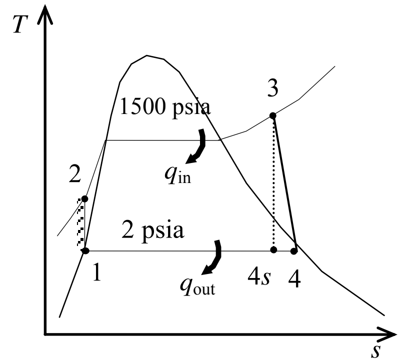
10-18E A simple steam Rankine cycle operates between the specified pressure limits. The mass flow rate, the power produced by the turbine, the rate of heat addition, and the thermal efficiency of the cycle are to be determined.

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

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

$$h_1 = h_{f@\,2\text{ psia}} = 94.02\text{ Btu/lbm}$$
$$\boldsymbol{v}_1 = \boldsymbol{v}_{f@\,2\text{ psia}} = 0.016230\text{ ft}^3\text{/lbm}$$

$$\begin{aligned} w_{\text{p,in}} &= \boldsymbol{v}_1(P_2 - P_1) \\ &= (0.016230\text{ ft}^3\text{/lbm})(1500-2)\text{psia}\left(\frac{1\text{ Btu}}{5.404\text{ psia}\cdot\text{ft}^3}\right) \\ &= 4.50\text{ Btu/lbm} \end{aligned}$$
$$h_2 = h_1 + w_{\text{p,in}} = 94.02 + 4.50 = 98.52\text{ Btu/lbm}$$



$$\left.\begin{aligned} P_3 &= 1500\text{ psia} \\ T_3 &= 800°\text{F} \end{aligned}\right\} \begin{aligned} h_3 &= 1363.1\text{ Btu/lbm} \\ s_3 &= 1.5064\text{ Btu/lbm}\cdot\text{R} \end{aligned}$$

$$\left.\begin{aligned} P_4 &= 2\text{ psia} \\ s_4 &= s_3 \end{aligned}\right\} \begin{aligned} x_{4s} &= \frac{s_4 - s_f}{s_{fg}} = \frac{1.5064 - 0.1750}{1.7444} = 0.7633 \\ h_{4s} &= h_f + x_{4s}h_{fg} = 94.02 + (0.7633)(1021.7) = 873.86\text{ Btu/lbm} \end{aligned}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} \longrightarrow h_4 = h_3 - \eta_T(h_3 - h_{4s}) = 1363.1 - (0.90)(1363.1 - 873.86) = 922.79\text{ kJ/kg}$$

Thus,

$$q_{\text{in}} = h_3 - h_2 = 1363.1 - 98.52 = 1264.6\text{ Btu/lbm}$$
$$q_{\text{out}} = h_4 - h_1 = 922.79 - 94.02 = 828.8\text{ Btu/lbm}$$
$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 1264.6 - 828.8 = 435.8\text{ Btu/lbm}$$

The mass flow rate of steam in the cycle is determined from

$$\dot{W}_{\text{net}} = \dot{m}w_{\text{net}} \longrightarrow \dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{2500\text{ kJ/s}}{435.8\text{ Btu/lbm}}\left(\frac{0.94782\text{ Btu}}{1\text{ kJ}}\right) = \mathbf{5.437\,lbm/s}$$

The power output from the turbine and the rate of heat addition are

$$\dot{W}_{\text{T,out}} = \dot{m}(h_3 - h_4) = (5.437\text{ lbm/s})(1363.1 - 922.79)\text{Btu/lbm}\left(\frac{1\text{ kJ}}{0.94782\text{ Btu}}\right) = \mathbf{2526\,kW}$$
$$\dot{Q}_{\text{in}} = \dot{m}q_{\text{in}} = (5.437\text{ lbm/s})(1264.6\text{ Btu/lbm}) = \mathbf{6876\,Btu/s}$$

and the thermal efficiency of the cycle is

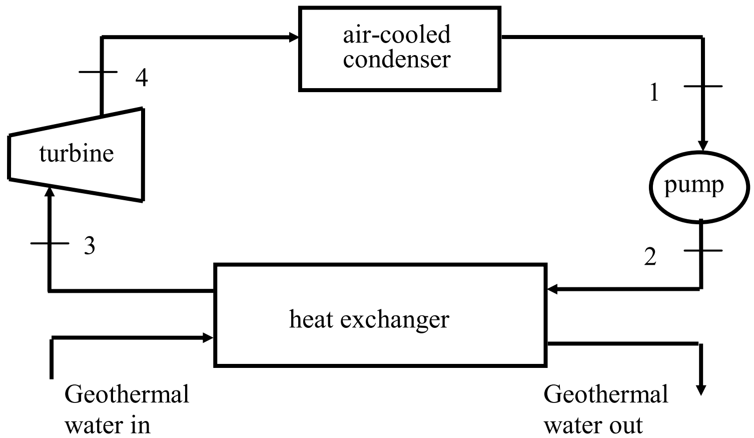
$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \frac{2500\text{ kJ/s}}{6876\text{ Btu/s}}\left(\frac{0.94782\text{ Btu}}{1\text{ kJ}}\right) = 0.3446 = \mathbf{34.5\%}$$

