(a) False

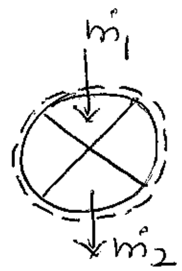
(b) False

(c) True

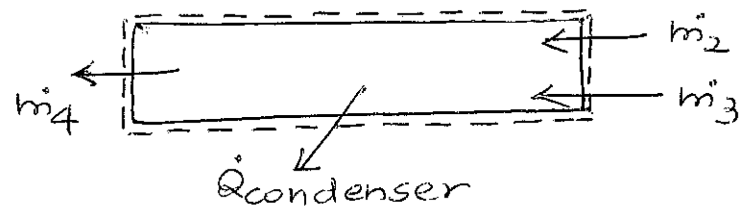
(d) $\Delta s < 0$

(e) Entropy generation of a reversible power cycle is zero

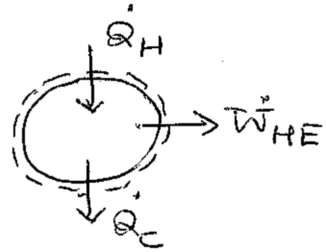
System



Flow of steam through the throttling valve is the system (a),(b)



Flow of water substance through the condenser is the system (c)



Power cycle is the system (d)

Assumptions

- Open system
- Steady state, steady flow
- 1-D, uniform flow
- Ignore change in KE and PE
- Throttling valve: $\dot{Q} = 0$, $\dot{W} = 0$
- Condenser: $\dot{W} = 0$

Basic Equations

$$\cancel{\left.\frac{dm}{dt}\right|_{system}}^{\,0} = \sum_{in} \dot{m}_{in} - \sum_{out} \dot{m}_{out}$$

$$\cancel{\left.\frac{dE}{dt}\right|_{system}}^{\,0} = \sum_{in} \dot{m}_{in}(h + ke + pe)_{in} - \sum_{out} \dot{m}_{out}(h + ke + pe)_{out} + \dot{Q} - \dot{W}$$

$$\cancel{\left.\frac{dS}{dt}\right|_{system}}^{\,0} = \sum_{in} \dot{m}_{in} s_{in} - \sum_{out} \dot{m}_{out} s_{out} + \sum_j \frac{\dot{Q}_j}{T_{j,boundary}} + \dot{\sigma}_{generation}$$

Solution

(a) Throttling valve:

Mass balance: $0 = \dot{m}_1 - \dot{m}_2 \Rightarrow \dot{m}_1 = \dot{m}_2 = 5 \frac{kg}{s}$

Energy balance: $0 = \dot{m}_1 h_1 - \dot{m}_2 h_2 + 0 - 0 \Rightarrow h_1 = h_2$

State 2 $\boxed{h_2 = 3278.4 \frac{kJ}{kg}}$

$P_2 = 10$ bar, $h_2 = 3278.4 \frac{kJ}{kg}$

$h_2 > h_g(P_2) \Rightarrow$ superheated vapor

$\boxed{T_2 \cong 400°C}$ $\boxed{s_2 \cong 7.4669 \frac{kJ}{kg-K}}$

(b) Throttling valve

Entropy balance: $0 = \dot{m}_1 s_1 - \dot{m}_2 s_2 + 0 + \dot{\sigma}_{throttle}$

Rate of entropy generation for throttling valve:

$$\dot{\sigma}_{throttle} = (\dot{m}_1 = \dot{m}_2)(s_2 - s_1) = 5 \frac{kg}{s} * (7.4669 - 6.6878) \frac{kJ}{kg-K}$$

$$\boxed{\dot{\sigma}_{throttle} = +3.9 \frac{kW}{K}}$$

(c) Condenser

Mass balance: $0 = (\dot{m}_2 + \dot{m}_3) - \dot{m}_4 \Rightarrow \dot{m}_4 = \dot{m}_2 + \dot{m}_3 = 20 \frac{kg}{s}$

Energy balance: $0 = (\dot{m}_2 h_2 + \dot{m}_3 h_3) - \dot{m}_4 h_4 + \dot{Q}_{condenser} - \dot{W}^{\,0}$

$$\dot{Q}_{condenser} = \dot{m}_4 h_4 - \dot{m}_2 h_2 - \dot{m}_3 h_3$$

$$= 20 \frac{kg}{s} * 762.52 \frac{kJ}{kg} - 5 \frac{kg}{s} * 3278.4 \frac{kJ}{kg} - 15 \frac{kg}{s} * 3094.4 \frac{kJ}{kg}$$

$$\dot{Q}_{condenser} = -47{,}557.6 \text{ kW}$$

Entropy balance: $0 = (\dot{m}_2 s_2 + \dot{m}_3 s_3) - \dot{m}_4 s_4 + \frac{\dot{Q}_{condenser}}{T_{boundary}} + \dot{\sigma}_{condenser}$

