text{ kJ/kg})(990.14 - 104.83) \text{ kJ/kg} = 203,622 \text{ kW} \]
\[ \eta_{th} = \frac{W_{T, out}}{\dot{W}_{in}} = \frac{10,842}{203,622} = 0.0532 = 5.3\% \]

(b) The specific exergies at various states are
\[ \psi_1 = h_1 - h_0 - T_0 (s_1 - s_0) = (990.14 - 104.83) \text{ kJ/kg} - (298 \text{ K})(2.6100 - 0.3672) \text{ kJ/kg.K} = 216.53 \text{ kJ/kg} \]
\[ \psi_2 = h_2 - h_0 - T_0 (s_2 - s_0) = (990.14 - 104.83) \text{ kJ/kg} - (298 \text{ K})(2.6841 - 0.3672) \text{ kJ/kg.K} = 194.44 \text{ kJ/kg} \]
\[ \psi_3 = h_3 - h_0 - T_0 (s_3 - s_0) = (2748.1 - 104.83) \text{ kJ/kg} - (298 \text{ K})(6.8207 - 0.3672) \text{ kJ/kg.K} = 719.10 \text{ kJ/kg} \]
\[ \psi_4 = h_4 - h_0 - T_0 (s_4 - s_0) = (2464.3 - 104.83) \text{ kJ/kg} - (298 \text{ K})(7.7739 - 0.3672) \text{ kJ/kg.K} = 151.05 \text{ kJ/kg} \]
\[ \psi_6 = h_6 - h_0 - T_0 (s_6 - s_0) = (640.09 - 104.83) \text{ kJ/kg} - (298 \text{ K})(1.8604 - 0.3672) \text{ kJ/kg.K} = 89.97 \text{ kJ/kg} \]

The exergy of geothermal water at state 6 is
\[ X_6 = \dot{m}_6 \psi_6 = (191.81 \text{ kg/s})(89.97 \text{ kJ/kg}) = 17,257 \text{ kW} \]
(c) Flash chamber:
\[ \dot{X}_{\text{dest, FC}} = \dot{m}_1 (\psi_1 - \psi_2) = (230 \text{ kg/s})(216.53 - 194.44) \text{kJ/kg} = 5080 \text{ kW} \]
\[ \eta_{\text{II,FC}} = \frac{\psi_2}{\psi_1} = \frac{194.44}{216.53} = 0.898 = 89.8\% \]

(d) Turbine:
\[ \dot{X}_{\text{dest, T}} = \dot{m}_3 (\psi_3 - \psi_4) - \dot{W}_T = (38.19 \text{ kg/s})(719.10 - 151.05) \text{kJ/kg} - 10842 \text{ kW} = 10854 \text{ kW} \]
\[ \eta_{\text{II,T}} = \frac{\dot{W}_T}{\dot{m}_3 (\psi_3 - \psi_4)} = \frac{10842 \text{ kW}}{(38.19 \text{ kg/s})(719.10 - 151.05) \text{kJ/kg}} = 0.500 = 50.0\% \]

(e) Plant:
\[ \dot{X}_{\text{in, Plant}} = \dot{m}_1 \psi_1 = (230 \text{ kg/s})(216.53 \text{kJ/kg}) = 49802 \text{ kW} \]
\[ \dot{X}_{\text{dest, Plant}} = \dot{X}_{\text{in, Plant}} - \dot{W}_T = 49802 - 10842 = 38960 \text{ kW} \]
\[ \eta_{\text{II,Plant}} = \frac{\dot{W}_T}{\dot{X}_{\text{in, Plant}}} = \frac{10842 \text{ kW}}{49802 \text{ kW}} = 0.2177 = 21.8\% \]

---

**Cogeneration**

10-63C The utilization factor of a cogeneration plant is the ratio of the energy utilized for a useful purpose to the total energy supplied. It could be unity for a plant that does not produce any power.

10-64C No. A cogeneration plant may involve throttling, friction, and heat transfer through a finite temperature difference, and still have a utilization factor of unity.

10-65C Yes, if the cycle involves no irreversibilities such as throttling, friction, and heat transfer through a finite temperature difference.

10-66C Cogeneration is the production of more than one useful form of energy from the same energy source. Regeneration is the transfer of heat from the working fluid at some stage to the working fluid at some other stage.