10-25 A binary geothermal power operates on the simple Rankine cycle with isobutane as the working fluid. The isentropic efficiency of the turbine, the net power output, 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.

Properties The specific heat of geothermal water is taken to be 4.18 kJ/kg.ºC.

Analysis (*a*) We need properties of isobutane, which are not available in the book. However, we can obtain the properties from EES.



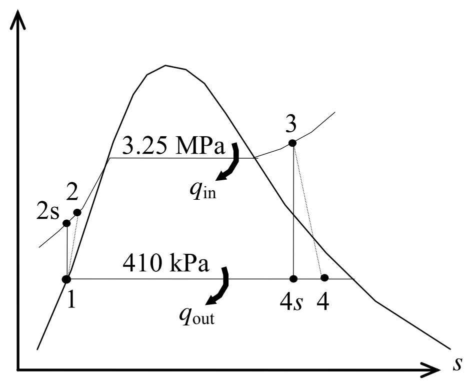
Turbine:

$$\left.\begin{array}{l} P_3 = 3250 \text{ kPa} \\ T_3 = 147°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 761.54 \text{ kJ/kg} \\ s_3 = 2.5457 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 410 \text{ kPa} \\ s_4 = s_3 \end{array}\right\} h_{4s} = 670.40 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 410 \text{ kPa} \\ T_4 = 179.5°\text{C} \end{array}\right\} h_4 = 689.74 \text{ kJ/kg}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} = \frac{761.54 - 689.74}{761.54 - 670.40} = \mathbf{0.788}$$



(*b*) Pump:

$$h_1 = h_{f\,@\,410\,\text{kPa}} = 273.01 \text{ kJ/kg}$$

$$v_1 = v_{f\,@\,410\,\text{kPa}} = 0.001842 \text{ m}^3/\text{kg}$$

$$\begin{aligned} w_{p,\text{in}} &= v_1(P_2 - P_1)/\eta_P \\ &= (0.001842 \text{ m}^3/\text{kg})(3250 - 410)\text{kPa}\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)/0.90 \\ &= 5.81 \text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{p,\text{in}} = 273.01 + 5.81 = 278.82 \text{ kJ/kg}$$

$$\dot{W}_{\text{T,out}} = \dot{m}(h_3 - h_4) = (305.6 \text{ kJ/kg})(761.54 - 689.74)\text{kJ/kg} = 21{,}941 \text{ kW}$$

$$\dot{W}_{\text{P,in}} = \dot{m}(h_2 - h_1) = \dot{m}w_{\text{p,in}} = (305.6 \text{ kJ/kg})(5.81 \text{ kJ/kg}) = 1777 \text{ kW}$$

$$\dot{W}_{\text{net}} = \dot{W}_{\text{T,out}} - \dot{W}_{\text{P,in}} = 21{,}941 - 1777 = \mathbf{20{,}165 \text{ kW}}$$

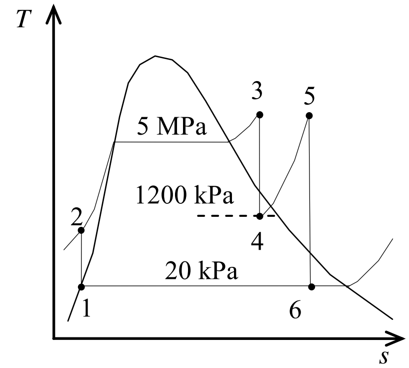
Heat Exchanger:

$$\dot{Q}_{\text{in}} = \dot{m}_{\text{geo}}c_{\text{geo}}(T_{\text{in}} - T_{\text{out}}) = (555.9 \text{ kJ/kg})(4.18 \text{ kJ/kg.°C})(160 - 90)\text{°C} = 162{,}656 \text{ kW}$$

(*c*) $$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \frac{20{,}165}{162{,}656} = \mathbf{0.124 = 12.4\%}$$

