Homework #4

solution
An ideal Rankine cycle operates with turbine inlet steam at 90 bar and 500°C, and a condenser temperature of 40°C. Calculate the efficiency and work ratio of this for the following cases:
(a) no feedwater heater,
(b) one open-type feedwater heater,
(c) one closed-type feedwater heater with drains cascaded back to the condenser, and
(d) one closed feedwater heater with drains pumped forward.
In each case the feedwater heater is optimally placed. Use TTD = 25°C.

(a) no feedwater heater:

\[ T_1 = 500°C \]

\[ P_1 = 90 \text{ bar} \]

\[ T_{sat} = 303.3°C \]

\[ h_1 = 3338.1 \text{ kJ/kg} \]

\[ s_1 = 6.4576 \text{ kJ/kg.k} \]

\[ P_2 = 0.07375 \text{ bar} \]

\[ T_2 = 40°C \]

\[ s_2 \leq s_{sat}(T_2) \]

\[ h_{sat} = 8167 \text{ kJ/kg} \]

\[ h_2 = 167.50 \text{ kJ/kg} \]

\[ h_{sat} = 22574 \text{ kJ/kg} \]

\[ h_2 = 2073.45 \text{ kJ/kg} \]

Work Ratio \( W_t = h_1 - h_2 = 1312.65 \text{ kJ/kg} \)

\[ W_p = 9.06 \text{ kJ/kg} \]

Work Ratio \( W_t \)

\[ \text{Efficiency} \quad \eta_{th} = \frac{W_{th}}{W_{in}} \]

\[ h_{in} = h_1 - h_4 = 3209.54 \text{ kJ/kg} \]

\[ \eta_{th} = 0.4062 \]
The optimum temperature for the feedwater heater is:

\[ T_{\text{FWH}} = T_c + \frac{T_b - T_c}{n+1} \]

\[ = 40^\circ C + \frac{(303.3^\circ C - 40^\circ C)}{2} \]

\[ = 171.65^\circ C \]

For convenience, let \( T_{\text{FWH}} = 170^\circ C \). This will be the same for cases (b), (c), and (d) since each had only one feedwater heater.

**State 5 - Steam bleed to OFH**

\[ T_5 = T_{\text{FWH}} = 170^\circ C \]

\[ S_5 = S_1 = 6.6576 \text{ kJ/kg k} \Rightarrow S_5 < S_0 \text{, 66630 kJ/kg k} \]

\[ \eta_5 = \frac{S_5 - S_4}{S_0 - S_4} = \frac{6.6576 \text{ kJ/kg k} - 2.0416 \text{ kJ/kg k}}{4.6214 \text{ kJ/kg k}} = 0.9988 \]

\[ h_5 = h_{s5} + \eta_5 (h_{s5} - h_{s4}) = 2764.56 \text{ kJ/kg} \]

\[ \rho_5 = 7.920 \text{ bar} \]

**State 4 - Low pressure pump exit/OEH inlet - Compressed liquid**

\[ P_4 = P_6 = P_5 = 7.920 \text{ bar} \]

\[ h_4 = h_3 + |W_P| \]

\[ |W_{P,HP}| = N_8 (P_4 - P_0) = (0.0010029 \text{ m}^3/\text{kg})(7.920 - 0.07375 \text{ bar})(10^5 \text{ Pa/1 bar}) = 791 \text{ J/kg} \]

\[ h_4 = 167.50 \text{ kJ/kg} + 0.791 \text{ kJ/kg} = 168.29 \text{ kJ/kg} \]

**State 6 - OFH exit - Saturated liquid**

\[ m_1 - m_5 \rightarrow \text{OFH} \rightarrow m \]

\[ (m_1 - m_5) h_4 + m_5 h_5 = m h_6 \]

\[ \text{divide through by } m_1; \text{ define } \eta_{RS} = \frac{m_5}{m} \]

\[ (1 - \eta_{RS}) h_4 + \eta_{RS} h_5 = h_6 \]

\[ \eta_{RS} = \frac{h_6 - h_4}{h_5 - h_4} = 0.2122 \]

**State 7 - High pressure pump exit - Compressed liquid**

\[ h_7 = h_6 + |W_{P,HP}| \]

\[ |W_{P,HP}| = N_8 (P_4 - P_0) = (0.0011145 \text{ m}^3/\text{kg})(90 - 7.92 \text{ bar})(10^5 \text{ Pa/1 bar}) = 9.15 \text{ kJ/kg} \]

\[ h_7 = 728.27 \text{ kJ/kg} \]
\[ W_{P,CP} = 0.79 \text{ kJ/kg} \]
\[ W_{P,HP} = 0.15 \text{ kJ/kg} \]
\[ W_{\text{net}} = (1 - M_{RS}) W_{P,CP} + W_{P,HP} = 9.77 \text{ kJ/kg} \]
\[ \Delta h_{t,net} = (h_f - h_5) + (1 - M_{RS})(h_8 - h_7) = 116.6 \text{ kJ/kg} \]
\[ W_{\text{net}} = 1156.23 \text{ kJ/kg} \]
\[ \eta_{in} = h_1 - h_7 = 3386.1 \text{ kJ/kg} - 728.27 \text{ kJ/kg} = 2657.83 \text{ kJ/kg} \]

\[ WR = 0.9916 \leftarrow \text{slightly lower than case (a), but higher efficiency} \]
\[ \eta_{ch} = 0.435 \]

(a) open feedwater heater, drained backwards to condenser:

(b) closed feedwater heater, drained backwards to condenser:

\[ T_{TD} = 25^\circ C \]
\[ h_5 = h_6 \]
\[ s_5 = s_6 \]
\[ s_7 = \frac{h_7 - h_4}{h_{fg} (40^\circ C)} = 0.2293 \]

state (7) - CFH drain - saturated

state (8) - CFH inlet - subcooled

\[ T_g = T_c - T_{TD} = 167.5^\circ C \]
\[ h_8 = 728.19 \text{ kJ/kg} \leftarrow \text{from compressed liquid tables} \]

\[ \dot{Q} = \dot{m}_5 (h_5 - h_6) = \dot{m}_5 (h_8 - h_4) \]
\[ M_{25} = \frac{\dot{m}_5}{\dot{m}} = \frac{h_8 - h_4}{h_5 - h_6} = 0.264 \]
\[ \Delta h_t = (h_f - h_5) + (1 - M_{25})(h_8 - h_7) = 113.3 \text{ kJ/kg} \]
\[ W_{\text{net}} = 1123.9 \text{ kJ/kg} \]
\[ W_P = N_3 (h_4 - h_3) = 9.06 \text{ kJ/kg} \]
\[ \eta_{in} = h_f - h_8 = 2677.91 \text{ kJ/kg} \]

\[ WR = 0.9920 \]
\[ \eta_{ch} = 0.4197 \]
(d) one closed feedwater heater pumped forward:

\[ T \]

\[ 500^\circ C \]
\[ 300^\circ C \]
\[ 200^\circ C \]
\[ 100^\circ C \]
\[ 40^\circ C \]

\[ \text{Steam bleed} \rightarrow \text{m} \rightarrow \text{m}_s \rightarrow \text{to pump} \]
\[ \text{Feedwater} \rightarrow \text{from pump} \]

\[ \dot{Q}_1 = \dot{m}_s (\dot{h}_5 - \dot{h}_6) = \dot{m} (\dot{h}_8 - \dot{h}_4) \]
\[ \dot{m}_s = \frac{\dot{h}_8 - \dot{h}_4}{\dot{h}_5 - \dot{h}_6} = 0.264 \]

\[ \dot{Q}_\text{in} = \dot{m} (\dot{h}_1 - \dot{h}_4) \]
\[ \dot{Q}_\text{in} = 3386.1 \text{ kJ/kg} - 713.49 \text{ kJ/kg} \]
\[ \dot{Q}_\text{in} = 2672.61 \text{ kJ/kg} \]

\[ \dot{W}_t = \dot{m}_s (\dot{h}_5 - \dot{h}_6) + (\dot{m} - \dot{m}_s) (\dot{h}_5 - \dot{h}_7) \]
\[ = \dot{m}_s (\dot{h}_5 - \dot{h}_6) + (1 - \dot{m}_s) (\dot{h}_5 - \dot{h}_7) \]

\[ \dot{W}_t = \dot{h}_1 - \dot{h}_5 + (1 - \dot{m}_s) (\dot{h}_5 - \dot{h}_7) = 1/33 \text{ kJ/kg} \]

(same as case c). \[ \frac{\dot{W}_{P+}}{1} = (\dot{m} - \dot{m}_s) (P_1 - P_3) = \dot{m} (1 - \dot{m}_s) \frac{\dot{W}_{P+}}{1} \]

\[ \dot{W}_{P+} = 1/133 \text{ kJ/kg} - 1/148 \text{ kJ/kg} = 1121.52 \text{ kJ/kg} \]

\[ \dot{W}_{\text{net}} = 1/133 \text{ kJ/kg} - 1/148 \text{ kJ/kg} = 1121.52 \text{ kJ/kg} \]

\[ \dot{W}_R = \frac{1121.52 \text{ kJ/kg}}{1121.52 \text{ kJ/kg}} = 0.9899 \]

\[ \eta = \frac{1121.52 \text{ kJ/kg}}{2672.61 \text{ kJ/kg}} = 0.4196 \]

States (1) - (6) are the same as in case (b).

State (7) - CFH drain - subcooled

\[ h_7 = h_6 + |\dot{W}_{P+}| \]
\[ |\dot{W}_{P+}| = \dot{m}_s (P_7 - P_6) = 9.15 \text{ kJ} \]

\[ h_7 = 728.27 \text{ kJ/kg} \]

State (8) - CFH exit - subcooled

\[ T_B = T_6 - TTD = 167.5^\circ C \]
\[ h_8 = 708.19 \text{ kJ/kg} \]

State (9) - exit of mixer for flows at states (8) and (7) - subcooled

\[ (\dot{m} - \dot{m}_s) h_8 + \dot{m}_5 h_7 = \dot{m} h_9 \]

\[ h_9 = (1 - \dot{m}_5) h_8 + \dot{m}_5 h_7 = 713.49 \text{ kJ/kg} \]
A 3800-MWth PWR is cooled with 15.3-MPa water that enters the core at 300°C and leaves at 332°C. In the once-through steam generator, the high pressure water is used to produce steam at 8.0 MPa and 315°C (1). The steam expands to 0.68 MPa (2) in the high-pressure turbine. Moisture (12) is separated and the saturated steam (3) is reheated with live steam (1) to 288°C (4). Before it enters the low-pressure turbine, the steam expands to 110 kPa (5), where a fraction is bled to a closed feed water heater. Expansion continues to the condenser pressure of 10 kPa (6). The separated moisture (12) is drained to an open feed water heater and the reheater condensate (13) is "trapped" (14) to the same heater. The closed feed water heater has a terminal temperature difference of 3°C. Each segment of the turbine expansion is 0.85 efficient and the pumps are 0.75 efficient.

(a) Sketch the cycle on a Ts diagram.
(b) Find the cooling water flow rate in the core, in l/min.
(c) Find the steam generation rate, in kg/hr.
(d) Determine the power output of the system, MWth, if the turbine drives a generator with an efficiency of 94 percent.
(e) What is the thermal efficiency of the cycle?

Property values from EES, Steam-IAPWS

-I think quality at 143 needs to be specified in order to stabilize the cycle
-In EES, the quality at 143 varies with each run, sometimes becoming superheated with reverse mass flows
-
status 143 is saturated liquid
Part (b) \( \dot{V}_a = \) ?

\[ \dot{V}_a = N_a \cdot \dot{m}_{pure} \]  

\[ \dot{m}_{pure} = \frac{Q_{pure}}{h_b - h_a} \]

\[ h_b \left( 332^\circ C, 15.3 \text{ MPa} \right) = 1531.6 \text{ kJ/kg} \]
\[ h_a \left( 300^\circ C, 15.3 \text{ MPa} \right) = 1338.0 \text{ kJ/kg} \]

\[ \dot{m}_{pure} = \frac{3,200,000 \text{ kW}}{\left( \frac{\text{1531.6 kJ/kg}}{\text{kg}} - \frac{1338.0 \text{ kJ/kg}}{\text{kg}} \right)} = 19,628 \text{ kg/s} \]

\[ N_a \left( 300^\circ C, 15.3 \text{ MPa} \right) = 0.001377 \text{ m}^3/\text{kg} \]

\[ \dot{V}_a = \left( 0.001377 \frac{\text{m}^3}{\text{kg}} \right)(19,628 \frac{\text{kg}}{\text{s}}) = 27.03 \text{ kg/s} \]

\[ \dot{V}_a = 27.03 \frac{\text{kg}}{\text{s}} = 1.622 \times 10^6 \frac{\text{L}}{\text{min}} \]

Part (c) \( \dot{m}_{SG} = ? \)

\[ \dot{m}_{SG} = \frac{Q_{end}}{h_i - h_{i1}} \]

(1) Superheated Vapor
\[ P_i = 8,000 \text{ kPa} \]
\[ T_i = 315^\circ C \]
\[ h_i = 2857.5 \text{ kJ/kg} \]
\[ s_i = 5.9151 \text{ kJ/kgk} \]

(2) Subcooled Liquid
\[ P_{i1} = 8,000 \text{ kPa} \]
\[ h_{i1,S} = h_i + \frac{N_{i1}}{\eta_p} (P_{i1} - P_0) \]
\[ h_{i1} = h_i + \frac{N_{i1}}{\eta_p} \left( N_{i1} (P_{i1} - P_0) \right) \]

