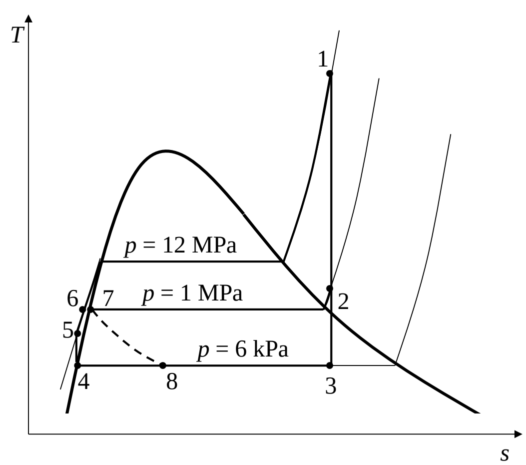
8.52 As indicated in Fig. P8.52, a power plant similar to that in Fig. 8.11 operates on a regenerative vapor power cycle with one closed feedwater heater. Steam enters the first turbine stage at state 1 where pressure is 12 MPa and temperature is 560°C. Steam expands to state 2 where pressure is 1 MPa and some of the steam is extracted and diverted to the closed feedwater heater. Condensate exits the feedwater heater at state 7 as saturated liquid at a pressure of 1 MPa, undergoes a throttling process through a trap to a pressure of 6 kPa at state 8, and then enters the condenser. The remaining steam expands through the second turbine stage to a pressure of 6 kPa at state 3 and then enters the condenser. Saturated liquid feedwater exiting the condenser at state 4 at a pressure of 6 kPa enters a pump and exits the pump at a pressure of 12 MPa. The feedwater then flows through the closed feedwater heater, exiting at state 6 with a pressure of 12 MPa. The net power output for the cycle is 330 MW. For isentropic processes in each turbine stage and the pump, determine
(a) the cycle thermal efficiency.
(b) the mass flow rate into the first turbine stage, in kg/s.
(c) the rate of entropy production in the closed feedwater heater, in kW/K.
(d) the rate of entropy production in the steam trap, in kW/K.

KNOWN: A regenerative vapor power cycle with one closed feedwater heater operates with steam as the working fluid. Operational data are provided.

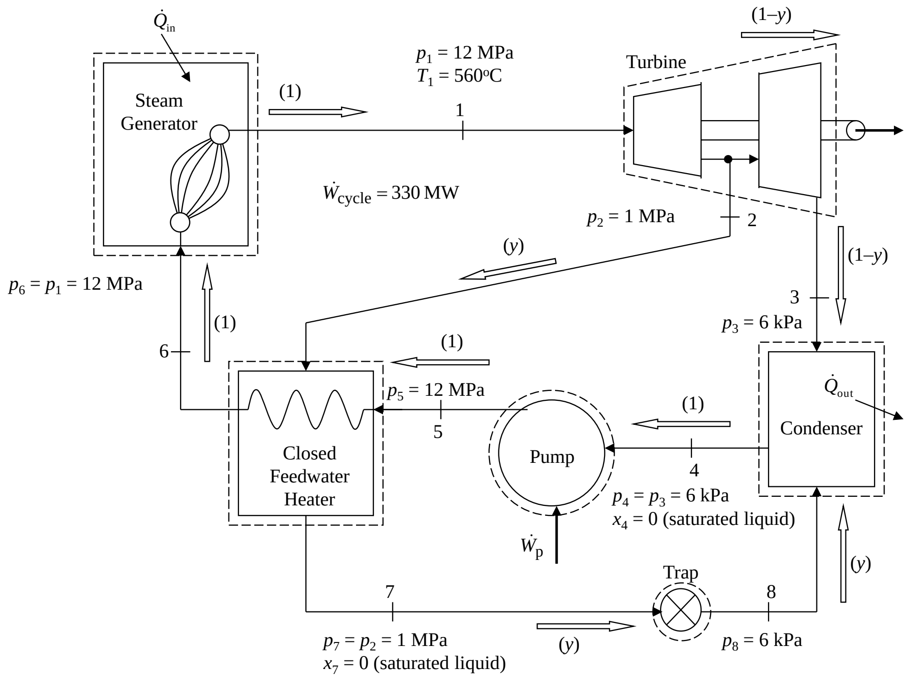
FIND: Determine (a) the cycle thermal efficiency, (b) the mass flow rate into the first turbine stage, in kg/s, (c) the rate of entropy production in the closed feedwater heater, in kW/K, and (d) the rate of entropy production in the steam trap, in kW/K.

SCHEMATIC AND GIVEN DATA:



State	p (kPa)	T (°C)	h (kJ/kg)	s (kJ/kg·K)	x
1	12,000	560	3506.2	6.6840	
2	1,000		2823.3	6.6840	
3	6		2058.2	6.6840	0.7892
4	6		151.53	0.5210	0
5	12,000		163.60	0.5210	
6	12,000		606.61	1.7808	
7	1,000		762.81	2.1387	0
8	6		762.81	2.4968	0.2530

P8.52



ENGINEERING MODEL:

1. Each component of the cycle is analyzed as a control volume at steady state. The control volumes are shown on the accompanying sketch by dashed lines.
2. All processes of the working fluid are internally reversible except for heat transfer through a finite temperature difference in the closed feedwater heater and throttling through the trap.
3. The turbines, pump, closed feedwater heater, and steam trap operate adiabatically.
4. Kinetic and potential energy effects are negligible.
5. Saturated liquid exits the closed feedwater heater, and saturated liquid exits the condenser.

