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ME 3322A: Thermodynamics: Fall 2014
Homework Set # 11
Due Date: November 25, 2014

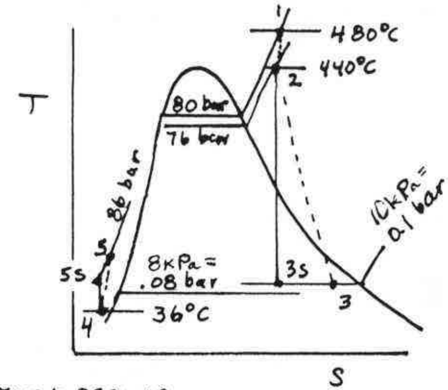
	Problem # in Textbook		Answer
	7th Ed.	8th Ed.	
1	8.22	8.22	a) 816×10^4 kW; b) 32.2%; d) 1963 kg/s
2	8.29	8.29	a) 3913.9 kJ/kg; b) 41.9%; c) 145.7 MW
3	8.34	8.34	a) 265.23 MW; c) 37.7%
4	8.46	8.46	a) 1.498E5 kW; c) 46.5%; d) 22.92 kg/s

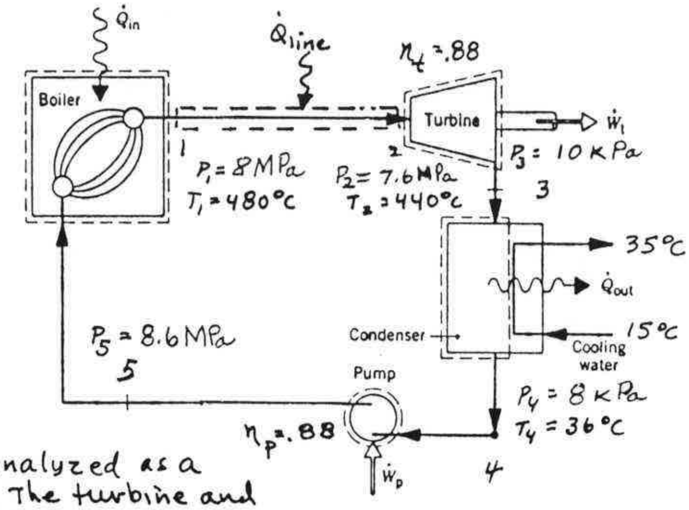
PROBLEM 8.22

KNOWN: Water is the working fluid in a vapor power plant. Data are known at various locations, and the mass flow rate is given.

FIND: Determine (a) the net power output, (b) thermal efficiency, (c) the rate of heat transfer from the line connecting the steam generator and the turbine, and (d) the mass flow rate of condenser cooling water.

SCHEMATIC & GIVEN DATA:





ENGINEERING MODEL: (1) Each component is analyzed as a control volume at steady state. (2) The turbine and pump operate adiabatically (3) Kinetic & potential energy effects are negligible. (4) For the cooling water, assume $h_{cw} \approx h_f(T)$.

ANALYSIS: First, fix each of the principal states.

State 1: $p_1 = 8\,MPa$, $T_1 = 480°C \Rightarrow h_1 = 3348.4\ kJ/kg$, $s_1 = 6.6586\ kJ/kg\cdot K$

State 2: $p_2 = 7.6\,MPa$, $T_2 = 440°C \Rightarrow$ Interpolating in Table A-4;
$h_2 = 3252.3\ kJ/kg$, $s_2 \approx 6.5526\ kJ/kg\cdot K$

State 3: State 3 is fixed using the turbine efficiency. First, at $p_3 = 10\,kPa$, $s_{3s} = s_2 = 6.5526 \Rightarrow x_{3s} = 0.787$; $h_{3s} = 2075.0\ kJ/kg$. Thus

$$\eta_t = \frac{(\dot{W}_t/\dot{m})}{(\dot{W}_t/\dot{m})_s} = \frac{h_2 - h_3}{h_2 - h_{3s}} \Rightarrow h_3 = h_2 - \eta_t(h_2 - h_{3s}) = 2216.3\ kJ/kg$$

