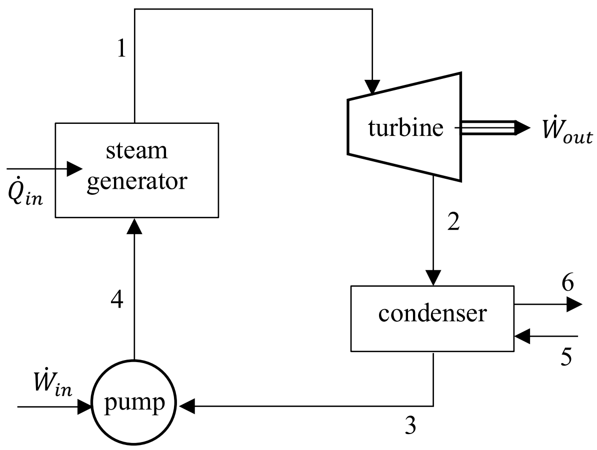
The figure below shows a simple vapor power plant operating at steady state with water as the working fluid. Data at key locations are given in the table. Stray heat transfer and kinetic and potential energy effects may be neglected. The mass flow rate through the system is 109 kg/s.



State	*p* [bar (abs)]	*T* [ºC]	*x* [-]
1	100	520	
2	0.08		0.90
3	0.08		0
4	100	43	
5	1	20	
6	1	35	

Determine:
a. the net power developed by the system,
b. the thermal efficiency of this power cycle,
c. the isentropic turbine efficiency,
d. the isentropic pump efficiency,
e. the mass flow rate of the cooling water in the condenser, and
f. the rates of entropy production for turbine, condenser, and pump.

SOLUTION:
First determine the specific enthalpy and specific entropy at all of the states using the property tables for water and the compressed liquid approximations.

State	***p* [bar (abs)]**	***T* [ºC]**	***x* [-]**	**phase**	***h* [kJ/kg]**	***s* [kJ/(kg.K)]**
1	100	520	N/A	SHV	3426.4	6.665
2	0.08	41.51	0.90	SLVM*	2335.96	7.46382
3	0.08	41.51	0	sat. liquid	173.08	0.59249
4	100	43	N/A	CL+	190.152	0.612250
5	1	20	N/A	CL+	86.199	0.296480
6	1	35	N/A	CL+	146.725	0.505130

* Calculation of specific enthalpy and specific entropy for an SLVM,

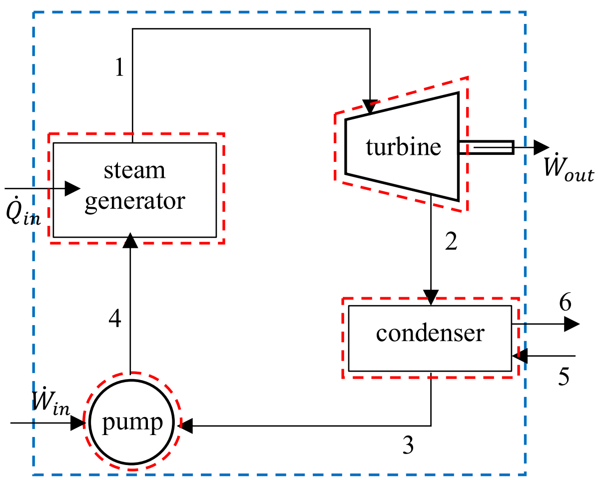
$$h_2 = (1 - x_2)h_{f2} + x_2 h_{g2} \quad \text{and} \quad s_2 = (1 - x_2)s_{f2} + x_2 s_{g2} \tag{1}$$

where h_{f2} = 173.84 kJ/kg, h_{g2} = 2576.2 kJ/kg; s_{f2} = 0.59249 kJ/(kg.K), s_{g2} = 8.2273 kJ/(kg.K)