(10) Saturated Liquid
\[ P_0 = 680 \text{ kPa} \]
\[ h_0 = h_f \left( 680 \text{ kPa} \right) = 671.9 \text{ kJ/kg} \]
\[ N_f = N_f \left( 680 \text{ kPa} \right) = 0.0011065 \text{ m}^3/\text{kg} \]
\[ h_i = 702.7 \text{ kJ/kg} \]

\[ \dot{m}_{SG} = \frac{3,200,000 \text{ kJ/s}}{\left( 296.35 \text{ kJ/kg} - 702.7 \text{ kJ/kg} \right)} = 1763.5 \text{ kg/s} \]

\[ \dot{m}_{SG} = 1763.5 \frac{\text{kg}}{\text{s}} = 6.35 \times 10^6 \frac{\text{kg}}{\text{hr}} \]
(6) saturated steam, \( x_6 = ? \)

\[ \dot{w}_e = \dot{q}_e \frac{\dot{v}_e}{\dot{m}_e} = \dot{m}_{sg} \frac{\dot{m}_e}{\dot{m}_{sg}} \]

\[ \dot{w}_e = \dot{m}_e (h_1 - h_2) + \dot{m}_3 (h_4 - h_5) + \dot{m}_6 (h_5 - h_6) \]

\[ \dot{m}_e = \frac{\dot{w}_e}{\dot{m}_{sg}} = \dot{m}_2 (h_1 - h_2) + \dot{m}_3 (h_4 - h_5) + \dot{m}_6 (h_5 - h_6) \]

\( \dot{m}_2 = \frac{\dot{m}_e}{\dot{m}_{sg}} \)

(2) saturated steam, \( x_2 = ? \)

\[ P_e = 680 \text{ kPa} \]

\[ T_e = T_{sat} = 163.8^\circ C \]

\[ \frac{S_e}{S} = \frac{S}{S} = 5.79161 \text{ kJ/kg.k} \]

\[ h_{e} (680 \text{ kPa}, 5.79161 \text{ kJ/kg.k}) = 2412 \text{ kJ/kg} \]

\[ h_e = h_1 - \frac{\dot{w}_e}{\dot{m}_e} (h_1 - h_{es}) = 2478.5 \text{ kJ/kg} \]

(3) saturated vapor

\[ P_a = 680 \text{ kPa} \]

\[ T_3 = T_{sat} = 163.8^\circ C \]

\[ h_3 = h_3 \text{ = } 2761.5 \text{ kJ/kg} \]

\[ S_3 = S_3 = 6.7769 \text{ kJ/kg.k} \]

(4) superheated vapor

\[ P_a = 680 \text{ kPa} \]

\[ T_4 = 288^\circ C \]

\[ h_4 = 3034.8 \text{ kJ/kg} \]

\[ S_4 = 7.2672 \text{ kJ/kg.k} \]

(5) unknown state

\[ P_{es} = 110 \text{ kPa} \]

\[ \frac{S_{es}}{S_4} = 7.2672 \text{ kJ/kg.k} > S_{es} = 7.3269 \text{ kJ/kg.k} \]

\[ h_{es} = 2653 \text{ kJ/kg} \]

\[ h_5 = h_4 - \frac{\dot{w}_e}{\dot{m}_e} (h_4 - h_{es}) = 2741.4 \text{ kJ/kg} \]

\[ S_5 = 7.4179 \text{ kJ/kg.k} \]

(6) saturated steam, \( x_6 = ? \)

\[ P_e = 10 \text{ kPa} \]

\[ \frac{S_{es}}{S} = 7.4179 \text{ kJ/kg.k} \]

\[ h_{es} = 2351 \text{ kJ/kg} \]

\[ h_6 = h_5 - \frac{\dot{w}_e}{\dot{m}_e} (h_5 - h_{es}) = 2405.2 \text{ kJ/kg} \]

(7) saturated liquid

\[ P_{es} = 10 \text{ kPa} \]

\[ h_7 = h_f (10 \text{kPa}) = 1918 \text{ kJ/kg} \]

\[ S_7 = S_f (10 \text{kPa}) = 0.00101 \text{ mJ/kg} \]
(8) Subcooled liquid

\[ P_8 = 680 \text{ kPa} \]

\[ h_{s8} = h_s + \frac{1}{\rho_s} \left( P_8 - P_s \right) = 192.5 \text{ kJ/kg} \]

\[ h_8 = h_s + \frac{1}{\rho_s} \left[ h_{s8} - h_s \right] = 192.7 \text{ kJ/kg} \]

(9) Unknown state, but suspect it is subcooled liquid

\[ P_9 = 680 \text{ kPa} \]

\[ T_9 - T_{s9,sat} - TTD = -99.3^\circ C < T_{s9,sat} = 163.6^\circ C \text{ ; therefore, subcooled liquid} \]

\[ h_9 = h_{s9} \left( 680 \text{ kPa}, 99.3^\circ C \right) = 416.6 \text{ kJ/kg} \]

(10) Unknown state, but suspect it is slightly subcooled liquid

\[ P_9 = 680 \text{ kPa} \]

determined from energy balance on open feedwater heater

(12) Saturated liquid

\[ P_{12} = 680 \text{ kPa} \]

\[ h_{12} = h_f \left( 680 \text{ kPa} \right) = 691.7 \text{ kJ/kg} \]

(13) Saturated liquid — design specification

\[ P_{13} = 9000 \text{ kPa} \]

\[ h_{13} = h_f \left( 9000 \text{ kPa} \right) = 1317.1 \text{ kJ/kg} \]

(14) Saturated steam

\[ P_{14} = 680 \text{ kPa} \]

\[ h_{14} = h_{13} = 1317.1 \text{ kJ/kg} \]

\[ \frac{\text{throttle}}{X_{14} = 0.3021 \text{ (mostly liquid)}} \]

(15) Saturated liquid — design specification

\[ P_{15} = 110 \text{ kPa} \]

\[ h_{15} = h_f \left( 110 \text{ kPa} \right) = 428.8 \text{ kJ/kg} \]

\[ h_f \left( 110 \text{ kPa} \right) = 428.8 \text{ kJ/kg} \]

\[ h_f \left( 110 \text{ kPa} \right) = 2679.2 \text{ kJ/kg} \]

(16) Saturated steam, \( X_{16} = ? \)

\[ P_e = 10 \text{ kPa} \]

\[ h_{16} = h_{15} = 428.8 \text{ kJ/kg} \]

\[ \frac{\text{throttle}}{X_{16} = 0.0991 \text{ (mostly liquid)}} \]

*State (10) and subsequently state (11) must be determined by balancing the energies on the open feed water heater.*

\[ \frac{m_{8}}{m_{9}} = 1 \]

\[ \frac{m_{12}}{m_{8}} = n \]

\[ \frac{m_{14}}{m_{8}} = m \]

\[ \frac{m_{16}}{m_{8}} = 1 - m - n \]

Energy balance:

\[ h_9 = n h_{12} + m h_{14} + (1 - m - n) h_8 \]
energy balance on open feed water heater:
\[(h_0 - h_a) = (1 - n)(h_2 - h_a) + m(h_4 - h_a)\]

energy balance on separator:
\[
(1 - m)h_2 = (1 - m - n)h_3 + nh_2
\]
\[
(1 - m)h_2 = (1 - m)h_3 + n(h_2 - h_3)
\]
\[
(1 - m)(h_2 - h_3) = n(h_2 - h_3)
\]
\[
m = 1 - \left(\frac{h_2 - h_3}{h_3 - h_2}\right)\]
\[n = 1 - \frac{h_2 - h_3}{h_3 - h_2}\]

energy balance on reheater:
\[
m(h_3 - h_b) = (1 - m - n)(h_4 - h_3)
\]
\[
(1 - 0.313 n)(h_3 - h_b) = (6.313 n)(h_4 - h_3)
\]
\[
(1 - 0.313 n)(2857.5 \text{ kJ/kg} - 1312.7 \text{ kJ/kg}) = (6.313 n)(3034.8 \text{ kJ/kg} - 2761.5 \text{ kJ/kg})
\]
\[n = 0.1186 \quad \text{kg/s} \quad \text{kg/s (SG)}\]
\[X_2 = \frac{1 - m - n}{1 - m} = \frac{1 - m - n}{1 - m} = 1 - \frac{n}{1 - m} = 0.8633 \checkmark\]
\[m = 0.1327 \quad \text{kg/s} \quad \text{kg/s (SG)}\]

At this point, states (10) and (n) can be determined. Before that, however, the mass flow ratio \(p\) will be determined through an energy balance on the closed feed water heater:
\[
r(h_5 - h_{15}) = (1 - m - n)(h_9 - h_b)
\]
\[
p = \frac{(0.7487 \text{ kg/s (SG)}) (416.6 \text{ kJ/kg} - 192.7 \text{ kJ/kg})}{(2741.4 \text{ kJ/kg} - 428.8 \text{ kJ/kg})} = 0.0734 \quad \text{kg/s} \quad \text{kg/s (SG)}
\]
\[10: h_0 = n h_1 + m h_4 + (1 - m - n) h_9 = 568.7 \text{ kJ/kg}\]
\[11: h_{11} = h_0 + \frac{1}{\rho} \left[\frac{\rho_0 (P_i - P_{10})}{\rho_0 (P_i - P_{10})}\right]
\]
\[N_0 \left(680 \text{ kPa}, 568.7 \text{ kJ/kg}\right) = 0.001675 \quad \text{m}^3/\text{kg}\]
\[h_{11} = 579.2 \text{ kJ/kg}\]
### Summary of Data

<table>
<thead>
<tr>
<th>enthalpies, kJ/kg</th>
<th>mass flow ratios, m/m_{in}</th>
</tr>
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<tbody>
<tr>
<td>h₁ = 28.575</td>
<td>m = 0.1327</td>
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<tr>
<td>h₂ = 24.765</td>
<td>n = 0.1186</td>
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<td>h₃ = 2761.5</td>
<td>p = 0.0734</td>
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**Part (c):** Mass flow through the steam generator, \( m_{SG} = ? \)

\[
m_{SG} = \frac{\bar{Q}_{th}}{h_{f} - h_{l}} = 1667.9 \text{ kg/s} = 6.0045 \times 10^6 \text{ kg/h}.
\]

**Part (d):** Electrical power output, \( We = ? \)

\[
We = \%e \times \dot{W}_e = \%e \times m_{SG} \times \dot{h}_e \quad \%e = 0.94
\]

\[
\dot{W}_e = (1 - m)X_{h_1} + (1 - m - n)\left(h_{H_4} - h_{SG}\right) + (1 - m - n - p)\left(h_{H_5} - h_{SG}\right)
\]

\[
\dot{W}_e = 328.7 \text{ kJ/kg (SG)} + 240.1 \text{ kJ/kg (SG)} + 208.6 \text{ kJ/kg (SG)} = 777.4 \text{ kJ/kg (SG)}
\]

\[
\dot{W}_e = 1.3 \text{ MW}_m
\]

\[
We = 1.21 \text{ MW}e
\]

**Part (e):** Cycle Efficiency

\[
\eta_{th} = \frac{\dot{W}_e}{\dot{Q}_{in}} = 0.3412
\]
A 3800-MWth PWR is cooled with 15.3-MPa water that enters the core at 300 degrees C and leaves at 332 degrees C. In the once-through steam generator, the high pressure water is used to produce steam at 8.0 MPa and 315 degrees C. The steam expands to 0.68 MPa in the high-pressure turbine. Moisture is separated and the saturated steam is reheated with live steam to 288 degrees C before it enters the low-pressure turbine. The steam expands to 110 kPa, where a fraction is bled to a closed feedwater heater. Expansion continues to the condenser pressure of 10 kPa. The separated moisture is drained to an open feedwater heater and the re heater condensate is "trapped" to the same heater. The closed feedwater heater has a terminal temperature difference of 3 degrees C. Each segment of the turbine expansion is 85% efficient and the pumps are 65% efficient.
"A 3800-MW/h PWR is cooled with 15.3-MPa water that enters the core at 300 degrees C and leaves at 332 degrees C. In the once-through steam generator, the high pressure water is used to produce steam at 8.0 MPa and 315 degrees C. The steam expands to 0.68 MPa in the high-pressure turbine. Moisture is separated and the saturated steam is reheated with live steam to 288 degrees C before it enters the low-pressure turbine. The steam expands to 110 kPa, where a fraction is bled to a closed feedwater heater. Expansion continues to the condenser pressure of 10 kPa. The separated moisture is drained to an open feedwater heater and the reheat condensate is "trapped" to the same heater. The closed feedwater heater has a terminal temperature difference of 3 degrees C. Each segment of the turbine expansion is 85% efficient and the pumps are 65% efficient.

(a) Sketch the cycle on a T-s diagram.
(b) Find the cooling water flow rate in the core, in L/min.
(c) Find the steam generation rate, in kg/hr.
(d) Determine the power output of the system, MW, if the turbine drives a generator with an efficiency of 94%.
(e) What is the thermal efficiency of the cycle?"