Further, with $h_3 = 2216.3\ kJ/kg$; $x_3 = .8461 \Rightarrow s_3 = 6.9958\ kJ/kg\cdot K$

State 4: $p_4 = 8\,kPa$, $T_4 = 36°C \Rightarrow h_4 \approx h_f(T_4) = 150.86\ kJ/kg$

State 5: $h_{5s} \approx h_4 + v_4(p_5 - p_4)$

$$= 150.86 + \left(1.0063\times10^{-3}\ \frac{m^3}{kg}\right)(86 - .08)\ bars\left(\frac{10^5\ N/m^2}{1\ bar}\right)\left(\frac{1\ kJ}{10^3\ N\cdot m}\right)$$

$$= 150.86 + 8.646 = 159.51\ kJ/kg$$

Thus, using the pump efficiency

$$\eta_p = \frac{(\dot{W}_p/\dot{m})_s}{(\dot{W}_p/\dot{m})} = \frac{h_{5s} - h_4}{h_5 - h_4} \Rightarrow h_5 = h_4 + \left(\frac{h_{5s} - h_4}{\eta_p}\right)$$

$$= 150.86 + \left(\frac{159.51 - 150.86}{.88}\right)$$

$$= 160.69\ kJ/kg$$

(a) To determine the net power output, we use energy and mass balances for the control volumes surrounding the turbine and pump to get

$$\dot{W}_{cycle} = \dot{W}_t - \dot{W}_p = \dot{m}\left[(h_2 - h_3) - (h_5 - h_4)\right]$$

Inserting values

$$\dot{W}_{cycle} = \left(79.53\ \frac{kg}{s}\right)\left[(3252.3 - 2216.3) - (160.69 - 150.86)\right]\frac{kJ}{kg}\left|\frac{1\ kW}{1\ kJ/s}\right|$$

$$= 8.161 \times 10^4\ kW \longleftarrow \dot{W}_{cycle}$$

(b) The thermal efficiency is

$$\eta = \frac{\dot{W}_{cycle}}{\dot{Q}_{in}} = \frac{\dot{W}_{cycle}}{\dot{m}(h_1 - h_5)} = \frac{8.161 \times 10^4}{(79.53)(3348.4 - 160.69)\left|\frac{1}{1}\right|}$$

$$= 0.322\ (32.2\%) \longleftarrow \eta$$

(c) For a control volume enclosing the line connecting the steam generator and the turbine

$$0 = \dot{Q}_{line} + \dot{m}(h_1 - h_2)$$

or

$$\dot{Q}_{line} = \dot{m}(h_2 - h_1) = \left(79.53\ \frac{kJ}{kg}\right)(3252.3 - 3348.4)\frac{kJ}{kg}\left|\frac{1\ kW}{1\ kJ/s}\right|$$

$$= -7643\ kW \longleftarrow \dot{Q}_{line}$$

(d) The mass flow rate of cooling water is found from

$$0 = \cancel{\dot{Q}_{cv}}^{\,0} - \cancel{\dot{W}_{cv}}^{\,0} + \dot{m}(h_3 - h_4) + \dot{m}_{cw}(h_{cw,in} - h_{cw,out})$$

or

$$\dot{m}_{cw} = \dot{m}\frac{(h_3 - h_4)}{(h_{cw,out} - h_{cw,in})}$$

From Table A-2, $h_{cw,out} \approx h_f(35°C) = 146.68$ kJ/kg and $h_{cw,in} \approx h_f(15°C) = 62.99$ kJ/kg.
Inserting values