\+ Calculation of specific enthalpy and specific entropy for a compressed liquid,

$$h_{CL}(p,T) \approx h_f(T) + [p - p_{sat}(T)]v_f(T) \quad \text{and} \quad s_{CL}(p,T) \approx s_f(T) \tag{2}$$

T_4 = 43 ºC, $p_{sat@43ºC}$ = 0.086508 bar (abs); h_{f4} = 180.07 kJ/kg, v_{f4} = 0.0010091 m^3/kg; s_{f4} = 0.612250 kJ/(kg.K)
T_5 = 20 ºC, $p_{sat@20ºC}$ = 0.023393 bar (abs); h_{f5} = 83.914 kJ/kg, v_{f5} = 0.023393 m^3/kg; s_{f5} = 0.296480 kJ/(kg.K)
T_6 = 20 ºC, $p_{sat@35ºC}$ = 0.056290 bar (abs); h_{f6} = 146.63 kJ/kg, v_{f6} = 0.0010060 m^3/kg; s_{f6} = 0.505130 kJ/(kg.K)



Apply the 1st Law to a CV surrounding the turbine,

$$\frac{dE_{CV}}{dt} = \sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) + \dot{Q}_{in} - \dot{W}_{out}, \quad (3)$$

where,

$$\frac{dE_{CV}}{dt} = 0 \quad \text{(assuming steady state operation)}, \quad (4)$$

$$\sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) = \dot{m}(h_1 - h_2), \quad (5)$$

(neglecting kinetic and potential energy changes; from COM $\dot{m}_1 = \dot{m}_2 = \dot{m}$)

$$\dot{Q}_{in} = 0 \quad \text{(assuming adiabatic operation)}, \quad (6)$$

$$\dot{W}_{out} = ?. \quad (7)$$

Substitute and solve for the power,

$$\dot{W}_{out} = \dot{m}(h_1 - h_2). \quad (8)$$

Using the data from the table and the given mass flow rate,

$$\dot{W}_{out} = 118.86 \text{ MW}.$$

Applying the 1st Law to a CV surrounding the pump,

$$\frac{dE_{CV}}{dt} = \sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) + \dot{Q}_{in} + \dot{W}_{in}, \quad (9)$$

where,

$$\frac{dE_{CV}}{dt} = 0 \quad \text{(assuming steady state operation)}, \quad (10)$$

$$\sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) = \dot{m}(h_3 - h_4), \quad (11)$$

(neglecting kinetic and potential energy changes; from COM $\dot{m}_3 = \dot{m}_4 = \dot{m}$)

$$\dot{Q}_{in} = 0 \quad \text{(assuming adiabatic operation)}, \quad (12)$$

$$\dot{W}_{in} = ?. \quad (13)$$

Substitute and solve for the power,

$$\dot{W}_{in} = \dot{m}(h_4 - h_3). \quad (14)$$

Using the data from the table and the given mass flow rate,

$$\dot{W}_{in} = 1.86 \text{ MW}.$$

Using the power in and power out results,

$$\boxed{\dot{W}_{out,net} = \dot{W}_{out} - \dot{W}_{in} = 117.00 \text{ MW}} \quad (15)$$

To determine the thermal efficiency for the power cycle, we need to first calculate the rate of heat addition into the steam generator. This value may be found by apply in the 1st Law to a CV surrounding the steam generator,

$$\frac{dE_{CV}}{dt} = \sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) + \dot{Q}_{in} - \dot{W}_{out}, \quad (16)$$

where,

$$\frac{dE_{CV}}{dt} = 0 \quad \text{(assuming steady state operation)}, \quad (17)$$

$$\sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) = \dot{m}(h_4 - h_1), \quad (18)$$

(neglecting kinetic and potential energy changes; from COM $\dot{m}_1 = \dot{m}_4 = \dot{m}$)

$$\dot{Q}_{in} = ?, \quad (19)$$

$$\dot{W}_{out} = 0 \quad \text{(the steam generator is a passive device)}. \quad (20)$$