"choice of steam tables"
fluid$ = 'Steam_JAPWS'

"==== Primary Coolant (pc) states (a;1), (b;2), and (c;3) on cycle diagram ===="
Q
  _dot_ pc = 3800 *1000 [kW]
P
  _b = 15.3 * 1000 [kPa]
T
  _b = 332 [C]
T
  _a = 300 [C]

P
  _a = P
  _b
h
  _b = enthalpy(fluid$, P=P
  _b, T=T
  _b)
h
  _a = enthalpy(fluid$, P=P
  _a, T=T
  _a)
Q
  _dot_ pc = m
  _dot_ pc * ( h
  _b - h
  _a )
h
  c = h
  b - Q
  _dot_ pc/m
  dot
  pc
T
  _c = T
  a
P
  c = pressure(fluid$, T=T
  c, h=h
  c)
s
  a = entropy(fluid$, P=P
  _a, h=h
  a)
s
  b = entropy(fluid$, P=P
  _b, h=h
  b)
s
  c = entropy(fluid$, T=T
  c, h=h
  c)

"part (b). volumetric flow rate [l/min] through reactor core"
V
  _dot
  pc_a = (v
  pc_a*m
  dot
  pc )/60*1000
v
  pc_a = volume(fluid$, P=P
  _a, T=T
  a)

"==== Rankine Cycle inputs ===="
P
  high= 8000 [kPa]
T
  high = 315 [C]
P
  reheate = 680 [kPa]
T
  reheate = 288 [C]
P
  bleed= 110 [kPa]
P
  low = 10 [kPa]
TTD = 3 [C]
s
  _eta_t = 0.85
s
  _eta_p = 0.75

"==== enthalpies ===="

"state (1). superheated vapor"
P
[1] = P
  high
T[1] = T
  high
h
[1] = enthalpy(fluid$, P=P[1], T=T[1])
s[1] = entropy(fluid$, P=P[1], T=T[1])"
"state (2). saturated steam"
P[2] = P_reheat
s_s[2] = s[1]
h_s[2] = enthalpy(fluid$, P=P[2], s=s_s[2])
T_s[2] = temperature(fluid$, P=P[2], s=s_s[2])
eta_1 = (h[1] - h[2])/(h[1] - h_s[2])
T[2] = temperature(fluid$, P=P[2], h=h[2])
s[2] = entropy(fluid$, P=P[2], h=h[2])
x[2] = quality(fluid$, P=P[2], h=h[2])

"solves for h2"

"state (3). saturated vapor"
T[3] = T_sat(fluid$, P=P[3])
x[3] = 1
h[3] = enthalpy(fluid$, P=P[3], x=x[3])
s[3] = entropy(fluid$, P=P[3], x=x[3])

"state (4). superheated vapor"
T[4] = T_reheat
h[4] = enthalpy(fluid$, P=P[4], T=T[4])
s[4] = entropy(fluid$, P=P[4], T=T[4])

"no pressure drop through closed heater"

"state (5). unknown state"
P[5] = P_bleed
h_s[5] = enthalpy(fluid$, P=P[5], s=s_s[5])
T_s[5] = temperature(fluid$, P=P[5], s=s_s[5])
eta_1 = (h[4]-h[5])/(h[4]-h_s[5])
T[5] = temperature(fluid$, P=P[5], h=h[5])
s[5] = entropy(fluid$, P=P[5], h=h[5])

"greater than s_c(P_bleed); therefore superheated"

"solves for h5"

"state (6). saturated steam"
P[6] = P_low
h_s[6] = enthalpy(fluid$, P=P[6], s=s_s[6])
T_s[6] = temperature(fluid$, P=P[6], s=s_s[6])
eta_1 = (h[5]-h[6])/(h[5]-h_s[6])
T[6] = temperature(fluid$, P=P[6], h=h[6])
s[6] = entropy(fluid$, P=P[6], h=h[6])
x[6] = quality(fluid$, P=P[6], h=h[6])

"solves for h6"

"state (7). saturated liquid"
T[7] = T_sat(fluid$, P=P[7])
x[7] = 0
h[7] = enthalpy(fluid$, P=P[7], x=x[7])
s[7] = entropy(fluid$, P=P[7], x=x[7])

"no pressure drop through condenser"

"state (8). subcooled liquid"
P[8] = P_reheat
v_7 = volume(fluid$, P=P[7], x=x[7])
s_s[8] = entropy(fluid$, P=P[8], h=h_s[8])
T_s[8] = temperature(fluid$, P=P[8], h=h_s[8])
eta_1 = (h_s[8] - h[7])/(h_s[8] - h[7])
s[8] = entropy(fluid$, P=P[8], h=h[8])
T[8] = temperature(fluid$, P=P[8], h=h[8])

"solves for h8"

"low-pressure feedwater pump"
w_p_ideal_cond = (1 - m_m - m_n)*(h_s[8] - h[7])
w_p_actual_cond = (1 - m_m - m_n)*(h[8] - h[7])
"state (9). unknown state, but suspect it is subcooled liquid"

\[ P[9] = P[8] \]  \quad \text{"no pressure drop through closed heater"}

\[ T[9] = T_{sat}(\text{fluid}\$,P=P[8]) - \text{TD} \]
\[ h[9] = \text{enthalpy}(\text{fluid}\$,P=P[9],T=T[9]) \]
\[ s[9] = \text{entropy}(\text{fluid}\$,P=P[9],T=T[9]) \]
\[ h_s\_lookup = h[9] \]
\[ h_p\_law = (h[5] - h[15])/(1 - m_m - m_n - m_p) + h[8] \]
\[ \text{determination of enthalpy from tables"} \]
\[ \text{determination of enthalpy from energy balance"} \]

"state (10). unknown state, but suspect it is slightly subcooled liquid"

\[ P[10] = P_{reheat} \]
\[ \text{"h_{10} determined from energy balance on open feedwater heater - see below"} \]
\[ T[10] = \text{temperature}(\text{fluid}\$,P=P[10],h=h[10]) \]
\[ s[10] = \text{entropy}(\text{fluid}\$,P=P[10],h=h[10]) \]

"state (11). subcooled liquid"

\[ P[11] = P_{high} \]
\[ v_{10} = \text{volume}(\text{fluid}\$,P=P[10],x=0) \]
\[ s_s[11] = \text{entropy}(\text{fluid}\$,P=P[11],h=h_s[11]) \]
\[ T_s[11] = \text{temperature}(\text{fluid}\$,P=P[11],h=h_s[11]) \]
\[ s[11] = \text{entropy}(\text{fluid}\$,P=P[11],h=h[11]) \]
\[ \text{"high-pressure feedwater pump"} \]
\[ \text{(w_p\_ideal\_ofh = h_s[11] - h[10])} \]
\[ \text{(w_p\_actual\_ofh = h[11] - h[10])} \]

"state (12). saturated liquid"

\[ P[12] = P_{reheat} \]
\[ x[12] = 0 \]
\[ h[12] = \text{enthalpy}(\text{fluid}\$,P=P[12],x=x[12]) \]
\[ s[12] = \text{entropy}(\text{fluid}\$,P=P[12],x=x[12]) \]

"state (13). saturated liquid; this is a design specification for the re heater"

\[ P[13] = P_{high} \]
\[ x[13] = 0 \]
\[ h[13] = \text{enthalpy}(\text{fluid}\$,P=P[13],x=x[13]) \]
\[ s[13] = \text{entropy}(\text{fluid}\$,P=P[13],x=x[13]) \]
\[ T[13] = \text{temperature}(\text{fluid}\$,P=P[13],x=x[13]) \]

"state (14). saturated steam"

\[ P[14] = P_{reheat} \]
\[ T[14] = T_{sat}(\text{fluid}\$,P=P[14]) \]
\[ s[14] = \text{entropy}(\text{fluid}\$,P=P[14],h=h[14]) \]

"state (15). saturated liquid; this is a design specification for the closed feedwater heater"

\[ P[15] = P_{bleed} \]
\[ x[15] = 0 \]
\[ h[15] = \text{enthalpy}(\text{fluid}\$,P=P[15],x=x[15]) \]
\[ s[15] = \text{entropy}(\text{fluid}\$,P=P[15],x=x[15]) \]
\[ T[15] = T_{sat}(\text{fluid}\$,P=P[15]) \]

"state (16). saturated steam"

\[ P[16] = P_{low} \]
\[ h[16] = h[15] \]
\[ x[16] = \text{quality}(\text{fluid}\$,P=P[16],h=h[16]) \]
\[ T[16] = T_{sat}(\text{fluid}\$,P=P[16]) \]
\[ s[16] = \text{entropy}(\text{fluid}\$,P=P[16],x=x[16]) \]
"--- energy balance on open feedwater heater -----"
\[ m_p = \frac{m \cdot p}{m \cdot p_{total}} \]
\[ m_n = \frac{m \cdot n}{m \cdot n_{total}} \]
\[ 1 = m_m + m_n + m_p \]
\[ h[10] = m_n^*h[12] + m_m^*h[14] + (1 - m_m - m_n)^*h[9] \]

"--- energy balance on phase separator ------"
\[ (1 - m_m)^*h[2] = (1 - m_m - m_n)^*h[3] + m_n^*h[12] \]

"--- energy balance on reheater -------"
\[ m_m^*(h[1] - h[13]) = (1 - m_m - m_n)^*(h[4] - h[3]) \]

"--- energy balance on closed feedwater heater ------"
\[ m_p^*(h[5] - h[13]) = (1 - m_m - m_n)^*(h[9] - h[8]) \]

"part (c). mass flow rate [kg/hr] through steam generator; m_dot solved in 'steam generator' section"
\[ Q_{dot}_{sg} = Q_{dot}_{pc} \]
\[ Q_{dot}_{sg} = m_{dot} * q_{in} \]

\[ m_{dot}_{sg} = m_{dot} * 3600 \text{ hr}^{-1} \]

"3600 sec/hr"

"part (d). electrical power output"
\[ \eta_{gen} = 0.94 \]
\[ W_{dot}_{t} = m_{dot}^*(w_{hpt} + w_{lpt}) \]
\[ w_{hpt} = (1 - m_m)^*(h[1] - h[2]) \]
\[ w_{lpt} = (1 - m_m - m_n)^*(h[4] - h[5]) + (1 - m_m - m_n - m_p)^*(h[5] - h[6]) \]
\[ w_t = w_{hpt} + w_{lpt} \]
\[ W_{dot}_{e} = W_{dot}_{t} * \eta_{gen} \]

"part (e). cycle efficiency"
\[ \eta_{th} = W_{dot}_{t}/Q_{dot}_{sg} \]

"saturation temperatures -- for reference only"
\[ T_{sat}[1] = T_{sat}(fluids, P=P[1]) \]
\[ T_{sat}[2] = T_{sat}(fluids, P=P[2]) \]
\[ T_{sat}[3] = T[3] \]
\[ T_{sat}[4] = T_{sat}(fluids, P=P[4]) \]
\[ T_{sat}[5] = T_{sat}(fluids, P=P[5]) \]
\[ T_{sat}[6] = T_{sat}(fluids, P=P[6]) \]
\[ T_{sat}[7] = T_{sat}(fluids, P=P[7]) \]
\[ T_{sat}[8] = T_{sat}(fluids, P=P[8]) \]
\[ T_{sat}[9] = T_{sat}(fluids, P=P[9]) \]
\[ T_{sat}[10] = T_{sat}(fluids, P=P[10]) \]
\[ T_{sat}[11] = T_{sat}(fluids, P=P[11]) \]
\[ T_{sat}[12] = T_{sat}(fluids, P=P[12]) \]
\[ T_{sat}[13] = T_{sat}(fluids, P=P[13]) \]
\[ T_{sat}[14] = T_{sat}(fluids, P=P[14]) \]
\[ T_{sat}[15] = T_{sat}(fluids, P=P[15]) \]
\[ T_{sat}[16] = T_{sat}(fluids, P=P[16]) \]

"--- data points for T-s diagram, simple cycle -----"
Tp[12] = temperature(fluid$, P=P[1], x=0)
Tp[13] = temperature(fluid$, P=P[1], x=1)
sp[1] = s[1]
sp[8] = s[8]
sp[9] = s[9]
sp[10] = s[10]
sp[12] = entropy(fluid$, P=P[1], x=0)
sp[13] = entropy(fluid$, P=P[1], x=1)
sp[14] = s[1]

"--- data points for T-s diagram, separator drain -------"

"--- data points for T-s diagram, closed feedwater heater steam bleed -------"
Tp_cfh[2] = T_sat(fluid$, P=P[5])
sp_cfh[2] = entropy(fluid$, P=P[5], x=1)
sp_cfh[4] = s[16]

"--- data points for T-s diagram, reheater steam bleed -------"
sp_rh[1] = s[1]
Tp_rh[2] = T_sat(fluid$, P=P[1])
sp_rh[2] = entropy(fluid$, P=P[1], x=1)

"--- data points for T-s diagram, primary coolant -------"
Tp_pc[1] = T_a
Tp_pc[2] = T_b
Tp_pc[3] = T_c
sp_pc[1] = s_a
sp_pc[2] = s_b
sp_pc[3] = s_c

"eof"

SOLUTION

Unit Settings: SI C kPa kJ mass deg
η_{gen} = 0.94
η_t = 0.85
fluid$ = "steam_iapws"
h_a = 1338 [kJ/kg]
h_c = 1338 [kJ/kg]
m = 1668 [kg/s]
m_g = 6.00E+06 [kg/hr]
m_b = 0.1186

P_a = 15300 [kPa]
P_{i,seed} = 110 [kPa]
P_{i,high} = 8000 [kPa]
P_{v,heat} = 680 [kPa]
\dot{Q}_{\text{v}} = 3.800E+06 [W]
s_b = 3.227 [kJ/kgK]
s_c = 3.227 [kJ/kgK]
T_a = 300 [C]
T_c = 300 [C]
T_{\text{v,heat}} = 288 [C]
v_f = 0.00110103 [m^3/kg]
v_{pc,a} = 0.001377 [m^3/kg]
W_{\text{t}} = 1.273E+06 [W]
W_{\text{p}} = 434.2 [kJ/kg]
W_{\text{p,ideal.cond}} = 0.5067 [kJ/kg]

13 potential unit problems were detected.

KEY VARIABLES
m_{bc} = 19633 [kg/s]
\dot{V}_{pc,a} = 1.622E+06 [L/min]
m = 1668 [kg/s]
W_t = 1.273E+06 [W]
m_g = 6.00E+06 [kg/hr]
\eta_h = 0.3349 [-]

part (b). volume flow rate through PWR

part (c). mass flow through steam generator

part (e). thermodynamic cycle efficiency

Arrays Table: Main

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part (e). thermodynamic cycle efficiency
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7. Weston 2.55 (see EES code)
"Weston 2.55

An ideal Rankine cycle has a throttle state of 2000 psia/1000 F and condenser pressure of 1 psia. There is a reheat and a closed feedwater heater with extraction from the cold reheat line and FWH condensate throttled to the condenser. Both reheat and extraction are at 200 psia. Assume that the feedwater leaving the FWH is at the temperature of the condensing extraction stream.

Determine the temperatures, pressures, entropies, and enthalpies at the inlets of all components, and compare the thermal efficiency of the cycle with the relevant Carnot efficiency. Neglect pump work. What is the quality of the steam at the turbine exit?

