10-57 A Rankine steam cycle modified with two closed feedwater heaters is considered. The *T-s* diagram for the ideal cycle is to be sketched. The fraction of mass extracted for the closed feedwater heater z and the cooling water flow rate are to be determined. Also, the net power output and the thermal efficiency of the plant are to be determined.

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

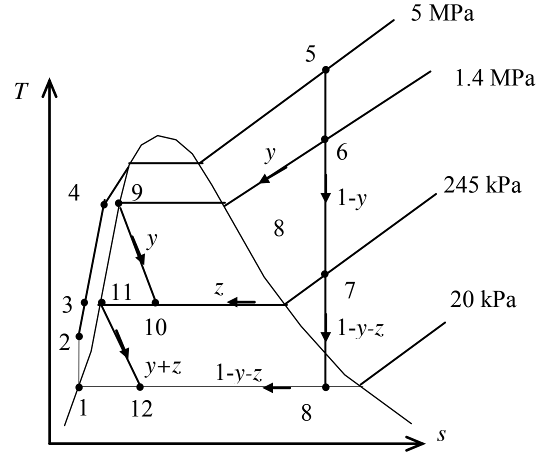
Analysis (*b*) Using the data from the problem statement, the enthalpies at various states are

$$h_1 = h_{f\ @\ 20\,\text{kPa}} = 251\ \text{kJ/kg}$$

$$\boldsymbol{v}_1 = \boldsymbol{v}_{f\ @\ 20\,\text{kPa}} = 0.00102\ \ \text{m}^3/\text{kg}$$

$$\begin{aligned} w_{\text{pI,in}} &= \boldsymbol{v}_1(P_2 - P_1) \\ &= (0.00102\ \ \text{m}^3/\text{kg})(5000 - 20\ \text{kPa})\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) \\ &= 5.1\ \text{kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 251 + 5.1 = 256.1\ \text{kJ/kg}$$



Also,

$$h_3 = h_{11} = h_{f\ @\ 245\text{kPa}} = 533\ \text{kJ/kg}$$

$$h_{12} = h_{11}\quad \text{(throttle valve operation)}$$

$$h_4 = h_9 = h_{f\ @1400\text{kPa}} = 830\ \text{kJ/kg}$$

$$h_{10} = h_9\quad \text{(throttle valve operation)}$$

An energy balance on the closed feedwater heater gives

$$1h_2 + zh_7 + yh_{10} = 1h_3 + (y+z)h_{11}$$

where z is the fraction of steam extracted from the low-pressure turbine. Solving for z,

$$z = \frac{(h_3 - h_2) + y(h_{11} - h_{10})}{h_7 - h_{11}} = \frac{(533 - 256.1) + (0.1446)(533 - 830)}{2918 - 533} = \mathbf{0.09810}$$

(c) An energy balance on the condenser gives

$$\dot{m}_8 h_8 + \dot{m}_w h_{w1} + \dot{m}_{12} h_{12} = \dot{m}_1 h_1 + \dot{m}_w h_{w2}$$

$$\dot{m}_w (h_{w2} - h_{w2}) = \dot{m}_8 h_8 + \dot{m}_{12} h_{12} - \dot{m}_1 h_1$$

Solving for the mass flow rate of cooling water, and substituting with correct units,

$$\begin{aligned} \dot{m}_w &= \frac{\dot{m}_5\left[(1 - y - z)h_8 + (y+z)h_{12} - 1h_1\right]}{c_{pw}\Delta T_w} \\ &= \frac{(75)\left[(1 - 0.1446 - 0.09810)(2477) + (0.1446 + 0.09810)(533) - 1(251)\right]}{(4.18)(10)} \\ &= \mathbf{3147\,kg/s} \end{aligned}$$

(d) The work output from the turbines is

$$\begin{aligned} w_{\text{T,out}} &= h_5 - yh_6 - zh_7 - (1 - y - z)h_8 \\ &= 3900 - (0.1446)(3406) - (0.09810)(2918) - (1 - 0.1446 - 0.09810)(2477) \\ &= 1245.4\ \text{kJ/kg} \end{aligned}$$