Substitute and solve for the rate of heat transfer,

$$\dot{Q}_{in} = \dot{m}(h_1 - h_4). \quad (21)$$

Using the data from the table and the given mass flow rate,

$$\dot{Q}_{in} = 352.75 \text{ MW}.$$

The thermal efficiency for the power cycle is,

$$\boxed{\eta = \frac{\dot{W}_{out,net}}{\dot{Q}_{in}} = 0.332 = 33.2\%} \quad (22)$$

The isentropic efficiency of the turbine is,

$$\eta_{turbine,isen.} = \frac{\dot{W}_{out}}{\dot{W}_{out,isen}} = \frac{h_1 - h_2}{h_1 - h_{2s}}, \tag{23}$$

where, for the isentropic case, p_{2s} = 0.08 bar (abs) and $s_{2s} = s_1$ = 6.665 kJ/(kg.K). Using the property tables for water,

$$x_{2s} = \frac{s_{2s} - s_{f2}}{s_{g2} - s_{f2}} = 0.79537, \tag{24}$$

where s_{f2s} = 0.59249 kJ/(kg.K) and s_{g2s} = 8.2273 kJ/(kg.K). Using this quality,

$$h_{2s} = (1 - x_{2s})h_{f2s} + x_{2s}h_{g2s} = 2084.61 \text{ kJ/kg}, \tag{25}$$

where h_{f2s} = 173.84 kJ/kg and h_{g2s} = 2576.2 kJ/kg. Substituting this value and the values from the table back into Eq. (23),

$$\boxed{\eta_{turbine,isen.} = 0.813 = 81.3\%}.$$

Similarly, the isentropic efficiency for the pump is,

$$\eta_{pump,isen.} = \frac{\dot{W}_{in,isen}}{\dot{W}_{in}} = \frac{h_{4s} - h_3}{h_4 - h_3}, \tag{26}$$

where, for the isentropic case, p_{4s} = 100 bar (abs) and $s_{4s} = s_3$ = 0.59249 kJ/(kg.K). Using the property tables for water we note that at p_{4s} = 100 bar, s_{4f} = 3.3606 kJ/(kg.K) > s_{4s} = 0.59249 kJ/(kg.K). Thus, state 4*s* must be a compressed liquid. The temperature, saturation pressure, and saturated liquid specific enthalpy from the SLVM table for this specific entropy are,

T_{4s} = 41.51 ºC, $p_{sat@T4s}$ = 0.08 bar (abs), v_f = 0.0010085 m^3/kg, and h_{f4s} = 173.84 kJ/kg.

Thus,

$$h_{4s} \approx h_f(T_{4s}) + [p_{4s} - p_{sat}(T_{4s})]v_f(T_{4s}) = 183.92 \text{ kJ/kg}. \tag{27}$$

Substituting this values and the values from the table back into Eq. (63),

$$\boxed{\eta_{pump,isen.} = 0.635 = 63.5\%}.$$

To find the mass flow rate of the cooling water, apply the 1st Law to a CV surrounding the condenser,

$$\frac{dE_{CV}}{dt} = \sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) + \dot{Q}_{in} - \dot{W}_{out}, \tag{28}$$

where,

$$\frac{dE_{CV}}{dt} = 0 \quad \text{(assuming steady state operation)}, \tag{29}$$

$$\sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) = (\dot{m}h_2 + \dot{m}_{CW}h_5) - (\dot{m}h_3 + \dot{m}_{CW}h_6), \tag{30}$$