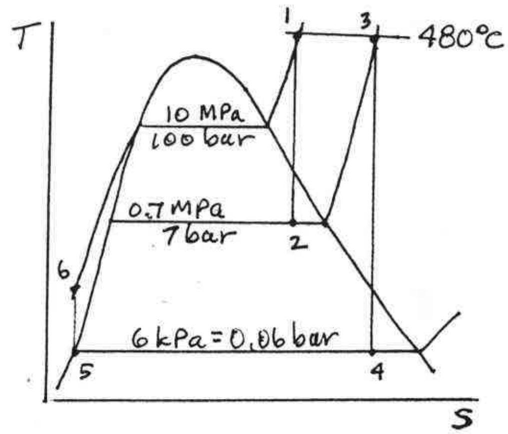
$$\dot{m}_{cw} = \left(79.53\ \frac{kg}{s}\right)\frac{(2216.3 - 150.86)}{(146.68 - 62.99)} = 1963\ kg/s \longleftarrow \dot{m}_{cw}$$

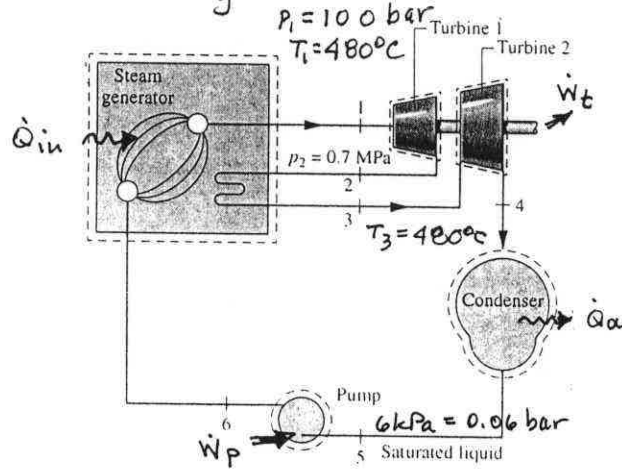
PROBLEM 8.29

KNOWN: Water is the working fluid in an ideal Rankine cycle with reheat. The states at the inlets to both turbine stages and the condenser exit are specified.

FIND: Determine (a) the rate of heat addition per kg of steam flowing, (b) the thermal efficiency, (c) the rate of heat transfer for the condenser per kg of steam condensing.

SCHEMATIC & GIVEN DATA:





ENGINEERING MODEL: See Example 8.3.

ANALYSIS: First, fix all of the principal states.

State 1: $p_1 = 100$ bar, $T_1 = 480°C \Rightarrow h_1 = 3321.4$ kJ/kg, $s_1 = 6.5282$ kJ/kg·K

State 2: $p_2 = 7$ bar, $s_2 = s_1 \Rightarrow x_2 = \dfrac{s_2 - s_{f2}}{s_{g2} - s_{f2}} = 0.9619$, $h_2 = 2684.8$ kJ/kg

State 3: $p_3 = 7$ bar, $T_3 = 480°C \Rightarrow h_3 = 3438.9$ kJ/kg, $s_3 = 7.8723$ kJ/kg·K

State 4: $p_4 = 0.06$ bar, $s_4 = s_3 \Rightarrow x_4 = \dfrac{s_4 - s_{f4}}{s_{g4} - s_{f4}} = 0.9413$, $h_4 = 2425.6 \frac{kJ}{kg}$

State 5: $p_5 = 0.06$ bar, sat. liquid $\Rightarrow h_5 = 151.53$ kJ/kg

State 6:
$$h_6 \approx h_5 + v_5(p_6 - p_5)$$
$$= 151.53 \frac{kJ}{kg} + (1.006 \times 10^{-3}) \frac{m^3}{kg} (100 - 0.06)\,\text{bar} \left| \frac{10^5 N/m^2}{1\ \text{bar}} \right| \left| \frac{1\ kJ}{10^3 N \cdot m} \right|$$
$$= 151.53 + 10.06 = 161.59\ \text{kJ/kg}$$