Resolve with 4% pressure drops in the main steam pass and reheat pass through the steam generator. Make a table comparing your results with those of the example to show the influence of the losses on plant performance. Calculate and display the percentage differences for each parameter. Assume turbine throttle conditions are unchanged.

\[ P_{\text{max}} = 2000 \text{ [psia]} \]
\[ T_{\text{max}} = 1000 + 460 \]
\[ P_{\text{min}} = 1 \text{ [psia]} \]
\[ P_{\text{reheat}} = 200 \text{ [psia]} \]
\[ P_{\text{extraction}} = P_{\text{reheat}} \]

\[ \text{TTD} = 0 \text{ [R]} \]

"(1) high pressure turbine inlet"
\[ P[1] = P_{\text{max}} \]
\[ T[1] = T_{\text{max}} \]
\[ h[1] = \text{enthalpy(steam,} P=P[1],T=T[1]) \]
\[ s[1] = \text{entropy(steam,} P=P[1],T=T[1]) \]

"(2) high pressure turbine exit"
\[ P[2] = P_{\text{reheat}} \]
\[ s[2] = s[1] \text{ "isentropic expansion"} \]
\[ T_{\text{sat}}[2] = T_{\text{sat}}(\text{steam,} P=P[2]) \]
\[ T[2] = \text{temperature(steam,} P=P[2], s=s[2]) \text{ "} T > T_{\text{sat}}; \text{ superheated"} \]
\[ h[2] = \text{enthalpy(steam,} P=P[2], s=s[2]) \]

"(3) reheat exit; low pressure turbine inlet"
\[ h[3] = \text{enthalpy(steam,} P=P[3],T=T[3]) \]
\[ s[3] = \text{entropy(steam,} P=P[3],T=T[3]) \]

"(4) low pressure turbine exit; condenser inlet"
\[ P[4] = P_{\text{min}} \]
\[ s[4] = s[3] \text{ "isentropic expansion"} \]
\[ T_{\text{sat}}[4] = T_{\text{sat}}(\text{steam,} P=P[4]) \]
\[ T[4] = \text{temperature(steam,} P=P[4], s=s[4]) \text{ "} T < T_{\text{sat}}; \text{ saturated"} \]
\[ h[4] = \text{enthalpy(steam,} P=P[4], s=s[4]) \]
\[ x[4] = \text{quality(steam,} P=P[4], s=s[4]) \]

"(5) condenser exit; pump inlet"
\[ T[5] = T_{\text{sat}}[4] \]
\[ v[5] = \text{enthalpy(steam,} P=P[5], x=0) \]
\[ s[5] = \text{entropy(steam,} P=P[5], x=0) \]
\[ h[5] = v[5]*\left(\frac{P[6] - P[5]}{144}\right) \text{ "convert to ft}^2\text{ and Btu"} \]

"(6) pump exit, closed FWH inlet"
\[ P[6] = P_{\text{max}} \]
\[ h[6] = h[5] + v[5]*\left(\frac{P[6] - P[5]}{144}\right) \text{ "convert to ft}^2\text{ and Btu"} \]
T[6] = temperature(steam,P=P[6],h=h[6])
-h[6] = entropy(steam,P=P[6],h=h[6])

"(7) FWH exit; steam generator inlet"
P[7] = P_max
h[7] = enthalpy(steam,P=P[7],T=T[7])
s[7] = entropy(steam,P=P[7],T=T[7])

"(8) FWH exit - extraction steam; throttle inlet"
P[8] = P_reheat
h[8] = enthalpy(steam,P=P[8],x=0)
s[8] = entropy(steam,P=P[8],x=0)

"(9) throttle exit"
P[9] = P_min
h[9] = h[8]
s[9] = entropy(steam,P=P[9],h=h[9])
x[9] = quality(steam,P=P[9],h=h[9])

"mass and energy balancas in FWH"

"turbine work and heat input"

"efficiencies"
eta_carnot = 1 - T[4]/T_max
eta_TH = w_T/q_in

"4% pressure loss in heat addition processes (steam generator & reheat)"
Pb[7] = P_max*1.04
Pb[2] = P_reheat*1.04
Pb[1] = P[1]

hb[1] = h[1]
hb[2] = enthalpy(steam,P=Pb[2],s=sb[2])
hb[7] = enthalpy(steam,P=Pb[7],T=Tb[7])
hb[8] = enthalpy(steam,P=Pb[8],x=0)

sb[1] = s[1]
sb[7] = entropy(steam,P=Pb[7],T=Tb[7])
sb[8] = entropy(steam,P=Pb[8],x=0)
### Arrays Table: Main

<table>
<thead>
<tr>
<th>( P_i ) [psia]</th>
<th>( h_i ) [Btu/lbm]</th>
<th>( T_i ) [R]</th>
<th>( T_{sat,i} ) [R]</th>
<th>( x_i )</th>
<th>( s_i ) [Btu/lbm-R]</th>
<th>( v_i ) [lbf/ft^2]</th>
<th>( m_i ) [lbm/s]</th>
<th>( P_{b1} ) [psia]</th>
<th>( T_{b1} ) [R]</th>
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<tbody>
<tr>
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<td>562.1</td>
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### Arrays Table: Main

<table>
<thead>
<tr>
<th>( h_{b1} ) [Btu/lbm]</th>
<th>( s_{b1} ) [Btu/lbm-R]</th>
<th>( m_{b1} ) [lbm/s]</th>
</tr>
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![Diagram](image)
A superheated nonideal steam cycle operates with inlet steam at 2400 psia and 1000°F and condenses at 1 psia. It has five feedwater heaters, all optimally placed. Assume the polytropic efficiencies of the turbine sections before, between, and after the bleed points to be all the same and equal to 0.90. Calculate (a) the specific enthalpies of the extraction steam to each feedwater heater, in Btu per pound mass and (b) the turbine overall polytropic efficiency; and (c) estimate the terminal temperature difference for each feedwater heater.

Property Values from EES.

**State 1** - Turbine inlet - superheated vapor

- \( p_1 = 2400 \text{ psia} \)
- \( T_1 = 1000 \text{ °F} = 540 \text{ °R} \)
- \( T_{s,t} = 1122 \text{ °R} \)
- \( h_1 = 1461 \text{ Btu/lbm} \)
- \( s_1 = 1.5533 \text{ Btu/lbm}°\text{R} \)

**State 2** - FWH 1 bleed

- \( T_{sat} - T_{s,t} - \Delta T = 1028 \text{ °R} \)
- \( P_z = 12.4 \text{ psia} \)
- \( S_{sg} = 1.366 \text{ Btu/lbm}°\text{R} \)
- \( S_{sg} > S_1 \); superheated
- \( h_2 = h_1 - \frac{T_{s,t}}{T_1} (h_1 - h_{sg}) = 1380 \text{ Btu/lbm} \)
- \( T_{s} = 1263 \text{ °R} \)
- \( S_2 = 1.621 \text{ Btu/lbm}°\text{R} \)

**State 3** - FWH 2 bleed

- \( T_{sat} = T_{s,t} - \Delta T = 890.6 \text{ °R} \)
- \( P_z = 9.41 \text{ psia} \)
- \( S_{sg} = 1.455 \text{ Btu/lbm}°\text{R} \)
- \( S_{sg} > S_2 \); superheated
- \( h_3 = 1287 \text{ Btu/lbm} \)
- \( h_3 = h_2 - \frac{T_{s,t}}{T_1} (h_2 - h_{sg}) = 1378 \text{ Btu/lbm} \)
- \( T_{s} = 920.1 \text{ °R} \)
- \( S_3 = 1.621 \text{ Btu/lbm}°\text{R} \)

**State 4** - FWH 3 bleed

- \( T_{sat} = T_{s,t} - \Delta T = 842.7 \text{ °R} \)
- \( P_z = 2.9 \text{ psia} \)
- \( S_{sg} = 1.545 \)
- \( S_{sg} > S_4 \); superheated
- \( h_4 = 1266 \text{ Btu/lbm} \)
- \( h_4 = h_3 - \frac{T_{s,t}}{T_1} (h_3 - h_{sg}) = 1277 \text{ Btu/lbm} \)
- \( T_{s} = 976 \text{ °R} \)
- \( S_4 = 1.632 \text{ Btu/lbm}°\text{R} \)

**State 5** - FWH 4 bleed

- \( T_{sat} = T_{s,t} - \Delta T = 748 \text{ °R} \)
- \( P_z = 58 \text{ psia} \)
- \( S_{sg} = 1.65 \text{ Btu/lbm}°\text{R} \)
- \( S_{sg} > S_5 \); saturated
- \( h_{sg} = 1110 \text{ Btu/lbm} \)
- \( h_5 = h_4 - \frac{T_{sat}}{T_1} (h_4 - h_{sg}) = 1120 \text{ Btu/lbm} \)
- \( T_5 = T_{sat} \)
- \( S_5 = 1.573 \text{ Btu/lbm}°\text{R} \)
- \( K_5 = 0.938 \)

**State 6** - FWH 5 bleed

- \( T_6 = T_{sat} - \Delta T = 655 \text{ °R} \)
- \( P_z = 10 \text{ psia} \)
- \( S_{sg} = S_6 \); saturated
- \( h_{sg} = 1006 \text{ Btu/lbm} \)
- \( h_6 = 1017 \text{ Btu/lbm} \)
- \( S_6 = 1.671 \text{ Btu/lbm}°\text{R} \)
- \( K_6 = 0.87 \)

**State 7** - Condenser inlet

- \( T_7 = T_6 = 58 \text{ °R} \)
- \( P_z = 1 \text{ psia} \)
- \( S_7 = S_6 \)
- \( h_{sg} = 888 \text{ Btu/lbm} \)
- \( h_7 = 90 \text{ Btu/lbm} \)
- \( S_7 = 1.674 \text{ Btu/lbm}°\text{R} \)
- \( K_7 = 0.803 \)
\( S_{75} = S \)
\( P_{75} = P \)
\( T_{75} = T \)
\( x_{75} = 0.75 \)
\( h_{f} = 855.8 \text{ Btu/lbm} \)

**Overall adiabatic turbine efficiency,**

\[
\eta_{overall} = \frac{h_{i} - h_{f}}{h_{i} - h_{f_{s}}} = 0.9249
\]

Estimate of TTD for feedwater heaters,

<table>
<thead>
<tr>
<th>Feedwater heater (FWH)</th>
<th>TTD</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>-5 to 0°F</td>
</tr>
<tr>
<td>2</td>
<td>-5 to 0°F</td>
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<tr>
<td>3</td>
<td>-5 to 0°F</td>
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<tr>
<td>4</td>
<td>0 -5°F</td>
</tr>
<tr>
<td>5</td>
<td>0 -5°F</td>
</tr>
</tbody>
</table>
Sodium Rankine Cycle

\( P_1 = 24.692 \text{ psia} \)
\( T_i = 2400^\circ R \)
\( T_2 = 1800^\circ R \)
\( \gamma_t = 0.85 \)
\( \gamma_e = 0.65 \)
\( W_{\text{th}} = 100 \text{kW} \)
\( U = 5 \text{ Btu/ft}^2\text{hr}^\circ F \)

Sodium as working fluid

**Using data from Appendix E of Power Plant Technology,**

1. **superheated vapor**
   \( P_1 = 24.692 \text{ psia} \)
   \( T_i = 2400^\circ R \)
   \( h_i = 2431.8 \text{ Btu/lbm} \)
   \( s_i = 1.8340 \text{ Btu/lbm}^\circ R \)

2. **saturated mixture**
   \( T_2 = 1800^\circ R \)
   \( P_2 = 0.23351 \text{ psia} \)
   \( s_{S2} = s_i \)
   \( s_{S2} = 0.9239 \text{ Btu/lbm}^\circ R \)
   \( s_{L2} = 2.1282 \text{ Btu/lbm}^\circ R \)
   \( h_{S2} = 468.5 \text{ Btu/lbm} \)
   \( h_{L2} = 2274.9 \text{ Btu/lbm} \)

3. **saturated liquid**
   \( h_3 = 1463.5 \text{ Btu/lbm} \)
   \( P_3 = 6.23351 \text{ psia} \)
   \( N_3 = 1.9760 \times 10^{-2} \text{ ft}^2/\text{lbm} \)

4. **subcooled liquid**
   \( \omega_p = N_3 (P_3 - P)/\gamma_p = 107.1 \text{ Btu/ft}^2/\text{lbm} \)
   \( h_4 = h_3 + \omega_p = 468.6 \text{ Btu/lbm} \)

\( h_4 = h_1 - h_2 = 508.5 \text{ Btu/lbm} \)
\( h_{\text{net}} = h_4 - h_p = 508.4 \text{ Btu/lbm} \)
\( \dot{W}_{\text{in}} = h_i - h_4 = 1963.2 \text{ Btu/lbm} \)
\( \dot{W}_{\text{out}} = h_2 - h_3 = 1454.8 \text{ Btu/lbm} \)
\( \dot{W}_{\text{th}} = 100 \text{ kW} \)

(a) \( \eta_{\text{th}} = ? \)
(b) \( \dot{W}_{\text{out}} = ? \)

(b) **區域面積**
\( \dot{W}_{\text{out}} = \dot{W}_{\text{out}} = 252851.6 \text{ Btu/hr} \)

(c) **過熱器面積**
\( A = \frac{\dot{W}_{\text{out}}}{U \Delta T} = 33.7 \text{ m}^2 \)
\( t = 1800^\circ R \)
An 850-MW Rankine cycle operates with turbine inlet stream at 1200 psia and 1000°F and condenser pressure at 1 psia. There are three feedwater heaters placed optimally as follows: (a) the high-pressure heater is of the closed type with drains cascaded backwards; (b) the intermediate-pressure heater is of the open type; (c) the low-pressure heater is of the closed type with drains pumped forward. Each of the turbine sections have the same polytropic efficiency of 90 percent. The pumps have polytropic efficiencies of 80 percent. Calculate (a) the mass flow rate of the turbine inlet in pounds mass per hour, (b) the mass flow rate to the condenser, (c) the mass flow rate of the condenser cooling water, in pounds mass per hour, if it undergoes a 25°F temperature rise, (d) the cycle efficiency, and (e) the cycle heat rate, in Btu per kilowatt-hour.

\[ \text{W}_{\text{net}} = 8.50 \text{ MWe} \]

\[ P_i = 1200 \text{ psia} \]
\[ T_i = 1000\,\text{°F} \]
\[ P_s = 1 \text{ psia} \]
\[ \eta_t = 0.90 \]
\[ \eta_p = 0.80 \]

(a) \( m_T = ? \)
(b) \( m_5 = ? \)
(c) \( m_{\text{coolant}} = ? \)
(d) \( \eta_{\text{th}} = ? \)
(e) \( \text{Heat Rate} = ? \)

Property values obtained using EES.
The optimum feedwater placement is found from:

\[ \Delta T_{\text{FWH}} = \frac{T_a - T_c}{n+1} = \frac{1027^\circ R - 561.3^\circ R}{4} = 116.4^\circ F \]

