**10-100** An 150-MW steam power plant operating on a regenerative Rankine cycle with an open feedwater heater is considered. The mass flow rate of steam through the boiler, the thermal efficiency of the cycle, and the irreversibility associated with the regeneration process are to be determined.

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

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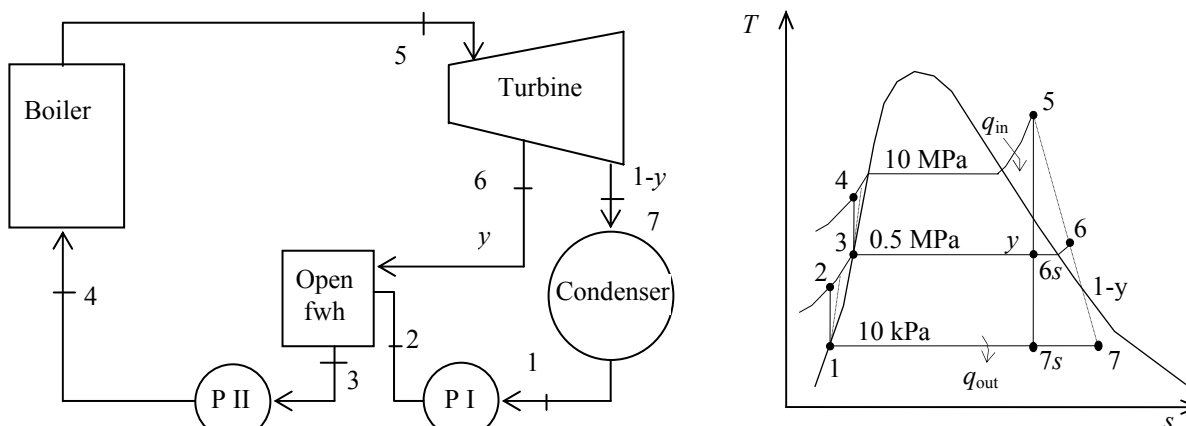
(*a*) From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f\,@\,10\,kPa} = 191.81\,kJ/kg$$

$$\nu_1 = \nu_{f\,@\,10\,kPa} = 0.00101\,m^3/kg$$

$$w_{pI,in} = \nu_1(P_2 - P_1)/\eta_p$$
$$= (0.00101\,m^3/kg)(500-10\,kPa)\left(\frac{1\,kJ}{1\,kPa\cdot m^3}\right)/(0.95)$$
$$= 0.52\,kJ/kg$$

$$h_2 = h_1 + w_{pI,in} = 191.81 + 0.52 = 19233\,kJ/kg$$

$$\left.\begin{array}{l}P_3 = 0.5\,MPa \\ satliquid\end{array}\right\}\begin{array}{l}h_3 = h_{f\,@\,0.5\,MPa} = 64009\,kJ/kg \\ \nu_3 = \nu_{f\,@\,0.5\,MPa} = 0.001093\,m^3/kg\end{array}$$

$$w_{pII,in} = \nu_3(P_4 - P_3)/\eta_p$$
$$= (0.001093\ m^3/kg)(10{,}000 - 500\,kPa)\left(\frac{1\,kJ}{1\,kPa\cdot m^3}\right)/(0.95)$$
$$= 10.93\ kJ/kg$$

$$h_4 = h_3 + w_{pII,in} = 640.09 + 10.93 = 651.02\ kJ/kg$$

$$\left.\begin{array}{l}P_5 = 10\,MPa \\ T_5 = 500°C\end{array}\right\}\begin{array}{l}h_5 = 3375.1\ kJ/kg \\ s_5 = 6.5995\ kJ/kg\cdot K\end{array}$$

$$x_{6s} = \frac{s_{6s} - s_f}{s_{fg}} = \frac{6.5995 - 1.8604}{4.9603} = 0.9554$$

$$\left.\begin{array}{l}P_{6s} = 0.5\,MPa \\ s_{6s} = s_5\end{array}\right\}\begin{array}{l}h_{6s} = h_f + x_{6s}h_{fg} = 640.09 + (0.9554)(2108.0) \\ = 2654.1\ kJ/kg\end{array}$$

$$\eta_T = \frac{h_5 - h_6}{h_5 - h_{6s}} \longrightarrow h_6 = h_5 - \eta_T(h_5 - h_{6s})$$
$$= 3375.1 - (0.80)(3375.1 - 2654.1)$$
$$= 2798.3\ kJ/kg$$

$$x_{7s} = \frac{s_{7s} - s_f}{s_{fg}} = \frac{6.5995 - 0.6492}{7.4996} = 0.7934$$

$$\left.\begin{array}{l} P_{7s} = 10 \text{ kPa} \\ s_{7s} = s_5 \end{array}\right\} \begin{array}{l} h_{7s} = h_f + x_{7s} h_{fg} = 191.81 + (0.7934)(2392.1) \\ = 2089.7 \text{ kJ/kg} \end{array}$$

$$\eta_T = \frac{h_5 - h_7}{h_5 - h_{7s}} \longrightarrow \begin{array}{l} h_7 = h_5 - \eta_T(h_5 - h_{7s}) \\ = 3375.1 - (0.80)(3375.1 - 2089.7) \\ = 2346.8 \text{ kJ/kg} \end{array}$$

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

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

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

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_6 h_6 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \longrightarrow y h_6 + (1-y) h_2 = 1(h_3)$$

where y is the fraction of steam extracted from the turbine ($= \dot{m}_6 / \dot{m}_3$). Solving for y,

$$y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{640.09 - 192.33}{2798.3 - 192.33} = 0.1718$$

Then,
$$q_{in} = h_5 - h_4 = 3375.1 - 651.02 = 2724.1 \text{ kJ/kg}$$
$$q_{out} = (1-y)(h_7 - h_1) = (1 - 0.1718)(2346.8 - 191.81) = 1784.7 \text{ kJ/kg}$$
$$w_{net} = q_{in} - q_{out} = 2724.1 - 1784.7 = 939.4 \text{ kJ/kg}$$

and

$$\dot{m} = \frac{\dot{W}_{net}}{w_{net}} = \frac{150,000 \text{ kJ/s}}{939.4 \text{ kJ/kg}} = \mathbf{159.7 \text{ kg/s}}$$

(*b*) The thermal efficiency is determined from

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1784.7 \text{ kJ/kg}}{2724.1 \text{ kJ/kg}} = \mathbf{34.5\%}$$

Also,

$$\left.\begin{array}{l} P_6 = 0.5 \text{ MPa} \\ h_6 = 2798.3 \text{ kJ/kg} \end{array}\right\} s_6 = 6.9453 \text{ kJ/kg} \cdot \text{K}$$

$$s_3 = s_{f \text{ @ 0.5 MPa}} = 1.8604 \text{ kJ/kg} \cdot \text{K}$$
$$s_2 = s_1 = s_{f \text{ @ 10 kPa}} = 0.6492 \text{ kJ/kg} \cdot \text{K}$$

Then the irreversibility (or exergy destruction) associated with this regeneration process is

$$i_{regen} = T_0 s_{gen} = T_0 \left(\sum m_e s_e - \sum m_i s_i + \frac{q_{surr}}{T_L}^{\nearrow 0} \right) = T_0 [s_3 - y s_6 - (1-y) s_2]$$
$$= (303 \text{ K})[1.8604 - (0.1718)(6.9453) - (1 - 0.1718)(0.6492)]$$
$$= \mathbf{39.25 \text{ kJ/kg}}$$