(a) For the control volume enclosing the steam generator
$$\dot{Q}_{in} = \dot{m}[(h_1 - h_6) + (h_3 - h_2)] \Rightarrow \dot{Q}_{in}/\dot{m} = (h_1 - h_6) + (h_3 - h_2)$$
$$\dot{Q}_{in}/\dot{m} = (3321.4 - 161.59) + (3438.9 - 2684.8)$$
$$= 3913.9\ \text{kJ/kg} \longleftarrow \dot{Q}_{in}/\dot{m}$$

(b) The thermal efficiency is $\eta = \dfrac{\dot{W}_{cycle}/\dot{m}}{\dot{Q}_{in}/\dot{m}}$
$$\dot{W}_{cycle}/\dot{m} = (h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)$$
$$= 636.6 + 1013.3 - 10.06 = 1639.8\ \text{kJ/kg}$$

Thus
$$\eta = \frac{1639.8}{3913.9} = 0.419\ (41.9\%) \longleftarrow \eta$$

PROBLEM 8.29 (Cont'd)

(c) For the condenser

$$\dot{Q}_{out} = \dot{m}(h_4 - h_5) \Rightarrow \frac{\dot{Q}_{out}}{\dot{m}} = h_4 - h_5$$

$$= 2425.6 - 151.53 = 2274.1 \ \frac{kJ}{kg} \longleftarrow \dot{Q}_{out}/\dot{m}$$

Alternatively

$$\dot{Q}_{out}/\dot{m} = \dot{Q}_{in}/\dot{m} - \dot{W}_{cycle}/\dot{m}$$

① $$= 3913.9 - 1639.8 = 2274.1 \ kJ/kg$$

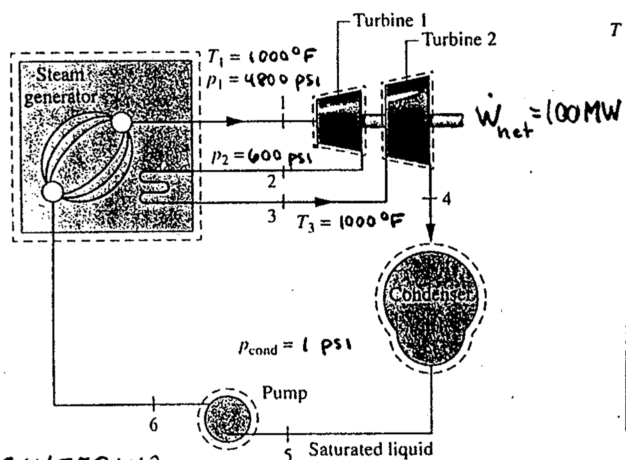
1. The results of this analysis can be compared to the results of Problem 8.2 to see some of the effects of incorporating reheat into the ideal Rankine cycle.

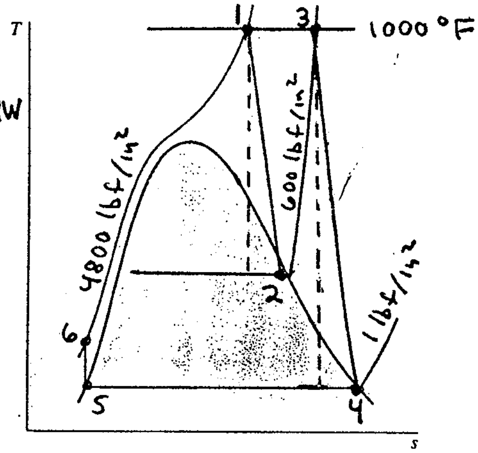
PROBLEM 8.34

KNOWN: Water is the working fluid in an ideal Rankine cycle modified to include two turbine stages with reheat between the stages. The turbine and pump efficiencies are 85 %.

FIND: (a) the rate of heat transfer to the working fluid passing through the steam generator, (b) the rate of heat transfer from the working fluid passing through the condenser, and (c) the cycle efficiency.