10-34 An ideal reheat Rankine with water as the working fluid is considered. The temperatures at the inlet of both turbines, 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 From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f@\,20\,\text{kPa}} = 251.42 \text{ kJ/kg}$$
$$\boldsymbol{v}_1 = \boldsymbol{v}_{f@\,20\,\text{kPa}} = 0.0010172 \text{ m}^3\text{/kg}$$

$$\begin{aligned} w_{\text{p,in}} &= \boldsymbol{v}_1(P_2 - P_1) \\ &= (0.0010172 \text{ m}^3\text{/kg})(5000 - 20)\text{kPa}\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) \\ &= 5.065 \text{ kJ/kg} \end{aligned}$$
$$h_2 = h_1 + w_{\text{p,in}} = 251.42 + 5.065 = 256.49 \text{ kJ/kg}$$

$$\left.\begin{aligned} P_4 &= 1200 \text{ kPa} \\ x_4 &= 0.96 \end{aligned}\right\} \begin{aligned} h_4 &= h_f + x_4 h_{fg} = 798.33 + (0.96)(1985.4) = 2704.3 \text{ kJ/kg} \\ s_4 &= s_f + x_4 s_{fg} = 2.2159 + (0.96)(4.3058) = 6.3495 \text{ kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_3 &= 5000 \text{ kPa} \\ s_3 &= s_4 \end{aligned}\right\} \begin{aligned} h_3 &= 3006.9 \text{ kJ/kg} \\ T_3 &= \mathbf{327.2°C} \end{aligned}$$

$$\left.\begin{aligned} P_6 &= 20 \text{ kPa} \\ x_6 &= 0.96 \end{aligned}\right\} \begin{aligned} h_6 &= h_f + x_6 h_{fg} = 251.42 + (0.96)(2357.5) = 2514.6 \text{ kJ/kg} \\ s_6 &= s_f + x_6 s_{fg} = 0.8320 + (0.96)(7.0752) = 7.6242 \text{ kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_5 &= 1200 \text{ kPa} \\ s_5 &= s_6 \end{aligned}\right\} \begin{aligned} h_5 &= 3436.0 \text{ kJ/kg} \\ T_5 &= \mathbf{481.1°C} \end{aligned}$$

Thus,

$$q_{\text{in}} = (h_3 - h_2) + (h_5 - h_4) = 3006.9 - 256.49 + 3436.0 - 2704.3 = 3482.0 \text{ kJ/kg}$$
$$q_{\text{out}} = h_6 - h_1 = 2514.6 - 151.42 = 2263.2 \text{ kJ/kg}$$

and

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{2263.2}{3482.0} = 0.3500 = \mathbf{35.0\%}$$

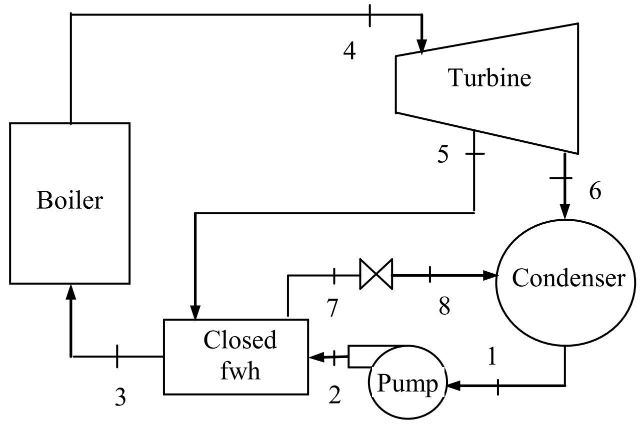
10-48 An ideal regenerative Rankine cycle with a closed feedwater heater is considered. The work produced by the turbine, the work consumed by the pumps, and the heat added in the boiler are to be determined.

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

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

$$h_1 = h_{f@20\,\text{kPa}} = 251.42\ \text{kJ/kg}$$
$$v_1 = v_{f@20\,\text{kPa}} = 0.001017\ \text{m}^3/\text{kg}$$

$$\begin{aligned} w_{\text{p,in}} &= v_1(P_2 - P_1) \\ &= (0.001017\ \text{m}^3/\text{kg})(3000-20)\text{kPa}\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) \\ &= 3.03\ \text{kJ/kg} \end{aligned}$$
$$h_2 = h_1 + w_{\text{p,in}} = 251.42 + 3.03 = 254.45\ \text{kJ/kg}$$