(neglecting kinetic and potential energy changes; from COM $\dot{m}_1 = \dot{m}_2 = \dot{m}, \dot{m}_5 = \dot{m}_6 = \dot{m}_{CW}$)

$$\dot{Q}_{in} = 0 \quad \text{(assuming adiabatic operation)}, \tag{31}$$

$$\dot{W}_{out} = 0 \quad \text{(the condenser is a passive device)}. \tag{32}$$

Substitute and solve for the cooling water mass flow rate,

$$0 = (\dot{m}h_2 + \dot{m}_{CW}h_5) - (\dot{m}h_3 + \dot{m}_{CW}h_6), \tag{33}$$

$$\dot{m}_{CW}(h_6 - h_5) = \dot{m}(h_2 - h_3), \tag{34}$$

$$\dot{m}_{CW} = \dot{m}\left(\frac{h_2 - h_3}{h_6 - h_5}\right). \tag{35}$$

Using the data from the table and the given mass flow rate of the cycle,

$$\boxed{\dot{m}_{CW} = 3900 \text{ kg/s}}.$$

The rates of entropy production for the turbine, pump, and condenser are found by applying the Entropy Equation to each component's control volume. For the turbine,

$\frac{dS_{CV}}{dt} = \sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \int_b \frac{\delta \dot{Q}_{in}}{T} + \dot{\sigma},$ (36)

where,

$\frac{dS_{CV}}{dt} = 0$ (assuming steady state operation), (37)

$\sum_{in} \dot{m}s - \sum_{out} \dot{m}s = \dot{m}(s_1 - s_2),$ (38)

$\int_b \frac{\delta \dot{Q}_{in}}{T} = 0$ (assuming adiabatic operation), (39)

$\dot{\sigma}_{turbine} = ?,$ (40)

Substitute and re-arrange to solve for the rate of entropy generation,

$0 = \dot{m}(s_1 - s_2) + \dot{\sigma}_{turbine},$ (41)

$\dot{\sigma}_{turbine} = \dot{m}(s_2 - s_1).$

Using the values listed in the table,

$\boxed{\dot{\sigma}_{turbine} = 87.071 \text{ kW/K}}.$

For the pump,

$\frac{dS_{CV}}{dt} = \sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \int_b \frac{\delta \dot{Q}_{in}}{T} + \dot{\sigma},$ (36)

where,

$\frac{dS_{CV}}{dt} = 0$ (assuming steady state operation), (37)

$\sum_{in} \dot{m}s - \sum_{out} \dot{m}s = \dot{m}(s_3 - s_4),$ (38)

$\int_b \frac{\delta \dot{Q}_{in}}{T} = 0$ (assuming adiabatic operation), (39)

$\dot{\sigma}_{pump} = ?,$ (40)

Substitute and re-arrange to solve for the rate of entropy generation,

$0 = \dot{m}(s_3 - s_4) + \dot{\sigma}_{pump},$ (41)

$\dot{\sigma}_{pump} = \dot{m}(s_4 - s_3).$

Using the values listed in the table,

$\boxed{\dot{\sigma}_{pump} = 2.1538 \text{ kW/K}}.$

For the condenser,

$\frac{dS_{CV}}{dt} = \sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \int_b \frac{\delta \dot{Q}_{in}}{T} + \dot{\sigma},$ (42)

where,

$\frac{dS_{CV}}{dt} = 0$ (assuming steady state operation), (43)

$\sum_{in} \dot{m}s - \sum_{out} \dot{m}s = (\dot{m}s_2 + \dot{m}_{CW}s_5) - (\dot{m}s_3 + \dot{m}_{CW}s_6),$ (44)

$\int_b \frac{\delta \dot{Q}_{in}}{T} = 0$ (assuming adiabatic operation), (39)

$\dot{\sigma}_{condenser} = ?,$ (40)

Substitute and re-arrange to solve for the rate of entropy generation,

$0 = (\dot{m}s_2 + \dot{m}_{CW}s_5) - (\dot{m}s_3 + \dot{m}_{CW}s_6) + \dot{\sigma}_{condenser},$ (41)

$\dot{\sigma}_{condenser} = \dot{m}(s_3 - s_2) + \dot{m}_{CW}(s_6 - s_5).$

Using the values listed in the table,

$\boxed{\dot{\sigma}_{condenser} = 63.735 \text{ kW/K}}.$