SCHEMATIC + GIVEN DATA:





ENGINEERING MODEL: Same as in Example 8.3

ANALYSIS: First, fix each of the principal states.

state 1: $P_1 = 4800\ \text{lbf/in}^2,\ T_1 = 1000°F \Rightarrow h_1 = 1317.4\ \text{Btu/lb},\ s_1 = 1.4078\ \text{Btu/lb°R}$

state 2: $P_2 = 600\ \text{lbf/in}^2,\ s_{2s} = s_1 \Rightarrow x_{2s} = 0.9500,\ h_{2s} = 1167.49\ \text{Btu/lb}$

$$\eta_t = 0.85 = \frac{(h_1 - h_2)}{(h_1 - h_{2s})} \Rightarrow h_2 = 1189.98\ \text{Btu/lb}$$

state 3: $P_3 = 600\ \text{lbf/in}^2,\ T_3 = 1000°F \Rightarrow h_3 = 1517.8\ \text{Btu/lb},\ s_3 = 1.7155\ \text{Btu/lb°R}$

state 4: $P_4 = 1\ \text{lbf/in}^2,\ s_{4s} = s_3 \Rightarrow x_{4s} = 0.8577,\ h_{4s} = 958.32\ \text{Btu/lb}$

$$\eta_t = 0.85 = \frac{(h_3 - h_4)}{(h_3 - h_{4s})} \Rightarrow h_4 = 1042.24\ \text{Btu/lb}$$

state 5: $P_5 = 1\ \text{lbf/in}^2$, sat. liq. $\Rightarrow h_5 = 69.74\ \text{Btu/lb},\ v_5 = 0.01614\ \text{ft}^3/\text{lb}$

state 6: $P_6 = 4800\ \text{lbf/in}^2,\ h_6 \approx h_5 + v_5(P_6 - P_5)/\eta_p$

$$h_6 = 69.74\ \frac{\text{Btu}}{\text{lb}} + \frac{(0.01614)}{0.85}\frac{\text{ft}^3}{\text{lb}}(4800-1)(144)\frac{\text{lbf}}{\text{in}^2}\left|\frac{1\ \text{Btu}}{778\ \text{ft·lbf}}\right| = 69.74 + 16.87 = 86.61\ \frac{\text{Btu}}{\text{lb}}$$

Next, determine the flow rate of the working fluid.

$$\dot W_{net} = \dot W_t - \dot W_p = \dot m[(h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)]$$

$$\dot m = \frac{\dot W_{net}}{(h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)} = \frac{(100\ \text{MW})\left|\frac{1000\ \text{kJ/s}}{1\ \text{MW}}\right|\left|\frac{1\ \text{Btu}}{1.0551\ \text{kJ}}\right|}{[(1317.4 - 1189.98) + (1517.8 - 1042.24) - (86.61 - 69.74)]\ \frac{\text{Btu}}{\text{lb}}}$$

$$= 161.7\ \text{lb/s}$$

(a) The rate of heat transfer to the working fluid in the steam generator is

$$\dot Q_{in} = \dot m(h_1 - h_6 + h_3 - h_2) = (161.7)\frac{\text{lb}}{\text{s}}(1317.4 - 86.61 + 1517.8 - 1189.98)\frac{\text{Btu}}{\text{lb}}$$

$$= 2.52 \times 10^5\ \frac{\text{Btu}}{\text{s}}\left|\frac{1.0551\ \text{kJ}}{1\ \text{Btu}}\right|\left|\frac{1\ \text{MW}}{1000\ \text{kJ/s}}\right| = 265.9\ \text{MW} \leftarrow \dot Q_{in}$$

PROBLEM 8.34 (cont'd)

(b) The rate of heat transfer from the working fluid in the condenser is

$$\dot{Q}_{out} = \dot{m}(h_4 - h_5) = (161.7)(1042.24 - 69.74)\left|\frac{1.0551}{1000}\right|$$