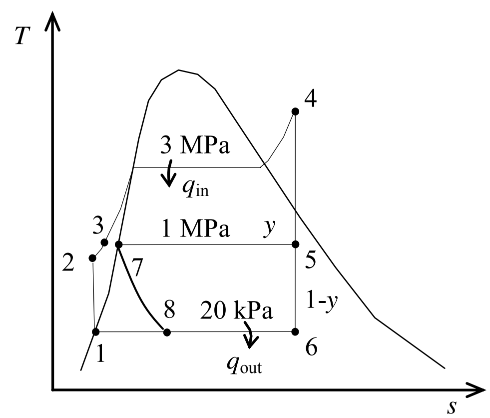


$$\left.\begin{aligned} P_4 &= 3000\ \text{kPa} \\ T_4 &= 350°\text{C} \end{aligned}\right\} \begin{aligned} h_4 &= 3116.1\ \text{kJ/kg} \\ s_4 &= 6.7450\ \text{kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_5 &= 1000\ \text{kPa} \\ s_5 &= s_4 \end{aligned}\right\} h_5 = 2851.9\ \text{kJ/kg}$$

$$\left.\begin{aligned} P_6 &= 20\ \text{kPa} \\ s_6 &= s_4 \end{aligned}\right\} \begin{aligned} x_6 &= \frac{s_6 - s_f}{s_{fg}} = \frac{6.7450 - 0.8320}{7.0752} = 0.8357 \\ h_6 &= h_f + x_6 h_{fg} = 251.42 + (0.8357)(2357.5) = 2221.7\ \text{kJ/kg} \end{aligned}$$

For an ideal closed feedwater heater, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure.



$$\left.\begin{aligned} P_7 &= 1000\ \text{kPa} \\ x_7 &= 0 \end{aligned}\right\} \begin{aligned} h_7 &= 762.51\ \text{kJ/kg} \\ T_7 &= 179.9°\text{C} \end{aligned}$$
$$h_8 = h_7 = 762.51\ \text{kJ/kg}$$
$$\left.\begin{aligned} P_3 &= 3000\ \text{kPa} \\ T_3 &= T_7 = 209.9°\text{C} \end{aligned}\right\} h_3 = 763.53\ \text{kJ/kg}$$

An energy balance on the heat exchanger gives the fraction of steam extracted from the turbine ($= \dot{m}_5 / \dot{m}_4$) for closed feedwater heater:

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$
$$\dot{m}_5 h_5 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_7 h_7$$
$$y h_5 + 1h_2 = 1h_3 + y h_7$$

Rearranging,

$$y = \frac{h_3 - h_2}{h_5 - h_7} = \frac{763.53 - 254.45}{2851.9 - 762.51} = 0.2437$$

Then,

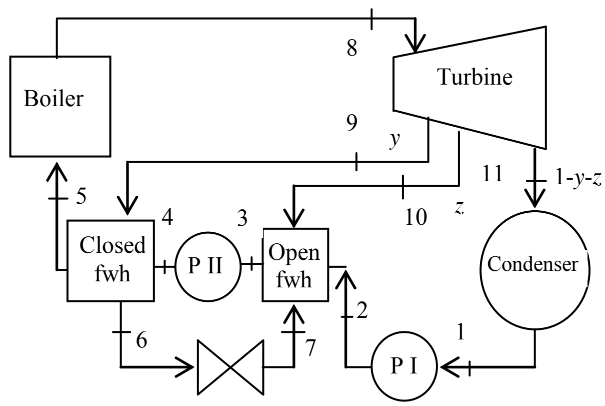
$$w_{\text{T,out}} = h_4 - h_5 + (1-y)(h_5 - h_6) = 3116.1 - 2851.9 + (1-0.2437)(2851.9 - 2221.7) = \mathbf{740.9\ kJ/kg}$$
$$w_{\text{P,in}} = \mathbf{3.03\ kJ/kg}$$
$$q_{\text{in}} = h_4 - h_3 = 3116.1 - 763.53 = \mathbf{2353\ kJ/kg}$$

Also, $w_{\text{net}} = w_{\text{T,out}} - w_{\text{P,in}} = 740.9 - 3.03 = 737.8\ \text{kJ/kg}$

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{737.8}{2353} = 0.3136$$

10-53 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 400 MW and the thermal efficiency of the cycle are to be determined.

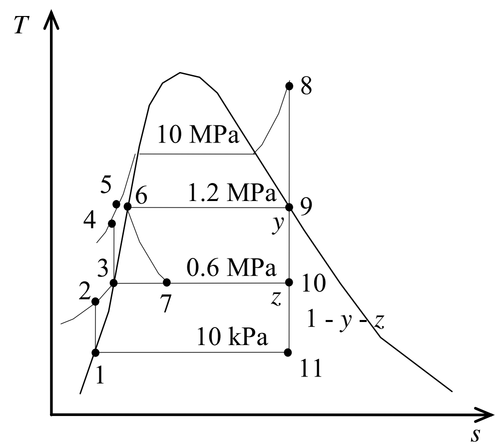
Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.