Thus,

\[ T_{\text{iz}} = T_a - \Delta T_{\text{FWH}} = 1027^\circ R - 116.4^\circ R = 910.6^\circ R \; ; \; \text{exit of high-pressure CFH} \]

\[ T_a = T_{\text{iz}} - \Delta T_{\text{FWH}} = 910.6^\circ R - 116.4^\circ R = 794.2^\circ R \; ; \; \text{exit of intermediate-pressure CFH} \]

\[ T_{\text{ih}} = T_a - \Delta T_{\text{FWH}} = 794.2^\circ R - 116.4^\circ R = 677.8^\circ R \; ; \; \text{exit of low-pressure CFH} \]

The feedwater pressures are the saturation pressures:

\[ P_{\text{iz}} = P_{\text{sat}} = P_a = 426.1 \text{ psia} \]
\[ P_a = P_{\text{sat}} = P_b = 109.5 \text{ psia} \]
\[ P_{\text{ih}} = P_{\text{sat}} = P_c = 16.57 \text{ psia} \]

### Energy Balances on Feedwater Heaters:

For High-Pressure CFH:

\[ m_s^* = 1 - m_z^2 - m_z^3 - m_z^4 \]

\[ T_{\text{sat}} - T_{\text{ih}} = \frac{T_{\Delta T_{\text{FWH}}}}{\Delta T_{\text{FWH}}} = -3^\circ R \]

\[ \dot{Q} = m_z^2 (h_3 - h_{1z}) = m_T (h_n - h_0) \]

\[ M_z^2 = \frac{m_z^2}{m_T} = \frac{h_n - h_0}{h_3 - h_{1z}} \]

For Intermediate-Pressure CFH:

\[ m_5 h_3 + m_z h_3 + m_5 h_{15} + m_5 h_8 = m_T h_q \]

\[ M_z^5 h_3 + M_z^5 h_{15} + M_z^5 h_{15} + M_z^5 h_8 = h_q \]

For Low-Pressure CFH:

\[ \dot{Q} = m_5^*(h_q - h_{14}) = m_5^*(h_8 - h_7) \]

\[ T_{\text{sat}} - T_{\text{es}} = \Delta T_{\text{FWH}} = +5^\circ R \]
state (1) - turbine inlet - superheated

\[ P_1 = 1200 \, \text{psia} \]
\[ T_1 = (1000 + 460) \, ^\circ R \]

\[ h_1 = 1500 \, \text{Btu/lbm} \]
\[ s_1 = 1.63 \, \text{Btu/lbm} \, ^\circ R \]

state (2) - high-pressure turbine bleed

\[ s_2 = s_1 = 1.63 \, \text{Btu/lbm} \, ^\circ R \]
\[ P_2 = P_{sat} (190.6 \, ^\circ R) = 426.1 \, \text{psia} \]

\[ s_2 = s_2 = 1.63 \, \text{Btu/lbm} \, ^\circ R \]
\[ Q_2 = 0.90 = \frac{h_2 - h_3}{h_1 - h_2} \]
\[ h_2 = 1339.0 \, \text{Btu/lbm} \]
\[ T_2 = 1182 \, ^\circ R \]

state (3) - intermediate-pressure turbine bleed

\[ s_3 = s_2 = 1.64 \, \text{Btu/lbm} \, ^\circ R \]
\[ P_3 = P_{sat} (994.2 \, ^\circ R) = 109.5 \, \text{psia} \]

\[ s_3 = s_3 = 1.64 \, \text{Btu/lbm} \, ^\circ R \]
\[ Q_3 = 0.90 = \frac{h_2 - h_3}{h_3 - h_3} \]
\[ h_3 = 1242 \, \text{Btu/lbm} \]
\[ T_3 = 890 \, ^\circ R \]

You can also use \( s_3 = s_1 \) and \( \eta_3 = \frac{h_1 - h_3}{h_1 - h_3} \) to find \( h_3 \).

The value of \( h_3 \) may differ slightly from that calculated to the left.

state (4) - low-pressure turbine bleed

\[ s_4 = s_3 = 1.658 \, \text{Btu/lbm} \, ^\circ R \]
\[ P_4 = P_{sat} (677.8 \, ^\circ R) = 16.57 \, \text{psia} \]

\[ s_4 < s_4 \, (P = 16.57 \, \text{psia}) \] - saturated

\[ \eta_4 = \frac{s_4 - s_4}{s_4 - s_4} = 0.938 \]

\[ h_4 = h_4 + \eta_4 (h_2 - h_3) = 1093 \, \text{Btu/lbm} \]

\[ Q_4 = 0.90 = \frac{h_3 - h_4}{h_3 - h_3} \]
\[ h_4 = 1108 \, \text{Btu/lbm} \]
\[ \eta_4 = 0.9534 \]

\[ s_4 = 1.681 \, \text{Btu/lbm} \, ^\circ R \]
\[ T_4 = P_{sat} = 677.8 \, ^\circ R \]
state (5) - turbine exhaust - saturated
\[ P_5 = 1 \text{ psia} \]
\[ T_5 = T_{sat} (P=1 \text{ psia}) = 561.4 \text{ °R} \]
\[ S_{5s} = S_a = 1.681 \text{ Btu/lbm °R} \]
\[ x_{5s} = 0.8391 \]
\[ h_{5s} = 938.7 \text{ Btu/lbm} \]
\[ P'_t = 0.90 = h_a - h_g \]
\[ h_a = h_g = 955.6 \text{ Btu/lbm} \]
\[ x_f = 0.8554 \]
\[ S_e = 1.171 \text{ Btu/lbm °R} \]

state (6) - condenser exhaust - saturated liquid
\[ P_6 = P_5 = 1 \text{ psia} \]
\[ T_6 = T_{sat} (P=1 \text{ psia}) = 561.4 \text{ °R} \]
\[ N_f = N_{fg} (1 \text{ psia}) = 0.0164 \text{ ft}^3/\text{lbm} \]
\[ h_g = h_f (1 \text{ psia}) = 61.92 \text{ Btu/lbm} \]

state (7) - condenser pump exit - subcooled
\[ P_7 = P_6 = 109.5 \text{ psia} \text{ (intermediate pressure bleed)} \]
\[ \dot{m} \Delta h_s = h_7 - h_6 = N_f (P_7 - P_6) \]
\[ \Delta h_s = (0.0164 \text{ ft}^3/\text{lbm}) (109.5 \text{ lb} \text{ ft}^2/\text{in}^2 - 1 \text{ lb} \text{ ft}^2/\text{in}^2) = \frac{144 \text{ in}^2}{\text{ft}^2} \cdot \frac{778 \text{ ft} \cdot \text{lb}}{\text{Btu}} \cdot \frac{1}{ar{\eta}_p} = -0.6052 \text{ Btu/lbm} \]
\[ h_7 = 70.13 \text{ Btu/lbm} \]

state (8) - low pressure CFH exit - saturated
\[ P_8 = P_3 = 109.5 \text{ psia} \]
\[ T_8 = T_{sat} (P=109.5 \text{ psia}) = 672.8 \text{ °R} \]
\[ h_g = 181.5 \text{ Btu/lbm} \] 
\[ \text{from compound liquid table} \]

state (9) - high pressure CFH exit - saturated
\[ P_9 = 1200 \text{ psia} \]
\[ T_9 = T_{sat} (P=1200 \text{ psia}) = 776.9 \text{ °R} \]
\[ h_f (P=1200 \text{ psia}) = 61.92 \text{ Btu/lbm} \]

state (10) - low pressure drain - saturated
\[ P_4 = 16.57 \text{ psia} \]
\[ h_4 = h_f (P=16.57 \text{ psia}) = 185.3 \text{ Btu/lbm} \]
\[ N_{14} = 0.01676 \text{ ft}^3/\text{lbm} \]

state (11) - low pressure pump exit - compressed
\[ P_i = P_3 = 109.5 \text{ psia} \]
\[ \Delta h_{i5} = N_f (P_i - P_4) = h_{15} - h_4 \]
\[ \Delta h_{i5} = - (0.01676 \text{ ft}^3/\text{lbm}) (109.5 \text{ lb} \text{ ft}^2/\text{in}^2 - 16.57 \text{ lb} \text{ ft}^2/\text{in}^2) = \frac{144 \text{ in}^2}{\text{ft}^2} \cdot \frac{778 \text{ ft} \cdot \text{lb}}{\text{Btu}} \cdot \frac{1}{ar{\eta}_p} = -0.3604 \text{ Btu/lbm} \]
\[ h_{15} = 186.6 \text{ Btu/lbm} \]

state (12) - OFH exit - saturated liquid
\[ P_4 = P_3 = 109.5 \text{ psia} \]
\[ h_f = h_f (P=109.5 \text{ psia}) = 305.6 \text{ Btu/lbm} \]
\[ N_f = N_{fg} = 0.01781 \text{ ft}^3/\text{lbm} \]

state (13) - high pressure pump exit - compressed
\[ P_o = 1200 \text{ psia} \]
\[ \Delta h_{90} = N_f (P_o - P_9) = h_{10} - h_9 \]
\[ \Delta h_{90} = - (0.01781 \text{ ft}^3/\text{lbm}) (1200 \text{ lb} \text{ ft}^2/\text{in}^2 - 109.5 \text{ lb} \text{ ft}^2/\text{in}^2) \cdot \frac{144 \text{ in}^2}{\text{ft}^2} = -4.493 \text{ Btu/lbm} \]
\[ h_{10} = 310.1 \text{ Btu/lbm} \]
state (12) - high-pressure CFH exit - saturated liquid
\[ P_{12} = P_i = 426.1 \text{ psia} \]
\[ h_{12} = h_f (P = 426.1 \text{ psia}) = 431.1 \text{ Btu/lbm} \]

state (13) - throttle exit - saturated
\[ P_{3} = P_s = 109.5 \text{ psia} \]
\[ h_3 = h_{12} = 431.1 \text{ Btu/lbm} \]

There are now 4 unknowns \( m^*_2, m^*_3, m^*_4, m^*_5 \) and 4 equations:

1. \[ m^*_2 = 1 - m^*_3 - m^*_4 - m^*_5 \quad \text{cons. of mass} \]
2. \[ m^*_2 = \frac{h_2 - h_{12}}{h_{12} - h_{12}} \quad \text{energy balance on high-pressure CFH} \]
3. \[ m^*_3 h_3 + m^*_2 h_{12} + m^*_4 h_{15} + m^*_5 h_8 = h_q \quad \text{energy balance on CFH} \]
4. \[ m^*_4 (h_4 - h_{14}) = m^*_5 (h_8 - h_7) \quad \text{energy balance on low-pressure CFH} \]

\[ m^*_2 = 0.1326 \]
\[ m^*_3 = 0.08538 \]
\[ m^*_4 = 0.08484 \]
\[ m^*_5 = 0.6977 \]

Pump Work:
\[ \omega_p = m^*_5 \left( \omega_{1} + m^*_4 \right) \text{ Btu/lbm} \]
\[ = 4.806 \text{ Btu/lbm} \]

Turbine Work:
\[ \omega_t = (h_{12} - h_2) + (1 - m^*_4) (h_2 - h_3) + (1 - m^*_3 - m^*_5) (h_3 - h_4) + m^*_5 (h_8 - h_5) \]
\[ = 451.7 \text{ Btu/lbm} \]

Net Work:
\[ \omega_{net} = \omega_t - \omega_p = 446.9 \text{ Btu/lbm} \]

Power:
\[ \dot{W}_{net} = 850 \text{hp} = 2.9 \times 10^9 \text{ Btu/hr} \]

Steam Mass Flow:
\[ \dot{m}_T = \dot{\omega}_{net} / \dot{W}_{net} = 6.489 \times 10^6 \text{ lbm/hr} \]

Condenser Mass Flow:
\[ \dot{m}_5 = \dot{m}_T \cdot M^*_5 = (0.6977)(6.489 \times 10^6 \text{ lbm/hr}) = 4.528 \times 10^6 \text{ lbm/hr} \]

Heat In:
\[ Q_{in} = h_1 - h_{12} = 1065 \text{ Btu/lbm} \]

\[ \dot{Q}_{th} = \frac{\omega_{net}}{Q_{in}} = 0.4196 \]
Cooling Water Mass Flow

\[ \dot{m}_{\text{out}} = m_5 (h_5 - h_6) = m_{\text{coolant}} \Delta T = 4.011 \cdot 10^9 \text{ Btu/hr} \]

\[ C = 1.0 \text{ Btu/lbm}^\circ \text{R} \]

\[ \Delta T = 25^\circ \text{R} \]

\[ m_{\text{coolant}} = 1.604 \cdot 10^8 \text{ lbm/hr} \]

Heat Rate

\[ HR = \frac{3412 \text{ Btu/hr}}{7 \text{ hr}} = 491 \text{ Btu/hr} \]
"A Rankine cycle operates with turbine throttle at 90 bar and 500°C, and condenser temperature of 40°C. Calculate the efficiency and work ratio for the following cases:
(a) no feedwater heating,
(b) one open feedwater heater,
(c) one closed feedwater heater throttled back to the condenser, and
(d) one closed feedwater heater with drain pumped forward.
In each case, the feedwater heater is optimally placed. Use TTD = 2.5°C.