The net work output from the cycle is

$$\begin{aligned} w_{\text{net}} &= w_{\text{T,out}} - w_{\text{P,in}} \\ &= 1245.4 - 5.1 = 1240.3\ \text{kJ/kg} \end{aligned}$$

The net power output is

$$\dot{W}_{\text{net}} = \dot{m}w_{\text{net}} = (75\ \text{kg/s})(1240.3\ \text{kJ/kg}) = 93{,}024\ \text{kW} = \mathbf{93.0\,MW}$$

The rate of heat input in the boiler is

$$\dot{Q}_{\text{in}} = \dot{m}(h_5 - h_4) = (75\ \text{kg/s})(3900 - 830)\ \text{kJ/kg} = 230{,}250\ \text{kW}$$

The thermal efficiency is then

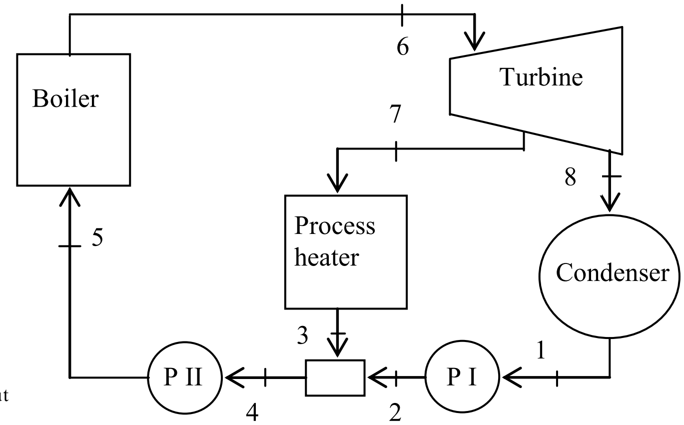
$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \frac{93{,}024\ \text{kW}}{230{,}250\ \text{kW}} = 0.404 = \mathbf{40.4\%}$$

10-69 A cogeneration plant is to generate power and process heat. Part of the steam extracted from the turbine at a relatively high pressure is used for process heating. The net power produced and the utilization factor of the plant 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),

$$h_1 = h_{f\,@\,10\text{ kPa}} = 191.81 \text{ kJ/kg}$$
$$v_1 = v_{f\,@\,10\text{ kPa}} = 0.00101 \text{ m}^3\text{/kg}$$



$$w_{pI,in} = v_1(P_2 - P_1) = (0.00101 \text{ m}^3\text{/kg})(1200 - 10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 1.20 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{pI,in} = 191.81 + 1.20 = 193.01 \text{ kJ/kg}$$

$$h_3 = h_{f\,@\,1.2\text{ MPa}} = 798.33 \text{ kJ/kg}$$

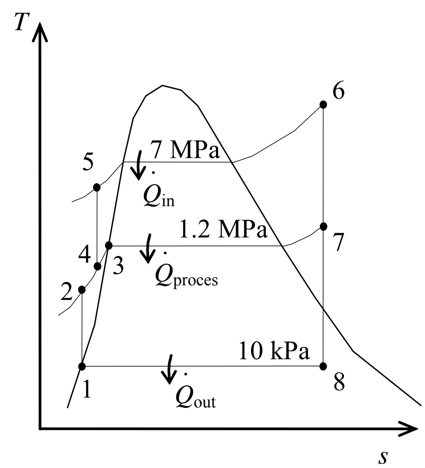
Mixing chamber:

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

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_4 h_4 = \dot{m}_2 h_2 + \dot{m}_3 h_3$$

or,
$$h_4 = \frac{\dot{m}_2 h_2 + \dot{m}_3 h_3}{\dot{m}_4} = \frac{(22.50)(192.41) + (7.50)(798.33)}{30} = 344.34 \text{ kJ/kg}$$

$$v_4 \cong v_{f\,@\,h_f = 344.34\text{ kJ/kg}} = 0.001031 \text{ m}^3\text{/kg}$$



$$w_{pII,in} = v_4(P_5 - P_4) = (0.001031 \text{ m}^3\text{/kg})(4000 - 1200 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 2.89 \text{ kJ/kg}$$

$$h_5 = h_4 + w_{pII,in} = 344.34 + 2.89 = 347.22 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_6 = 4 \text{ MPa} \\ T_6 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_6 = 3446.0 \text{ kJ/kg} \\ s_6 = 7.0922 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_7 = 1.2 \text{ MPa} \\ s_7 = s_6 \end{array}\right\} h_7 = 3080.4 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_8 = 10 \text{ kPa} \\ s_8 = s_6 \end{array}\right\} \begin{array}{l} x_8 = \dfrac{s_8 - s_f}{s_{fg}} = \dfrac{7.0922 - 0.6492}{7.4996} = 0.8591 \\ h_8 = h_f + x_8 h_{fg} = 191.81 + (0.8591)(2392.1) = 2246.9 \text{ kJ/kg} \end{array}$$

Then,

$$\dot{W}_{T,out} = \dot{m}_6(h_6 - h_7) + \dot{m}_8(h_7 - h_8) = (55 \text{ kg/s})(3446.0 - 3080.4)\text{kJ/kg} + (0.75 \times 55 \text{ kg/s})(3080.4 - 2246.9)\text{kJ/kg} = 54{,}494 \text{ kW}$$

$$\dot{W}_{p,in} = \dot{m}_1 w_{pI,in} + \dot{m}_4 w_{pII,in} = (0.75 \times 55 \text{ kg/s})(1.20 \text{ kJ/kg}) + (55 \text{ kg/s})(2.89 \text{ kJ/kg}) = 208.3 \text{ kW}$$

$$\dot{W}_{net} = \dot{W}_{T,out} - \dot{W}_{p,in} = 54{,}494 - 208.3 = \mathbf{54{,}285 \text{ kW}}$$

Also,
$$\dot{Q}_{process} = \dot{m}_7(h_7 - h_3) = (0.25 \times 55 \text{ kg/s})(3080.4 - 798.33) \text{ kJ/kg} = 31{,}379 \text{ kW}$$

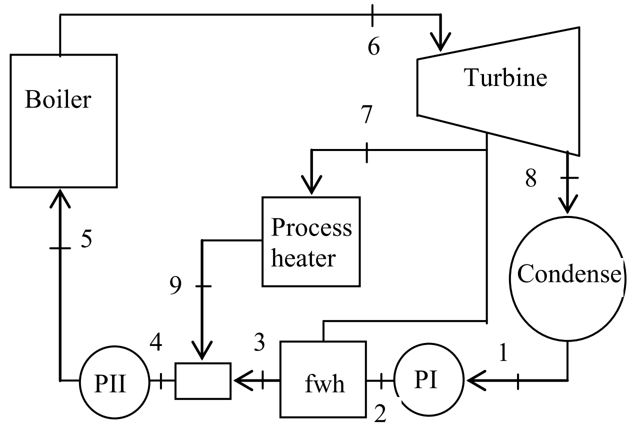
$$\dot{Q}_{in} = \dot{m}_5(h_6 - h_5) = (55 \text{ kg/s})(3446.0 - 347.22) = 170{,}435 \text{ kW}$$

and
$$\varepsilon_u = \frac{\dot{W}_{net} + \dot{Q}_{process}}{\dot{Q}_{in}} = \frac{54{,}285 + 31{,}379}{170{,}435} = 0.5026 = \mathbf{50.3\%}$$