1 $$\dot{Q}_{out} = 165.9 \text{ MW} \longleftarrow \dot{Q}_{out}$$

(c) The cycle thermal efficiency is

$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_{sg}} = \frac{100 \text{ MW}}{265.9 \text{ MW}} = 0.376 \; (37.6\%) \longleftarrow \eta$$

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1. The overall energy balance holds for the cycle:

$$\dot{Q}_{in} = \dot{W}_{net} + \dot{Q}_{out}$$

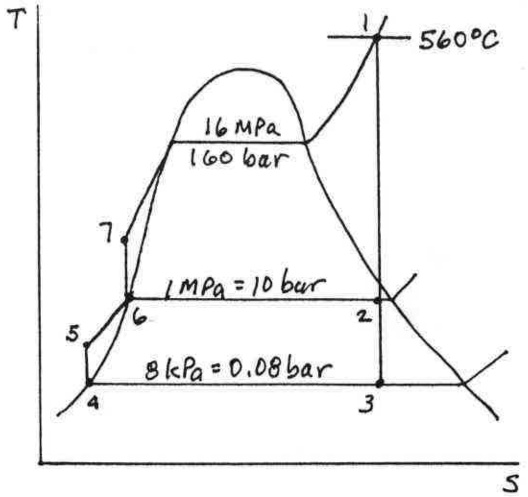
$$265.9 \text{ MW} = 100 \text{ MW} + 165.9 \text{ MW}$$

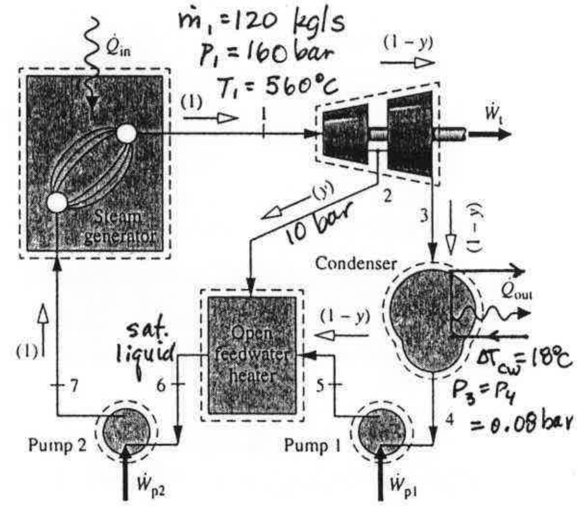
PROBLEM 8.46

KNOWN: Water is the working fluid in an ideal regenerative Rankine cycle with one open feedwater heater. Data at various locations are known. The mass flow rate entering the first-stage turbine is given, and the temperature rise of cooling water passing through the condenser is specified.

FIND: Determine (a) the net power, (b) the rate of heat transfer $\dot{Q}_{in}$, (c) the thermal efficiency, and (d) the mass flow rate of cooling water.

SCHEMATIC & GIVEN DATA:





ENGINEERING MODEL: Same as Example 8.5, except turbine stages and pumps operate in an internally reversible manner.

ANALYSIS: First, fix each principal state.

State 1: $p_1 = 160$ bar, $T_1 = 560°C \Rightarrow h_1 = 3465.4$ kJ/kg, $s_1 = 6.5132$ kJ/kg·K

State 2: $p_2 = 10$ bar, $s_2 = s_1 \Rightarrow x_2 = \dfrac{s_2 - s_{f2}}{s_{g2} - s_{f2}} = 0.9836$, $h_2 = 2745.1$ kJ/kg

State 3: $p_3 = 0.08$ bar, $s_3 = s_2 \Rightarrow x_3 = \dfrac{s_3 - s_{f3}}{s_{g3} - s_{f3}} = 0.7753$, $h_3 = 2037.0$ kJ/kg