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

$$h_1 = h_{f@\,10\text{ kPa}} = 191.81\text{ kJ/kg}$$
$$\boldsymbol{v}_1 = \boldsymbol{v}_{f@\,10\text{ kPa}} = 0.00101\ \text{m}^3/\text{kg}$$

$$\begin{aligned} w_{pI,\text{in}} &= \boldsymbol{v}_1(P_2 - P_1) \\ &= (0.00101\ \text{m}^3/\text{kg})(600 - 10\ \text{kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 0.60\ \text{kJ/kg} \end{aligned}$$
$$h_2 = h_1 + w_{pI,\text{in}} = 191.81 + 0.60 = 192.40\ \text{kJ/kg}$$



$$\left.\begin{array}{l} P_3 = 0.6\text{ MPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} h_3 = h_{f@\,0.3\text{ MPa}} = 670.38\text{ kJ/kg} \\ \boldsymbol{v}_3 = \boldsymbol{v}_{f@\,0.3\text{ MPa}} = 0.001101\ \text{m}^3/\text{kg} \end{array}$$

$$w_{pII,\text{in}} = \boldsymbol{v}_3(P_4 - P_3)$$
$$= (0.001101\ \text{m}^3/\text{kg})(10000 - 600\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$
$$= 10.35\text{ kJ/kg}$$
$$h_4 = h_3 + w_{pII,\text{in}} = 670.38 + 10.35 = 680.73\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_6 = 1.2\text{ MPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} h_6 = h_7 = h_{f@\,1.2\text{ MPa}} = 798.33\text{ kJ/kg} \\ T_6 = T_{\text{sat}@\,1.2\text{ MPa}} = 188.0°\text{C} \end{array}$$

$$T_6 = T_5,\ P_5 = 10\text{ MPa} \rightarrow h_5 = 798.33\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_8 = 10\text{ MPa} \\ T_8 = 600°\text{C} \end{array}\right\} \begin{array}{l} h_8 = 3625.8\text{ kJ/kg} \\ s_8 = 6.9045\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_9 = 1.2\text{ MPa} \\ s_9 = s_8 \end{array}\right\} h_9 = 2974.5\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_{10} = 0.6\text{ MPa} \\ s_{10} = s_8 \end{array}\right\} h_{10} = 2820.9\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_{11} = 10\text{ kPa} \\ s_{11} = s_8 \end{array}\right\} \begin{array}{l} x_{11} = \dfrac{s_{11} - s_f}{s_{fg}} = \dfrac{6.9045 - 0.6492}{7.4996} = 0.8341 \\ h_{11} = h_f + x_{11}h_{fg} = 191.81 + (0.8341)(2392.1) = 2187.0\text{ kJ/kg} \end{array}$$

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

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta\dot{E}_{\text{system}}^{\nearrow 0\text{ (steady)}} = 0$$
$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$
$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_9(h_9 - h_6) = \dot{m}_5(h_5 - h_4) \longrightarrow y(h_9 - h_6) = (h_5 - h_4)$$

where y is the fraction of steam extracted from the turbine ($= \dot{m}_{10}/\dot{m}_5$). Solving for y,

$$y = \frac{h_5 - h_4}{h_9 - h_6} = \frac{798.33 - 680.73}{2974.5 - 798.33} = 0.05404$$

For the open FWH,

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

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

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_7 h_7 + \dot{m}_2 h_2 + \dot{m}_{10} h_{10} = \dot{m}_3 h_3 \longrightarrow y h_7 + (1 - y - z) h_2 + z h_{10} = (1) h_3$$

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

$$z = \frac{(h_3 - h_2) - y(h_7 - h_2)}{h_{10} - h_2} = \frac{670.38 - 192.40 - (0.05404)(798.33 - 192.40)}{2820.9 - 192.40} = 0.1694$$

Then,

$$q_{\text{in}} = h_8 - h_5 = 3625.8 - 798.33 = 2827 \text{ kJ/kg}$$

$$q_{\text{out}} = (1 - y - z)(h_{11} - h_1) = (1 - 0.05404 - 0.1694)(2187.0 - 191.81) = 1549 \text{ kJ/kg}$$

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 2827 - 1549 = 1278 \text{ kJ/kg}$$

and

$$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{400{,}000 \text{ kJ/s}}{1278 \text{ kJ/kg}} = \mathbf{313.0\ kg/s}$$

(*b*) $$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1549 \text{ kJ/kg}}{2827 \text{ kJ/kg}} = 0.452 = \mathbf{45.2\%}$$