10-72 A cogeneration plant modified with regeneration is to generate power and process heat. The mass flow rate of steam through the boiler for a net power output of 25 MW is 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),



$$h_1 = h_{f\ @\ 10\ \text{kPa}} = 191.81\ \text{kJ/kg}$$
$$v_1 = v_{f\ @\ 10\ \text{kPa}} = 0.00101\ \text{m}^3/\text{kg}$$

$$w_{\text{pI,in}} = v_1(P_2 - P_1) = (0.00101\ \text{m}^3/\text{kg})(1600 - 10\ \text{kPa})\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = 1.61\ \text{kJ/kg}$$

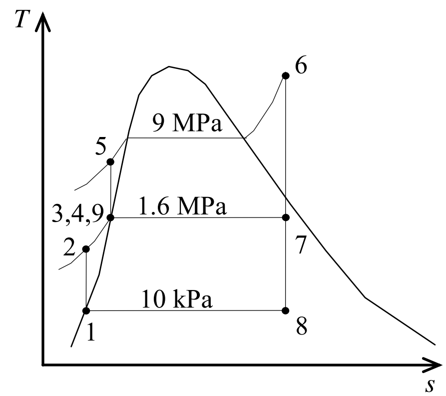
$$h_2 = h_1 + w_{\text{pI,in}} = 191.81 + 1.61 = 193.41\ \text{kJ/kg}$$

$$h_3 = h_4 = h_9 = h_{f\ @\ 1.6\ \text{MPa}} = 858.44\ \text{kJ/kg}$$

$$v_4 = v_{f\ @\ 1.6\ \text{MPa}} = 0.001159\ \text{m}^3/\text{kg}$$

$$w_{\text{pII,in}} = v_4(P_5 - P_4) = (0.001159\ \text{m}^3/\text{kg})(9000 - 400\ \text{kPa})\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = 8.57\ \text{kJ/kg}$$

$$h_5 = h_4 + w_{\text{pII,in}} = 858.44 + 8.57 = 867.02\ \text{kJ/kg}$$



$$\left.\begin{array}{l} P_6 = 9\ \text{MPa} \\ T_6 = 400°\text{C} \end{array}\right\} \begin{array}{l} h_6 = 3118.8\ \text{kJ/kg} \\ s_6 = 6.2876\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_7 = 1.6\ \text{MPa} \\ s_7 = s_6 \end{array}\right\} \begin{array}{l} x_7 = \dfrac{s_7 - s_f}{s_{fg}} = \dfrac{6.2876 - 2.3435}{4.0765} = 0.9675 \\ h_7 = h_f + x_7 h_{fg} = 858.44 + (0.9675)(1934.4) = 2730.0\ \text{kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_8 = 10\ \text{kPa} \\ s_8 = s_6 \end{array}\right\} \begin{array}{l} x_8 = \dfrac{s_8 - s_f}{s_{fg}} = \dfrac{6.2876 - 0.6492}{7.4996} = 0.7518 \\ h_8 = h_f + x_8 h_{fg} = 191.81 + (0.7518)(2392.1) = 1990.2\ \text{kJ/kg} \end{array}$$

Then, per kg of steam flowing through the boiler, we have

$$w_{\text{T,out}} = (h_6 - h_7) + (1 - y)(h_7 - h_8) = (3118.8 - 2730.0)\ \text{kJ/kg} + (1 - 0.35)(2730.0 - 1990.2)\ \text{kJ/kg} = 869.7\ \text{kJ/kg}$$

$$w_{\text{p,in}} = (1 - y)w_{\text{pI,in}} + w_{\text{pII,in}} = (1 - 0.35)(1.61\ \text{kJ/kg}) + (8.57\ \text{kJ/kg}) = 9.62\ \text{kJ/kg}$$

$$w_{\text{net}} = w_{\text{T,out}} - w_{\text{p,in}} = 869.7 - 9.62 = 860.1\ \text{kJ/kg}$$

Thus,

$$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{25{,}000\ \text{kJ/s}}{860.1\ \text{kJ/kg}} = \mathbf{29.1\ kg/s}$$