Isentropic efficiencies: \( \eta_{\text{pump}} = 0.70 \) & \( \eta_{\text{turbine}} = 0.89 \)

```plaintext
T_trottle = 500 [°C]
P_throttle = 90 [bar]
T_condenser = 40 [°C]

TTD = 2.5 [°C]

\( \eta_p = 0.70 \)
\( \eta_t = 0.89 \)

fluid$ = 'steam'

"--- (a) simple cycle -----"

[1] turbine inlet - superheated vapor
\( T_a[1] = T_{\text{trottle}} \)
\( P_a[1] = P_{\text{throttle}} \)
\( h_a[1] = \text{enthalpy}(\text{fluid}$,$ P=P_a[1], T=T_a[1]) \)
\( s_a[1] = \text{entropy}(\text{fluid}$,$ P=P_a[1], T=T_a[1]) \)

[2] turbine exit - saturated mixture
\( T_a[2] = T_{\text{condenser}} \)
\( P_a[2] = \text{pressure}(\text{fluid}$,$ T=T_a[2], x=1) \)
\( s_a_s[2] = s_a[1] \)
\( h_a_s[2] = \text{enthalpy}(\text{fluid}$,$ T=T_a[2], s=s_a_s[2]) \)
\( \eta_t = (h_a[1] - h_a[2])/(h_a[1] - h_a_s[2]) \)

[3] pump inlet - saturated liquid
\( T_a[3] = T_{\text{condenser}} \)
\( h_a[3] = \text{enthalpy}(\text{fluid}$,$ T=T_a[3], x=0) \)
"\( V_a[3] = \text{volume}(\text{fluid}$,$ T=T_a[3], x=0)"\)
\( s_a[3] = \text{entropy}(\text{fluid}$,$ P=T_a[3], x=0) \)

[4] pump exit - compressed liquid
\( P_a[4] = P_{\text{throttle}} \)
\( h_a_s[4] = \text{enthalpy}(\text{fluid}$,$ P=P_a[4], s=s_a[3]) \)
\( \eta_p = (h_a_s[4] - h_a[3])/(h_a[4] - h_a[3]) \)
\( s_a[4] = \text{entropy}(\text{fluid}$,$ P=P_a[4], h=h_a[4]) \)
\( T_a[4] = \text{temperature}(\text{fluid}$,$ P=P_a[4], h=h_a[4]) \)

"work ratio and efficiency"
\( w_a = h_a[1] - h_a[2] \)
\( w_a_p = h_a[4] - h_a[3] \)
\( w_a = w_a - w_a_p \)
\( q_a = h_a[1] - h_a[4] \)
\( \eta_{a\_th} = (w_a - w_a_p)/q_a \)
\( W_{Ra} = (w_a - w_a_p)/w_a \)
\( 3W_{Ra} = w_a_p/w_a \)

"--- (b) one OFH ------"

"FWH placement"
\[ T_{\text{throttle\_sat}} = t_{\text{sat}}(P_{\text{throttle}}) \]
\[ T_{\text{FWH}} = T_{\text{condenser}} + (T_{\text{throttle\_sat}} - T_{\text{condenser}})/2 \]

1. **Turbine inlet - superheated steam**
   \[
   P_b[1] = P_a[1] \\
   h_b[1] = h_a[1] \\
   s_b[1] = s_a[1]
   \]

2. **Steam bleed from turbine - check for saturation; state 2 will change**
   \[
   T_{\text{sat}}[5] = T_{\text{FWH}} \\
   P_b[5] = \text{pressure}(fluid,S, T=T_{\text{sat}}[5], x=1) \\
   h_b[5] = \text{enthalpy}(fluid, P=P_b[5], s=s_b[1]) \\
   T[5] = \text{temperature}(fluid, P=P_b[5], h=h_b[5]) \\
   \]
   *check to see state of steam*
   \[
   h_{\text{g}}[5] = \text{enthalpy}(fluid, T=T_{\text{sat}}[5], x=1) \\
   T_{\text{g}} < h[5], \text{ therefore steam is superheated}*
   \]
   \[
   s_b[5] = \text{entropy}(fluid, T=T_b[5], h=h_b[5])
   \]

3. **Turbine exit - saturated mixture**
   \[
   T_b[2] = T_{\text{condenser}} \\
   \]
   \[
   h_b[2] = \text{enthalpy}(fluid, P=P_b[2], s=s_b[2]) \\
   \]

4. **Pump inlet - saturated liquid**
   \[
   T_b[3] = T_{\text{condenser}} \\
   s_b[3] = s_a[3]
   \]

5. **Pump exit - compressed liquid**
   \[
   h_b[4] = \text{enthalpy}(fluid, P=P_b[4], s=s_b[3]) \\
   s_b[4] = \text{entropy}(fluid, P=P_b[4], h=h_b[4]) \\
   T_b[4] = \text{temperature}(fluid, P=P_b[4], h=h_b[4])
   \]

6. **Exit of FWH - saturated liquid**
   \[
   T_b[6] = \text{temperature}(fluid, P=P_b[6], x=0) \\
   h_b[6] = \text{enthalpy}(fluid, P=P_b[6], x=0) \\
   s_b[6] = \text{entropy}(fluid, P=P_b[6], x=0)
   \]

7. **Pump exit - compressed liquid**
   \[
   P_b[7] = P_{\text{throttle}} \\
   h_b[7] = \text{enthalpy}(fluid, P=P_b[7], s=s_b[6]) \\
   s_b[7] = \text{entropy}(fluid, P=P_b[7], h=h_b[7]) \\
   T_b[7] = \text{temperature}(fluid, P=P_b[7], h=h_b[7])
   \]

8. **Mass balance in OFH**
   \[
   \]

9. **Work ratio and efficiency**
   \[
   w_b[1] = (h_b[4] - h_b[3]) \\
   \]
   \[
   q_b[\text{in}] = h_b[1] - h_b[7] \\
   e_{\text{b\_th}} = w_b[\text{net}]/q_b[\text{in}]
   \]
WRb = wnute/wnb * 1
WBRb = (wp * wp2)/wnb * 1

--- (c) one CFH throttled -------
"states that do not change from part (b): 1, 2, 3, 5, 6"
"states that do not change from part (a): 4"

"[7] CFH condensate exit - saturated mixture"

"[8] CHF feedwater exit - compressed liquid"
Pc[8] = P_throttle
hc[8] = enthalpy(fluid$, T=Tc[8], P=Pc[8])

"mass balance in CHF"

"work ratio and efficiency"
wc_net = wcl - wc_p
etac_th = wc_net/qc_in
WRC = wc_net/wcl
BWRc = wc_net/wc_l

--- (d) one CFH pumped ------
"states that do not change from part (b): 1, 2, 3, 5, 6"
"states that do not change from part (a): 4"
"states that do not change from part (c): 7, 8"

"mass balance in CHF"

"[9] inlet to the steam generator - requires energy and mass balance"
Pd[9] = P_throttle
Td[9] = temperature(fuid$, P=Pd[9], h=hd[9])

"work ratio and efficiency"
wdsn = wdl - wdp
etad_th = wdsn/qd_in
Wr = wdsn/wdl
BWRd = wdsn/wdl

"eof"
### SOLUTION

**Init Settings: SI C bar kJ mass deg**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
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<td>BWRa</td>
<td>0.0111 [-]</td>
</tr>
<tr>
<td>BWRd</td>
<td>0.9874 [-]</td>
</tr>
<tr>
<td>BWRb</td>
<td>0.01323 [-]</td>
</tr>
<tr>
<td>( \eta_{in} )</td>
<td>0.3605 [-]</td>
</tr>
<tr>
<td>( \eta_{in} )</td>
<td>0.3795 [-]</td>
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<tr>
<td>( \eta_R )</td>
<td>0.89 [-]</td>
</tr>
<tr>
<td>( \eta_R )</td>
<td>0.9889 [-]</td>
</tr>
<tr>
<td>Mbs</td>
<td>0.2089 [-]</td>
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<td>Ttrollet</td>
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<td>wb2</td>
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<td>( \eta_{in} )</td>
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</table>

### KEY VARIABLES

**(a) simple cycle**

- wa = 12.92 [kJ/kg]
- wb = 1169 [kJ/kg]
- wa_net = 1156 [kJ/kg]
- qa = 3206 [kJ/kg]
- WRa = 0.9889 [-]
- WWRa = 0.0111 [-]
- \( \eta_{out} \) = 0.3605 [-]

**(b) with OFH**

- Mbs = 0.2089 [-]
- wb_net = 1040 [kJ/kg]
- wb1 = 1054 [kJ/kg]
- wb2 = 13.01 [kJ/kg]
- qba = 2647 [kJ/kg]
- WRb = 0.9889 [-]
- BWRb = 0.9874 [-]
- \( \eta_{in} \) = 0.3929 [-]

**(c) with CFH throttled**

- Mbs = 0.2055 [-]
- wcb = 12.92 [kJ/kg]
- wc_net = 1011 [kJ/kg]
- qcn = 2666 [kJ/kg]
- BWRc = 0.9874 [-]
- \( \eta_{in} \) = 0.3792 [-]

**(d) with CFH pumped**

- Mds = 0.2555 [-]
- wdb = 1024 [kJ/kg]
- wdp = 12.92 [kJ/kg]
- \( \eta_{in} \) = 0.3785 [-]

7 potential unit problems were detected.
### Arrays Table: Main

<table>
<thead>
<tr>
<th>P_{a_{i}}</th>
<th>T_{a_{i}}</th>
<th>h_{a_{i}}</th>
<th>h_{s_{a_{i}}}</th>
<th>s_{a_{i}}</th>
<th>s_{a_{i},i}</th>
<th>P_{b_{i}}</th>
<th>T_{b_{i}}</th>
<th>T_{b_{sat,i}}</th>
<th>h_{b_{i}}</th>
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<td>[kJ/kg]</td>
<td>[kJ/kg-K]</td>
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<td>[bar]</td>
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### Arrays Table: Main

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<th>s_{b_{i}}</th>
<th>s_{b_{a_{i}}}</th>
<th>P_{c_{i}}</th>
<th>T_{c_{i}}</th>
<th>h_{c_{i}}</th>
<th>P_{d_{i}}</th>
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</table>
Reheat, regenerative cycle producing 200 MW at the turbine coupling with throttle conditions of 15.5 MPa and 540 degrees C; reheat is at 8.0 MPa and 590 degrees C; one closed feedwater heater is at 3.4 MPa; an open feedwater heater is at 170 kPa; and the condenser pressure is 13 kPa. The drain from the closed feedwater heater is pumped into the steam generator.
Determine the thermal efficiency, the required steam flow rate, and the moisture at the turbine exhaust for a reheat, regenerative cycle which is to produce 200 MW at the turbine coupling if the throttle conditions are 15.5 MPa and 540 degrees C; reheat is at 8.0 MPa and 590 degrees C; one closed feedwater heater is at 3.4 MPa; an open feedwater heater is at 170 kPa; and the condenser pressure is 13 kPa. The turbine and pump efficiencies are 84%. The terminal temperature difference for the closed feedwater heaters is 3 degrees C and the drain from the closed feedwater heater is pumped into the steam generator.

"Turbine Power"
\[ W_{\text{dcl}} = 200 \text{ MWe} \]

"turbine inlet pressure and temperature"
\[ P_{\text{hpl_inlet}} = 15500 \text{ kPa} \]
\[ T_{\text{hpl_inlet}} = (540 + 273) \text{ K} \]

"reheat inlet pressure and temperature"
\[ P_{\text{lpt_inlet}} = 6800 \text{ kPa} \]
\[ T_{\text{lpt_inlet}} = (590 + 273) \text{ K} \]

"feedwater heater bleeds"
\[ P_{\text{cfh}} = 3400 \text{ kPa} \]
\[ P_{\text{cfr}} = 170 \text{ kPa} \]

"condenser pressure"
\[ P_{\text{cond}} = 13 \text{ kPa} \]

"turbine, pump efficiencies"
\[ \eta_{\text{t}} = 0.84 \]
\[ \eta_{\text{p}} = 0.84 \]

"feedwater heater effectiveness"
\[ TTD = 3 \text{ [K]} \]

"condenser water cooling temperature drop"
\[ DT_{\text{condenser}} = 25 \text{ [C]} \]

--- Thermodynamic States ------

"1. high pressure turbine inlet - superheated vapor"
\[ P[1] = P_{\text{hpt_inlet}} \]
\[ T[1] = T_{\text{hpt_inlet}} \]
\[ s[1] = \text{entropy(steam,P=}[P[1],T=T[1]]) \]
\[ h[1] = \text{enthalpy(steam,P=}[P[1],T=T[1]]) \]

"2. high pressure turbine exit - reheat inlet"
\[ P[2] = P_{\text{lpt_inlet}} \]
\[ h_{2s} = \text{enthalpy(steam,P=}[P[2],s=s[1])] \]
\[ h[2] = h[1] - \eta_{\text{t}}'(h[1] - h_{2s}) \]
\[ x[2] = \text{quality(steam,P=}[P[2],h=h[2])] \]

"checking quality - x[2] > 1, superheated vapor"
\[ s[2] = \text{entropy(steam,P=}[P[2],h=h[2])] \]
\[ T[2] = \text{temperature(steam,P=}[P[2],h=h[2])] \]

"3. reheat exit - low pressure turbine inlet - superheated vapor"
\[ T[3] = T_{\text{lpt_inlet}} \]
\[ s[3] = \text{entropy(steam,P=}[P[3],T=T[3]]) \]
\[ h[3] = \text{enthalpy(steam,P=}[P[3],T=T[3]]) \]

"4. low pressure turbine exit - CFH inlet"
\[ P[4] = P_{\text{cfh}} \]
\[ h_{4s} = \text{enthalpy(steam,P=}[P[4],s=s[3])] \]
x[4] = quality(steam, P=P[4], h=h[4])
   "checking quality - x[4]>1, superheated vapor"
   s[4] = entropy(steam, P=P[4], h=h[4])
   T[4] = temperature(steam, P=P[4], h=h[4])

"5. OFH inlet"
P[5] = P_oh
   h_5s = enthalpy(steam, P=P[5], s=s[3])
   x[5] = quality(steam, P=P[5], h=h[4])
   "checking quality - x[5] >1, superheated vapor"
   s[5] = entropy(steam, P=P[5], h=h[5])
   T[5] = temperature(steam, P=P[5], h=h[5])

"6. Condenser inlet"
P[6] = P_cond
   h_6s = enthalpy(steam, P=P[6], s=s[3])
   x[6] = quality(steam, P=P[6], h=h[6])
   "checking quality - x<1, saturated liquid-vapor mixture
   need to use quality in the property calls"
