[1] (from Hw # 4) A power plant operates on a regenerative vapor power cycle with one open feedwater heater. Steam enters the first turbine stage at 12 MPa, 520 °C and expands to 1 MPa, where some of the steam is extracted and diverted to the open feedwater heater operating at 1 MPa. The remaining steam expands through the second turbine stage to the condenser pressure of 6 kPa. Saturated liquid exits the open feedwater heater at 1 MPa. For isentropic processes in the turbines and pumps, determine for the cycle (a) the thermal efficiency and (b) mass flow rate into the first turbine stage, in kg/h, for a net power output of 330MW.

[2] (from Hw # 4) Consider a regenerative vapor power cycle with two feedwater heaters, a closed one and an open one. Steam enters the first turbine stage at 80 bar, 480 °C, and expands to 20 bar. Some steam is extracted at 20 bar and fed to the closed feedwater heater. The remainder expands through the second stage turbine to 3 bar, where an additional amount is extracted and fed into the open feedwater heater, which operates at 3 bar. The steam expanding through the third stage turbine exits at the condenser pressure of 0.08 bar. Feedwater leaves the closed feedwater heater at 205°C, 80 bar, and condensate exiting as saturated liquid at 20 bar is trapped into the open feedwater heater. The net power output of the cycle is 100 MW. If the turbine stages and pumps are isentropic, determine

(a) the thermal efficiency
(b) the mass flow rate of steam entering the first turbine, in kg/h
1) Solution

**SCHEMATIC & GIVEN DATA:**

**ASSUMPTIONS:** Same as Example 8.5, except that the turbine stages operate in an internally reversible manner.

**ANALYSIS:** First, fix each principal state.

**State 1:** $P_1 = 120$ bar, $T_1 = 520^\circ$C $\Rightarrow h_1 = 3401.8$ kJ/kg, $s_1 = 6.5555$ kJ/kg·K

**State 2:** $P_2 = 10$ bar, $s_2 = s_1 \Rightarrow x_2 = 0.9931$, $h_2 = 2764.2$ kJ/kg

**State 3:** $P_3 = 0.06$ bar, $s_3 = s_4 \Rightarrow x_3 = 0.7777$, $h_3 = 2018.3$ kJ/kg

**State 4:** $P_4 = 0.06$ bar, sat. liquid $\Rightarrow h_4 = 151.53$ kJ/kg

**State 5:** $h_5 = h_4 + P_0 (P_5 - P_0)$

$$= 151.53 \text{ kJ/kg} + (1.0064 \times 10^{-5} \text{ m}^3/\text{kg})(10 - 0.06) \text{ bar} \left| \frac{10^5 \text{ N/m}^2}{1 \text{ bar}} \right| \left| \frac{1 \text{ kJ}}{10^5 \text{ N·m}} \right|$$

$$= 151.53 + 1.00 = 152.53 \text{ kJ/kg}$$

**State 6:** $P_6 = 10$ bar, sat. liquid $\Rightarrow h_6 = 762.81$ kJ/kg

**State 7:** $P_7 = 120$ bar, $h_7 = h_6 + P_0 (P_7 - P_0)$

$$= 762.81 + (1.1273 \times 10^{-5})(120 - 10) \left| \frac{10^5 \text{ N/m}^2}{10^5 \text{ N/m}} \right| = 775.21 \text{ kJ/kg}$$

(a) Applying energy and mass balances to the control volume enclosing the open heater, the fraction of flow extracted at location 2 is

$$\frac{y}{\theta} = \frac{h_6 - h_5}{h_2 - h_5} = \frac{762.81 - 152.53}{2764.2 - 152.53} = 0.2337 \quad (1)$$

For the control volume surrounding the turbine stages

$$\frac{\dot{W}_k}{m_1} = (h_1 - h_2) + (1 - y)(h_2 - h_3) \tag{2}$$

$$= (3401.8 - 2764.2) + (1 - 0.2337)(2764.2 - 2018.3) = 1209.2 \text{ kJ/kg}$$

And, for the pumps

$$\frac{\dot{W}_p}{m_1} = (h_7 - h_6) + (1 - y)(h_5 - h_4) \tag{3}$$

$$= (775.21 - 762.81) + (1 - 0.2337)(151.53 - 151.53) = 13.17 \text{ kJ/kg}$$
For the working fluid passing through the steam generator
\[ \dot{Q} = \dot{m}_1 (h_1 - h_7) = 3401.8 - 775.21 = 2626.6 \text{ kJ/kg} \] (4)

Thus, the thermal efficiency is
\[ \eta = \frac{W_{\text{net}}/\dot{m}_1 - W_P/\dot{m}_1}{\dot{Q} / \dot{m}_1} = 0.455 \quad (45.5 \%) \] \] (5)