ANALYSIS:

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

$$y = \frac{h_6 - h_5}{h_2 - h_7} = \frac{(606.61 - 163.60)\text{ kJ/kg}}{(2823.3 - 762.81)\text{ kJ/kg}} = 0.2150$$

For the control volume surrounding the turbine stages

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

$$\frac{\dot{W}_t}{\dot{m}_1} = (3506.2 - 2823.3)\frac{\text{kJ}}{\text{kg}} + (1 - 0.2150)(2823.3 - 2058.2)\frac{\text{kJ}}{\text{kg}} = 1283.5\text{ kJ/kg}$$

For the pump

$$\frac{\dot{W}_{\text{p}}}{\dot{m}_1} = (h_5 - h_4)$$

$$\frac{\dot{W}_{\text{p}}}{\dot{m}_1} = (163.60 - 151.53)\frac{\text{kJ}}{\text{kg}} = 12.07 \text{ kJ/kg}$$

For the working fluid passing through the steam generator

$$\frac{\dot{Q}_{\text{in}}}{\dot{m}_1} = h_1 - h_6 = (3506.2 - 606.61)\frac{\text{kJ}}{\text{kg}} = 2899.6 \text{ kJ/kg}$$

Thus, the thermal efficiency is

$$\eta = \frac{\dot{W}_{\text{t}}/\dot{m}_1 - \dot{W}_{\text{p}}/\dot{m}_1}{\dot{Q}_{\text{in}}/\dot{m}_1} = \frac{(1283.5 - 12.07)\text{ kJ/kg}}{2899.6\text{ kJ/kg}} = \underline{\mathbf{0.438\ (43.8\%)}}$$

(b) The ***net*** power developed is

$$\dot{W}_{\text{cycle}} = \dot{m}_1(\dot{W}_{\text{t}}/\dot{m}_1 - \dot{W}_{\text{p}}/\dot{m}_1)$$

Thus,

$$\dot{m}_1 = \frac{\dot{W}_{\text{cycle}}}{(\dot{W}_{\text{t}}/\dot{m}_1 - \dot{W}_{\text{p}}/\dot{m}_1)}$$

$$\dot{m}_1 = \frac{330\text{ MW}}{(1283.5 - 12.07)\frac{\text{kJ}}{\text{kg}}}\left|\frac{1000\frac{\text{kJ}}{\text{s}}}{1\text{ MW}}\right| = \underline{\mathbf{259.6\ kg/s}}$$

(c) The rate of entropy production in the closed feedwater heater is determined using the steady-state form of the entropy rate balance:

$$0 = \cancel{\sum_j \frac{\dot{Q}_j}{T_j}} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{\sigma}_{\text{cv}}$$

Since the feedwater heater is adiabatic, the heat transfer term drops. Thus,

$$\dot{\sigma}_{cv} = \sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i = \dot{m}_6 s_6 + \dot{m}_7 s_7 - \dot{m}_5 s_5 - \dot{m}_2 s_2$$

$$\dot{\sigma}_{cv} = \dot{m}_1[s_6 - s_5 + y(s_7 - s_2)]$$

$$\dot{\sigma}_{cv} = 259.6\frac{\text{kg}}{\text{s}}[1.7808 - 0.5210 + (0.2150)(2.1387 - 6.6840)]\frac{\text{kJ}}{\text{kg}\cdot\text{K}}\left|\frac{1\,\text{kW}}{1\,\text{kJ/s}}\right| = \mathbf{73.35\ kW/K}$$

Heat transfer between a finite temperature difference within the closed feedwater heater is a source of irreversibility that produces entropy.

(d) The rate of entropy production in the steam trap is determined using the one-inlet, one-exit, steady-state form of the entropy rate balance:

$$0 = \cancel{\sum_j \frac{\dot{Q}_j}{T_j}} + \dot{m}(s_i - s_e) + \dot{\sigma}_{cv}$$

where $\dot{m}$ is the mass flow rate through the steam trap.

Since the steam trap is adiabatic, the heat transfer term drops. Thus,

$$\dot{\sigma}_{cv} = \dot{m}(s_e - s_i) = \dot{m}_7(s_8 - s_7) = y\dot{m}_1(s_8 - s_7)$$

$$\dot{\sigma}_{cv} = (0.2150)\left(259.6\frac{\text{kg}}{\text{s}}\right)(2.4968 - 2.1387)]\frac{\text{kJ}}{\text{kg}\cdot\text{K}}\left|\frac{1\,\text{kW}}{1\,\text{kJ/s}}\right| = \mathbf{19.99\ kW/K}$$

The throttling process in the steam trap is a source of irreversibility that produces entropy.