State 4: $p_4 = 0.08$ bar, sat. liquid $\Rightarrow h_4 = 173.88$ kJ/kg

State 5: $h_5 \approx h_4 + v_4(p_5 - p_4)$

$$= 173.88 \frac{kJ}{kg} + (1.0084 \times 10^{-3}) \frac{m^3}{kg} (10 - 0.08) \text{ bar} \left| \frac{10^5 \text{ N/m}^2}{1 \text{ bar}} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N·m}} \right|$$

$$= 173.88 + 1.00 = 174.88 \text{ kJ/kg}$$

State 6: $p_6 = 10$ bar, sat. liquid $\Rightarrow h_6 = 762.81$ kJ/kg

State 7: $h_7 \approx h_6 + v_6(p_7 - p_6) = 762.81 + (1.1273 \times 10^{-3})(160 - 10) \left| \dfrac{10^5}{10^3} \right| = 779.72 \dfrac{kJ}{kg}$

(a) For the control volume enclosing the turbine stages

$$\dot{W}_t = \dot{m}_1 [(h_1 - h_2) + (1 - y)(h_2 - h_3)]$$

To get y, apply mass and energy balances the the control volume enclosing the feedwater heater to get

$$y = \frac{h_6 - h_5}{h_2 - h_5} = \frac{762.81 - 174.88}{2745.1 - 174.88} = 0.2287$$

Thus

$$\dot{W}_t = \left(120 \frac{kg}{s}\right) [(3465.4 - 2745.1) + (1 - 0.2287)(2745.1 - 2037.0)] \frac{kJ}{kg} \left| \frac{1 \text{ kW}}{1 \text{ kJ/s}} \right|$$

$$= 1.519 \times 10^5 \text{ kW}$$

PROBLEM 8.46 (Cont'd.)

For the pumps

$$\dot{W}_p = \dot{W}_{p_1} + \dot{W}_{p_2} = \dot{m}_1 \left[(1-y)(h_5 - h_4) + (h_7 - h_6) \right]$$

$$= (120)\left[(1-0.2287)(174.88-173.88)+(779.72-762.81)\right]\left|\frac{1}{1}\right|$$

$$= 2122 \text{ kW}$$

Thus, the net power developed is

$$\dot{W}_{cycle} = \dot{W}_t - \dot{W}_p = 1.498 \times 10^5 \text{ kW}$$ $\dot{W}_{cycle}$

(b) For the steam generator

$$\dot{Q}_{in} = \dot{m}_1 (h_1 - h_7) = (120)(3465.4 - 779.72)\left|\frac{1}{1}\right| = 3.223 \times 10^5 \text{ kW}$$ $\dot{Q}_{in}$

(c) The thermal efficiency is $\eta = \dot{W}_{cycle}/\dot{Q}_{in} = 0.465$ (46.5%) η

(d) The rate of heat transfer from the working fluid to the cooling water passing through the condenser is

$$\dot{Q}_{out} = \dot{m}_1 (1-y)(h_3 - h_4) = (120)(1-0.2287)(2037.0 - 173.88)\left|\frac{1}{1}\right| = 1.724 \times 10^5 \text{ kW}$$

Thus, the mass flow rate of cooling water is

$$\dot{Q}_{out} = \dot{m}_{cw}(h_{out,cw} - h_{in,cw})$$

Assuming $h_{out,cw} - h_{in,cw} = c_{cw} \Delta T_{cw}$, and using $c_{cw} = 4.179 \frac{\text{kJ}}{\text{kg K}}$, we get

$$\dot{m}_{cw} = \frac{\dot{Q}_{out}}{c_{cw} \Delta T_{cw}} = \frac{1.724 \times 10^5 \text{ kW}}{(4.179)(18) \frac{\text{kJ}}{\text{kg}}} \left| \frac{1 \text{ kJ/s}}{1 \text{ kW}} \right| = 2292 \frac{\text{kg}}{\text{s}}$$ $\dot{m}_{cw}$