(b) The net power developed is
\[ W_{\text{cycle}} = \dot{m}_1 \left[ W_{\text{net}}/\dot{m}_1 - W_P/\dot{m}_1 \right] \] (7)

\[ \Rightarrow \dot{m}_1 = \frac{W_{\text{cycle}}}{[W_{\text{net}}/\dot{m}_1 - W_P/\dot{m}_1]} \]
\[ \frac{330 \times 10^3 \text{ kJ/kg}}{(1209.2 - 11.17) \text{ kJ/kg}} \mid \frac{3600}{1 \text{ min}} \]
\[ = 9.93 \times 10^5 \text{ kg/min} \]
2) Solution

\[ T \]

State 1. \( P_1 = 80 \text{ bar}, \ T_1 = 480^\circ \text{C} \Rightarrow h_1 = 3346.4 \frac{\text{kJ}}{\text{kg}} \]
\[ s_1 = 6.6586 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \]

State 2. \( P_2 = 20 \text{ bar}, \ s_2 = 5.6, \ h_2 = 2763.5 \frac{\text{kJ}}{\text{kg}} \]

State 3. \( P_3 = 36 \text{ bar}, \ s_3 = 5.5, \ h_3 = 1.6718 \frac{\text{kJ}}{\text{kg}} \]
\[ h_3 = 2763.5 \frac{\text{kJ}}{\text{kg}} \]

State 4. \( P_4 = 90 \text{ bar}, \ s_4 = 5.1, \ h_4 = 0.5926 \frac{\text{kJ}}{\text{kg}} \]
\[ h_4 = 2763.5 \frac{\text{kJ}}{\text{kg}} \]

State 5. \( P_5 = 0.08 \text{ bar}, \ s_5, \ h_5 \Rightarrow h_5 = 173.84 \frac{\text{kJ}}{\text{kg}} \]

State 6. \( h_6 = h_5 + \frac{V_5 (P_5 - P_4)}{10^5} = 18.58 + (1000 \times 10^{-3}) (5 - 0.08) \frac{10^5}{10^3} = 174.17 \frac{\text{kJ}}{\text{kg}} \]

State 7. \( P_7 = 3.6 \text{ bar}, \ s_6, \ h_6 \Rightarrow h_7 = 561.47 \frac{\text{kJ}}{\text{kg}} \]

State 8. \( h_8 = h_7 + \frac{V_7 (P_7 - P_6)}{10^5} = 561.47 + 1.67 \times 10^{-3} (60 - 3) \frac{10^5}{10^3} = 569.75 \frac{\text{kJ}}{\text{kg}} \]

State 9. \( P_9 = 50 \text{ bar}, \ T_9 = 200^\circ \text{C} \Rightarrow h_9 = 878.84 \frac{\text{kJ}}{\text{kg}} \]

State 10. \( P_{10} = 20 \text{ bar}, \ s_{10}, \ h_{10} \Rightarrow h_{10} = 968.79 \frac{\text{kJ}}{\text{kg}} \]

State 11. \( h_{11} = h_{10} = 968.79 \frac{\text{kJ}}{\text{kg}} \)
Use energy rate balance for closed feedwater heater.

\[ \dot{Q} = \dot{m} (h_6 - h_8) + \dot{m} (h_s - h_9) \]

\[ \Rightarrow \dot{y}' = \frac{h_6 - h_8}{h_s - h_8} = \frac{-567.75 - 878.34}{2963.5 - 908.79} = 0.1503 \]

For open feedwater heater,

\[ \dot{Q} = \dot{m} (h_6 + (1 - y'_1 - y_0) h_8 + y'_0 h_9 - h_1) \]

\[ \Rightarrow \dot{y}' = \frac{2589.6 + (1 - 0.1503 - 0.1) 174.17 + 0.1503 \times 908.79 - 567.75}{2470.1} = 0.1147 \]

For turbine stages,

\[ \frac{\dot{W}_t}{\dot{m}} = (h_1 - h_2) + (1 - y'_2) (h_2 - h_3) + (1 - y'_2 - y'_3) (h_3 - h_4) = 1075.1 \text{ kJ/kg} \]

For Pumps:

\[ \frac{\dot{W}_p}{\dot{m}} = (h_8 - h_7) + (1 - y'_4 - y'_5) (h_6 - h_5) = 8.47 \text{ kJ/kg} \]

For steam generator,

\[ \frac{\dot{G}_{	ext{in}}}{\dot{m}} = h_1 - h_2 = 2470.1 \text{ kJ/kg} \]

The thermal efficiency is,

\[ \eta = \frac{\dot{W}_t - \dot{W}_p}{\dot{G}_{\text{in}}} = \frac{1075.1 - 8.47}{2470.1} = 0.4318 = 43.18\% \]

Mass flow rate:

\[ \dot{W}_{\text{cycle}} = \dot{m} \left( \frac{\dot{W}_t}{\dot{m}} - \frac{\dot{W}_p}{\dot{m}} \right) = \dot{m} x (1075.1 - 8.47) \frac{\text{kJ}}{\text{kg}} = 100 \text{ MW} \]

\[ \dot{m} = \frac{93.75 \text{ kg/s}}{3.375 \times 10^5 \text{ kg/s}} = 3.375 \times 10^{-5} \text{ kg/s} \]