   s[6] = entropy(steam, P=P[6], x=x[6])
   T[6] = temperature(steam, P=P[6], x=x[6])

"7. condenser exit - pump inlet - saturated liquid"
   x[7] = 0  "saturated liquid"
   h[7] = enthalpy(steam, P=P[7], x=x[7])
   s[7] = entropy(steam, P=P[7], x=x[7])
   T[7] = temperature(steam, P=P[7], x=x[7])
   v[7] = volume(steam, P=P[7], x=x[7])  "need specific volume to determine pump work"

"8. pump exit - compressed liquid"
   "pump matches pressure of turbine inlet to open feedwater heater"
   w_pump_ideal_76 = v[7]*(P[8] - P[7])
   w_pump_actual_78 = w_pump_ideal_78/eta_p
   h[8] = h[7] + w_pump_actual_78
   s[8] = entropy(steam, P=P[8], h=h[8])
   T[8] = temperature(steam, P=P[8], h=h[8])
   "note that EES doesn't handle compressed liquid properties well"

"9. exit of open feedwater heater - saturated liquid"
P[9] = P[5]  "same pressure as inlet to open feedwater heater"
   x[9] = 0  "saturated liquid"
   h[9] = enthalpy(steam, P=P[9], x=x[9])
   s[9] = entropy(steam, P=P[9], x=x[9])
   T[9] = temperature(steam, P=P[9], x=x[9])
   v[9] = volume(steam, P=P[9], x=x[9])

"10. pump exit - compressed liquid"
   "pump raises pressure to the high pressure turbine inlet"
   w_pump_ideal_910 = v[9]*(P[10] - P[9])
   w_pump_actual_910 = w_pump_ideal_910/eta_p
   h[10] = h[9] + w_pump_actual_910
   s[10] = entropy(steam, P=P[10], h=h[10])
   T[10] = temperature(steam, P=P[10], h=h[10])
   "note that EES doesn't handle compressed liquid properties well"

"11. feedwater exiting closed heater - inlet to steam generator"
"temperature is 3 deg. C below T_sat of steam bleed at 4"
T[11] = (T_4_sat - TTD)
T_4_sat = temperature(steam,P=P[4],x=0)

h'[11] = enthalpy(steam,P=P[11],T=T[11])

"12. condensed steam exiting closed heater - saturated liquid"
T[12] = T_4_sat
x[12] = 0
s[12] = entropy(steam,P=P[12],x=x[12])
h[12] = enthalpy(steam,P=P[12],x=x[12])
v[12] = volume(steam,P=P[12],x=x[12])

"13. steam pumped to steam generator"
w_pump_ideal_1213 = v[12]*(P[13] - P[12])
w_pump_actual_1213 = w_pump_ideal_1213/eta_p
T[13] = temperature(steam,P=P[13],h=h[13])
s[13] = entropy(steam,P=P[13],T=T[13])

"14. inlet to steam generator"
P[14] = P[1]
T[14] = temperature(steam,P=P[14],h=h[14])
s[14] = entropy(steam,P=P[14],h=h[14])

{--- mass & energy balances and work & heat calculations ------}
1 = M_4 + M_5 + M_6

"energy balance on the open feedwater heater"

"energy balance on the closed feedwater heater"


"turbine work and mass flow of steam"
m_dot = W_dot_L/w_L

"pump work"
w_dot_p_78 = w_pump_actual_78 * (M_6) * m_dot
w_dot_p_910 = w_pump_actual_910 * (M_5 + M_6) * m_dot
w_dot_p_1213 = w_pump_actual_1213 * (M_4) * m_dot
w_dot_p_net = W_dot_p_78 + W_dot_p_910 + W_dot_p_1213

"net cycle work"
W_dot_net = W_dot_L - W_dot_p_net

"heat input"
q_in = (h[1] - h[14]) + (h[3] - h[2])
Q_dot_in = m_dot*q_in

"thermal efficiency"
eta_th = W_dot_net/Q_dot_in
HR = 3712/eta_th

"moisture content at turbine exhaust:"
moisture = 1 - x[6]
"m_dot_condenser"
Q_dot_condenser = (M_6*m_dot)*(h[6]-h[7])
cp = Cp(steam,T=258,P=100)
Q_dot_condenser=m_dot_condenser*Cp*DT_condenser

{data array for drawing cycle on T-s diagram}
Td[11] = temperature(steam,P=P[1],x=0) "saturated liquid in steam generator"
Td[12] = temperature(steam,P=P[1],x=1) "saturated vapor in steam generator"
Td[13] = temperature(steam,P=P[1],s=5.5) "force the line to follow the P_1 curve"
Td[14] = temperature(steam,P=P[1],s=5.75)
Td[15] = temperature(steam,P=P[1],s=6.0)
Td[16] = temperature(steam,P=P[1],s=6.25)

sd[1] = s[1]
sd[8] = s[8]
sd[9] = s[9]
sd[10] = s[10]
sd[11] = entropy(steam,P=P[1],x=0) "saturated liquid in steam generator"
sd[12] = entropy(steam,P=P[1],x=1) "saturated vapor in steam generator"
sd[13] = 5.5 "force the line to follow the P_1 curve"
sd[14] = 5.75
sd[15] = 6.0
sd[16] = 6.25
sd[20] = s[1] "closes the diagram"

{closed feedwater heater steam bleed line}
Tc[2] = temperature(steam,P=P[4],s=6.75) ; sc[2] = 6.75 "force the line to follow the P_4 curve"
Tc[4] = temperature(steam,P=P[4],x=1) ; sc[4] = entropy(steam,P=P[4],x=1) "saturated vapor"
Tc[5] = temperature(steam,P=P[4],x=0) ; sc[5] = entropy(steam,P=P[4],x=0) "saturated liquid"

{open feedwater heater steam bleed line}
To[2] = temperature(steam,P=P[5],x=1) ; so[2] = entropy(steam,P=P[5],x=1) "saturated vapor"

" end"
SOLUTION

Unit Settings: SI K kPa kJ mass deg

\[ cp = 4.183 \]

\[ \eta^t = 0.84 \] [-]

\[ \eta^h = 0.4033 \] [-]

\[ h_{hs} = 3209 \text{ [kJ/kg]} \]

\[ h_{ts} = 2626 \text{ [kJ/kg]} \]

\( \text{moisture} = 0.05297 [-] \)

\( \text{Ms} = 0.08545 \)

\( \dot{m} = 176.9 \text{ [kg/s]} \)

\( P_{ch} = 3400 \text{ [kPa]} \)

\( P_{\text{split,inlet}} = 15500 \text{ [kPa]} \)

\( P_{ch} = 170 \text{ [kPa]} \)

\( Q_{in} = 487476 \text{ [kW]} \)

\( T_{T} = 3 \text{ [K]} \)

\( T_{n,p,\text{inlet}} = 813 \text{ [K]} \)

\( W_{n,\text{net}} = 196617 \text{ [kW]} \)

\( W_{n,78} = 24.43 \text{ [kW]} \)

\( W_{n,\text{net}} = 3383 \text{ [kJ/kg]} \)

\( W_{\text{pump,actual,1213}} = 17.74 \text{ [kJ/kg]} \)

\( W_{\text{pump,actual,910}} = 19.27 \text{ [kJ/kg]} \)

\( W_{\text{pump,ideal,78}} = 0.159 \text{ [kJ/kg]} \)

\( \dot{w} = 1131 \text{ [kg/s]} \)

\( DT_{\text{condenser}} = 25 \text{ [C]} \)

\( \eta^t = 0.84 \) [-]

\( \text{HR} = 9203 \text{ [Btu/kWh]} \)

\( h_{ms} = 3318 \text{ [kJ/kg]} \)

\( h_{hs} = 2218 \text{ [kJ/kg]} \)

\( M_s = 0.1848 \)

\( M_s = 0.7298 \)

\( \dot{m}_{\text{condenser}} = 2781 \text{ [kg/s]} \)

\( P_{\text{cond}} = 13 \text{ [kPa]} \)

\( \dot{P}_{\text{split, outlet}} = 8000 \text{ [kPa]} \)

\( Q_{\text{condenser}} = 290859 \text{ [kJ/kg]} \)

\( Q_{n} = 2756 \text{ [kJ/kg]} \)

\( T_{n,s} = 514.1 \text{ [K]} \)

\( T_{n,p,\text{inlet}} = 863 \text{ [K]} \)

\( W_{p,1213} = 579.6 \text{ [kJ/kg]} \)

\( W_{p,910} = 2779 \text{ [kW]} \)

\( W_{n} = 200000 \text{ [kW]} \)

\( \dot{w}_{\text{pump,actual,78}} = 0.1893 \text{ [kJ/kg]} \)

\( \dot{w}_{\text{pump,actual,910}} = 14.9 \text{ [kJ/kg]} \)

\( \dot{w}_{\text{pump,ideal,910}} = 16.19 \text{ [kJ/kg]} \)

56 potential unit problems were detected.

**KEY VARIABLES**

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<th>moisture = 0.05297 [-]</th>
<th>condenser pump</th>
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<td>( W_{\text{pump,actual,78}} = 0.1803 \text{ [kJ/kg]} )</td>
<td>OFH pump</td>
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<td>( \eta^h = 0.4033 ) [-]</td>
<td>mass flow rate of steam</td>
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**Arrays Table: Main**

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An advanced-type supercritical powerplant has a turbine inlet stream at 7000 psia and 4000°F, double reheat at 1600 psia and 400 psia, both to 1200°F, and condenser at 1 psia. The three turbine sections have polytropic efficiencies of 0.93, 0.91, and 0.89 in order of descending pressures. The pump has a polytropic efficiency of 0.85. The plant receives one unit train of coal daily, which is composed of 100 cars carrying 110 short tons each. The coal has a heating value of 11,000 Btu/lbm. The turbine-generator combined mechanical and electrical efficiency is 0.90. The steam-generator efficiency is 0.87. Eighty percent of the gross out put is used to run plant auxiliaries. Ignoring, for simplicity, all steam-line pressure drops and all feedwater heating, calculate (a) the plant gross and net outputs, in megawatts, (b) the plant cycle, gross and net efficiencies, and (c) the cycle and station gross and net heat ratios, in Btu/kWhr.

\[
\begin{align*}
T_i &= 4000\,\text{°F} \\
T_1 &= 1860\,\text{°R} \\
P_i &= 7000\,\text{psia} \\
P_1 &= 1600\,\text{psia} \\
P_2 &= 400\,\text{psia} \\
P_3 &= 400\,\text{psia} \\
P_4 &= 1\,\text{psia} \\
P_5 &= 1\,\text{psia} \\
T_2 &= 1200\,\text{°F} \\
T_3 &= 1200\,\text{°F} \\
T_4 &= 1200\,\text{°F} \\
\end{align*}
\]

Property values obtained from EES.

**State 1 - High-Pressure Turbine Inlet**

\[
\begin{align*}
P_i &= 7000\,\text{psia} \\
T_i &= 1860\,\text{°R} \\
\text{Super-critical} \\
\h_1 &= 1637\,\text{Btu/lbm} \\
\text{S}_1 &= 1.534\,\text{Btu/lbm}°\text{R} \\
\end{align*}
\]

**State 2 - High-Pressure Turbine Exit**

\[
\begin{align*}
P_2 &= 1600\,\text{psia} \\
\text{Super-critical} \\
\text{S}_2 &= \text{S}_1 \\
\h_2 &= 1608\,\text{Btu/lbm} \quad \h_1 = \frac{\text{h}_1}{\text{h}_0} \quad \text{h}_2 = \text{h}_1 - \frac{\text{h}_1}{\text{h}_0} \\
\text{h}_2 &= 1424\,\text{Btu/lbm} \\
\end{align*}
\]

**State 3 - Intermediate-Pressure Turbine Inlet**

\[
\begin{align*}
P_3 &= 400\,\text{psia} \\
T_3 &= 1660\,\text{°R} \\
\text{Super-critical} \\
\h_3 &= 1607\,\text{Btu/lbm} \\
\text{S}_3 &= 1.668\,\text{Btu/lbm}°\text{R} \\
\end{align*}
\]

**State 4 - Intermediate-Pressure Turbine Exit**

\[
\begin{align*}
P_4 &= 1\,\text{psia} \\
\text{Super-critical} \\
\text{S}_4 &= \text{S}_3 \\
\text{S}_4 &= 1.668\,\text{Btu/lbm}°\text{R} \\
\text{h}_4 &= 1024\,\text{Btu/lbm}°\text{R} \\
\text{h}_5 &= \text{h}_4 + \text{h}_{5,4} \quad \text{h}_{5,4} = 1091\,\text{Btu/lbm}°\text{R} \\
\text{h}_6 &= \text{h}_4 + \text{h}_{6,4} \quad \text{h}_{6,4} = 986\,\text{Btu/lbm}°\text{R} \\
\end{align*}
\]
State 7 - Condenser Exit; Pump Inlet
\[ P_7 = P_6 \]
\[ h_7 = h_f (P_7) = 69.72 \text{ Btu/lbm} \]
\[ N_7 = N_f (P_7) = 0.01614 \text{ ft}^3/\text{lbm} \]

State 8 - Pump Exit; Steam Generator Inlet
\[ h_8 = h_7 + w_p \]
\[ w_p = N_7 (P_8 - P_7) / \rho_f = 27.87 \text{ Btu/lbm} \]
\[ h_8 = 97.6 \text{ Btu/lbm} \]

-enthalpies known at each exit of all processes -

- turbine work:
\[ w_t = (h_i - h_f) \left( \frac{T_i}{T_f} \right) \frac{\rho_i}{\rho_f} \theta_{\text{hp}} + (h_3 - h_4) \theta_{\text{tbp}} + (h_3 - h_6) \theta_{\text{e}} = 854.1 \text{ Btu/lbm} \]

- net work:
\[ w_{\text{net}} = w_t - w_p = 826.3 \text{ Btu/lbm} \]

- heat in:
\[ q_{\text{in}} = (h_i - h_f) + (h_3 - h_4) + (h_3 - h_6) = 1739 \text{ Btu/lbm} \]

- cycle efficiency:
\[ \eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 0.4761 \]

- Heat from Coal:
\[ q_{\text{coal}} = (100 \%)(110 \frac{\text{bhp}}{\text{hr}})(2000 \frac{\text{bhp}}{\text{lbm}})(144 \frac{\text{hr}}{\text{hr}})(11000 \frac{\text{lbm}}{\text{hr}}) = \frac{2.42 \times 10^9 \text{ Btu}}{\text{hr}} \]

- Heat Input:
\[ q_{\text{in}} = q_{\text{coal}} \cdot 1.03 = 8.773 \times 10^9 \text{ Btu/hr} \]

- Steam Mass Flow:
\[ v_{\text{steam}} = q_{\text{in}} / q_{\text{in}} = 4.524 \times 10^4 \text{ lbm/hr} \]

(a) Plant Gross & Net Power:
\[ w_{\text{plant, gross}} = v_{\text{steam}} \cdot h_i = 1019 \text{ MW} \]
\[ w_{\text{plant, net}} = (1 - 0.08) w_{\text{plant, gross}} = 937.7 \text{ MW} \]

Auxiliary power draw = 8%

(b) Plant Cycle, Gross & Net efficiencies:
\[ \eta_{\text{cycle}} = \frac{\eta_{\text{th}}}{\eta_{\text{gen}}} = 42.61 \% \]
\[ \eta_{\text{gross}} = w_{\text{plant, gross}} / q_{\text{coal}} = 34.49 \% \]
\[ \eta_{\text{net}} = \eta_{\text{gross}} \cdot \eta_{\text{gen}} = 31.04 \% \]

(c) Cycle Heat Rates, Plant Gross & Net Heat Rates:
\[ HR_{\text{cycle}} = \frac{3412}{\eta_{\text{th}}} = 8008 \text{ Btu/\text{hr}} \]
\[ HR_{\text{gross}} = \frac{3412}{\eta_{\text{gross}}} = 9893 \text{ Btu/\text{hr}} \]
\[ HR_{\text{net}} = \frac{3412}{\eta_{\text{net}}} = 10,993 \text{ Btu/\text{hr}} \]
An advanced-type supercritical powerplant has turbine inlet steam at 7000 psia and 1400 degree F, double reheat at 1600 psia and 400 psia, both to 1200 degree F, and condenser at 1 psia. The three turbine sections have polytropic efficiencies of 0.93, 0.91, and 0.89 in order of descending pressures. The pump has a polytropic efficiency of 0.75. The plant receives one unit train of coal daily, which is composed of 100 cars carrying 110 tons each. The coal has a heating value of 11,000 Btu/lbm. The turbine-generator combined mechanical and electrical efficiency is 0.90. The steam generator efficiency is 0.87. Eight percent of the gross output is used to run plant auxiliaries. Ignoring, for simplicity, all steam-line pressure drops and all feedwater heaters, calculate (a) the plant gross and net outputs, in megawatts, (b) the plant cycle, gross and net efficiencies, and (c) the cycle, and station gross and net heat rates, in Btu/kWh.}

"high pressure turbine inlet"
\[ P_{hp} = 7000 \text{ [psia]} \]
\[ T_{hp} = (1400 + 460) \text{ [R]} \]

"intermediate pressure turbine inlet"
\[ P_{ip} = 1600 \text{ [psia]} \]
\[ T_{ip} = (1200 + 460) \text{ [R]} \]

"low pressure turbine inlet"
\[ P_{lp} = 400 \text{ [psia]} \]
\[ T_{lp} = (1200 + 460) \text{ [R]} \]

"condenser inlet"
\[ P_c = 1 \text{ [psia]} \]

"efficiencies"
\[ \eta_{t_{hp}} = 0.93 \]
\[ \eta_{t_{ip}} = 0.91 \]
\[ \eta_{t_{lp}} = 0.89 \]
\[ \eta_{p} = 0.75 \]
\[ \eta_{gen} = 0.90 \]
\[ \eta_{SG} = 0.87 \]

"auxiliary component power draw"
\[ w_{aux} = 0.08 \text{ "note that this includes the pump work"} \]

{calculate enthalpies at inlet/exit of each process}

"state 1 - high pressure turbine inlet"
\[ P[1] = P_{hp} \]
\[ T[1] = T_{hp} \]
\[ h[1] = \text{enthalpy}(steam,P=P[1],T=T[1]) \]
\[ s[1] = \text{entropy}(steam,P=P[1],T=T[1]) \]

"state 2 - high pressure turbine exit"
\[ P[2] = P_{ip} \]
\[ s[2] = s[1] \text{ "entropy for an isentropic expansion - should verify that steam is superheated"} \]
\[ h[2] = \text{enthalpy}(steam,P=P[2],s=s[2]) \text{ "enthalpy for an isentropic expansion"} \]
\[ \eta_{t_{hp}} = (h[1] - h[2])/(h[1] - h_{s[2]}) \text{ "solve for h_2 using polytropic efficiency"} \]

"state 3 - intermediate pressure turbine inlet"
\[ P[3] = P_{ip} \]
\[ T[3] = T_{ip} \]
\[ h[3] = \text{enthalpy}(steam,P=P[3],T=T[3]) \]
\[ s[3] = \text{entropy}(steam,P=P[3],T=T[3]) \]

"state 4 - intermediate pressure turbine exit"
\[ P[4] = P_{lp} \]
\[ s[4] = s[3] \text{ "entropy for an isentropic expansion - should verify that steam is superheated"} \]
\[ h[4] = \text{enthalpy}(steam,P=P[4],s=s[4]) \text{ "enthalpy for an isentropic expansion"} \]
\[ \eta_{t_{ip}} = (h[3] - h[4])/(h[3] - h_{s[4]}) \text{ "solve for h_2 using polytropic efficiency"} \]

"state 5 - low pressure turbine inlet"
\[ P[5] = P_{lp} \]
\[ T[5] = T_{lp} \]
\[ h[5] = \text{enthalpy}(\text{steam}, P=P[5], T=T[5]) \]
\[ s[5] = \text{entropy}(\text{steam}, P=P[5], T=T[5]) \]

"state 6 - condenser inlet"
\[ P[6] = P_{c} \]
\[ s_{c}(6) = s[5] \text{ "entropy for an isentropic expansion - need to check for saturation"} \]
\[ s_g(6) = \text{entropy}(\text{steam},P=P[6], X=x) \text{ "saturated vapor entropy at condenser"} \]
\[ s_{c}(6) < s_g(6), \text{ therefore the steam is saturated at the condenser for an isentropic expansion"} \]
\[ h_{c}(6) = \text{enthalpy}(\text{steam},P=P[5], s=s_{c}[6]) \text{ "enthalpy for an isentropic expansion"} \]
\[ h_g(6) = \text{enthalpy}(\text{steam},P=P[6], x=1) \text{ "saturated vapor enthalpy"} \]
\[ h[6] < h_g(6), \text{ therefore the steam is saturated at the condenser for the actual expansion"} \]

"state 7 - condenser exit, pump inlet"
\[ h[7] = \text{enthalpy}(\text{steam},P=P[7], X=x) \text{ "saturated liquid"} \]
\[ v[7] = \text{volume}(\text{steam},P=P[7], X=x) \]

"state 8 - pump exit, steam generator inlet"
\[ P[8] = P[1] \]
\[ h[8] = h[7] + w_p \]
\[ w_p = (v[7] - (P[8] - P[7]))c_1/J/\text{eta}_p \]
\[ c_1 = 144 \text{ [in}^2/\text{ft}^2] \text{ "lb/(ft}^2 \text{) to lb/(ft}^2 \text{) unit conversion"} \]
\[ J = 778 \text{ [ft-lb/ft] "ft-lb to Btu unit conversion"} \]

"specific turbine work, net work, heat input"
\[ w_{t} = (h[1] - h[2])\text{eta}_t_{hp} + (h[3] - h[4])\text{eta}_t_{ip} + (h[5] - h[6])\text{eta}_t_{lp} \]
\[ w_{net} = w_{t} - w_p \]
\[ q_{in} = (h[1] - h[8]) + (h[3] - h[2]) + (h[5]-h[4]) \]

"cycle efficiency"
\[ \text{eta}_th = \frac{w_{net}}{q_{in}} \]

"heat input and rate of coal consumption"
\[ Q_{dot-coal} = m_{dot-coal} \times \text{HHV-coal} \text{ "heat from coal"} \]
\[ Q_{dot-in} = Q_{dot-coal} \times \text{eta}_SG \text{ "heat added to steam"} \]
\[ \text{HHV-coal} = 11000 \text{ [Btu/lbm]} \]
\[ d_{1} = 100 \text{ [car/day]} \]
\[ d_{2} = 110 \text{ [ton/day]} \]
\[ d_{3} = 2000 \text{ [lbm/ton]} \]
\[ d_{4} = 24 \text{ [hr/day]} \]
\[ m_{dot-coal} = 100 \times 110 \times 2000 / 24 \]

"steam mass flow rate"
\[ m_{dot-steam} = \frac{Q_{dot-in}}{q_{in}} \]

"plant gross and net power output"
\[ c_{2} = 3412 \text{ [Btu/hr/kW]} \text{ "Btu/hr to kW unit conversion"} \]
\[ c_{3} = 1000 \text{ [kW/MW]} \text{ "kW to MW unit conversion"} \]
\[ W_{dot-t gross} = \frac{m_{dot-steam} \times w_{t}}{c_{2}c_{3}} \]
\[ W_{dot-plant gross} = W_{dot-t gross} \times \text{eta_gen} \]
\[ W_{dot-plant net} = (1 - \text{eta}_aux) \times W_{dot-plant gross} \]

"plant gross and net efficiencies"
\[ \text{eta}_plant_gross = \frac{W_{dot-plant gross}}{c_{2}c_{3}/Q_{dot-coal}} \]
\[ \text{eta}_plant_net = \frac{\text{eta}_plant_gross}{\text{eta}_gen} \]

"note: plant shows low efficiencies because no feedwater heaters are considered."

"plant heat rates"
\[ \text{HR} \_cycle = c_{2} / \text{eta}_th \times 3412 / \text{cycle efficiency} - I used c_{2} in order to get the correct units" \]
\[ \text{HR} \_gross = c_{2} / \text{eta}_plant_gross \]
\[ \text{HR} \_net = c_{2} / \text{eta}_plant_net \]
The following properties are not required to analyze the cycle, but are computed anyway for completeness and for generating the T-s diagram. The values are hidden in the arrays window for simplification. The variables can be displayed using the Variable Info (F9) dialog.

\[
\begin{align*}
T[2] &= \text{temperature(steam, } P=P[2], h=h[2]) \\
T[4] &= \text{temperature(steam, } P=P[4], h=h[4]) \\
T[6] &= \text{temperature(steam, } P=P[6], X=1) \\
T[8] &= \text{temperature(steam, } P=P[8], h=h[8]) \\
T_s[2] &= \text{temperature(steam, } P=P[2], s=s_s[2]) \\
T_s[4] &= \text{temperature(steam, } P=P[4], s=s_s[4]) \\
T_s[6] &= \text{temperature(steam, } P=P[6], s=s_s[6]) \\
s[2] &= \text{entropy(steam, } P=P[2], h=h[2]) \\
s[4] &= \text{entropy(steam, } P=P[4], h=h[4]) \\
s[6] &= \text{entropy(steam, } P=P[6], h=h[6]) \\
s[7] &= \text{entropy(steam, } P=P[7], X=0) \\
s_s[8] &= \text{entropy(steam, } P=P[8], h=h[8]) \\
\text{eta_p} \\
s[8] &= \text{entropy(steam, } P=P[8], h=h[8]) \\
x_s[6] &= (s_s[6] - \text{entropy(steam, } P=P[6], X=0))/(\text{entropy(steam, } P=P[6], X=1) - \text{entropy(steam, } P=P[6], X=0)) \\
v[1] &= \text{volume(steam, } P=P[1], h=h[1]) \\
v[2] &= \text{volume(steam, } P=P[2], h=h[2]) \\
v[3] &= \text{volume(steam, } P=P[3], h=h[3]) \\
v[4] &= \text{volume(steam, } P=P[4], h=h[4]) \\
v[5] &= \text{volume(steam, } P=P[5], h=h[5]) \\
v[6] &= \text{volume(steam, } P=P[6], h=h[6]) \\
v[8] &= \text{volume(steam, } P=P[8], h=h[8]) \\
\end{align*}
\]

"line from state 1 to state 8"
Duplicate i=1,8
  T_line[i] = T[i]
  s_line[i] = s[i]
End

"constant high pressure line for T-s diagram"
\[
\begin{align*}
ds_hp &= 0.2 \text{ [Btu/lbm-R]} \\
s_hp[1] &= ds_hp; T_hp[1] &= \text{temperature(steam, } P=P_{hp}, s=s_hp[1]) \\
n &= 7 \\
\text{Duplicate i=2,n} \\
s_hp[i] &= s_hp[i-1] + ds_hp \\
T_hp[i] &= \text{temperature(steam, } P=P_{hp}, s=s_hp[i]) \\
\text{End} \\
s_hp[8] &= s[1]; T_hp[8] &= T[1] \quad \text{"finish line to state 1"}
\end{align*}
\]
SOLUTION

Unit Settings: \( \text{Eng R psia mass deg} \)

\[
\begin{align*}
\text{ds}_{\text{mp}} &= 0.2 \ [\text{Btu/lbm-R}] \\
\eta_{\text{plant, gross}} &= 0.3449 \\
\eta_{\text{mp}} &= 0.4261 \\
\dot{h}_{\text{R gross}} &= 9893 \ [\text{Btu/kW-hr}] \\
\dot{m}_{\text{steam}} &= 916667 \ [\text{lbm/hr}] \\
n &= 7 \\
\dot{P}_{\text{mp}} &= 7000 \ [\text{psia}] \\
\dot{P}_{\text{p}} &= 400 \ [\text{psia}] \\
\dot{Q}_{\text{n}} &= 8.772E+09 \ [\text{Btu/hr}] \\
\dot{W}_{\text{plant, gross}} &= 1019 \ [\text{MW}] \\
\dot{W}_{\text{gross}} &= 1132 \ [\text{MW}] \\
\dot{w}_{\text{p}} &= 27.87 \ [\text{Btu/lbm}]
\end{align*}
\]

6 potential unit problems were detected.

**Key Variables**

- \( \dot{Q}_{\text{n}} = 1939 \ [\text{Btu/lbm}] \)
- \( w_{\text{p}} = 27.87 \ [\text{Btu/lbm}] \)
- \( w_{\text{t}} = 854.1 \ [\text{Btu/lbm}] \)
- \( \eta_{\text{h}} = 0.4261 \)
- \( \dot{m}_{\text{steam}} = 4.524E+06 \ [\text{lbm/hr}] \)
- \( \dot{W}_{\text{plant, gross}} = 937.7 \ [\text{MW}] \)
- \( \dot{W}_{\text{gross}} = 1132 \ [\text{MW}] \)
- \( \eta_{\text{plant, gross}} = 0.3449 \)

**Arrays Table: Main**

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<th>( h ) [Btu/lbm]</th>
<th>( P ) [psi]</th>
<th>( v ) [ft^3/lbm]</th>
<th>( T ) [R]</th>
<th>( s ) [Btu/lbm-R]</th>
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state points of cycle