Rate of entropy generation for condenser:

$$\dot{\sigma}_{condenser} = \dot{m}_4 s_4 - \dot{m}_2 s_2 - \dot{m}_3 s_3 - \frac{\dot{Q}_{condenser}}{T_{boundary}}$$

$$= 20 \frac{kg}{s} * 2.1381 \frac{kJ}{kg-K} - 5 \frac{kg}{s} * 7.4669 \frac{kJ}{kg-K} - 15 \frac{kg}{s} * 7.1979 \frac{kJ}{kg-K} - \frac{-47{,}557.6 \text{ kW}}{(27+273) \text{ K}}$$

$$\boxed{\dot{\sigma}_{condenser} = +56 \frac{kW}{K}}$$

(d) Actual thermal efficiency of the power cycle:

$$\eta_{th} = 25\%$$

Maximum thermal efficiency of the power cycle for a reversible system:

$$\eta_{th,rev} = 1 - \frac{T_{C,HE}}{T_{H,HE}} = 1 - \frac{(0+273)K}{(27+273)K} = 0.09 \text{ or } 9\%$$

$\eta_{th} > \eta_{th,rev.} \Rightarrow$ $\boxed{\text{power cycle (heat engine) is impossible}}$

Alternatively

$$\eta_{th} = \left|\frac{\dot{W}_{net}}{\dot{Q}_{in}}\right| = \frac{\dot{W}_{HE}}{|\dot{Q}_{condenser}|} \Rightarrow \dot{W}_{HE} = 11,889.4 \text{ kW}$$

$$\dot{Q}_H = 47,557.6 \text{ kW}$$

Energy balance: $\dot{Q}_H - |\dot{Q}_c| = \dot{W}_{HE}$

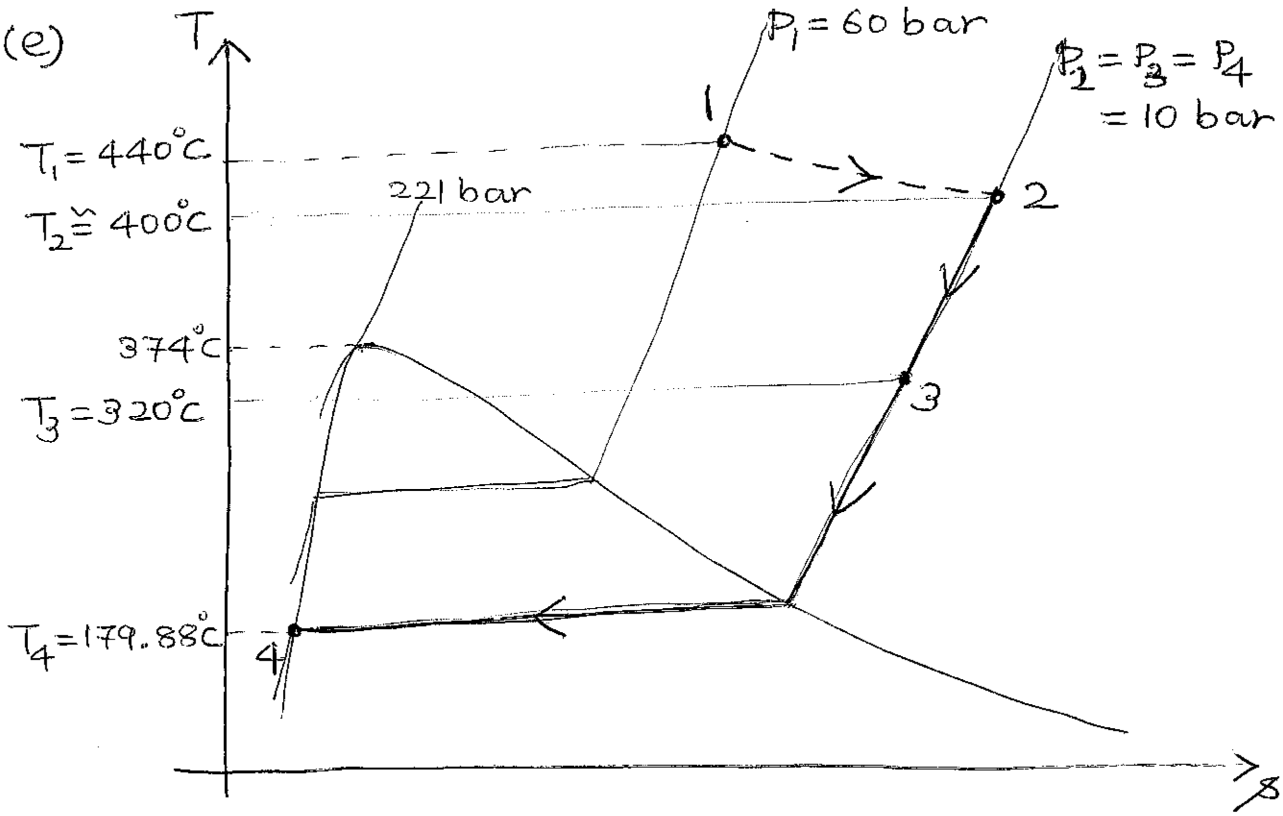
$\Rightarrow |\dot{Q}_c| = 35,668.2 \text{ kW}$ or $\dot{Q}_c = -35,668.2 \text{ kW}$

Entropy balance: $\dot{\sigma}_{HE} = -\sum_j \frac{\dot{Q}_j}{T_{j,boundary}}$

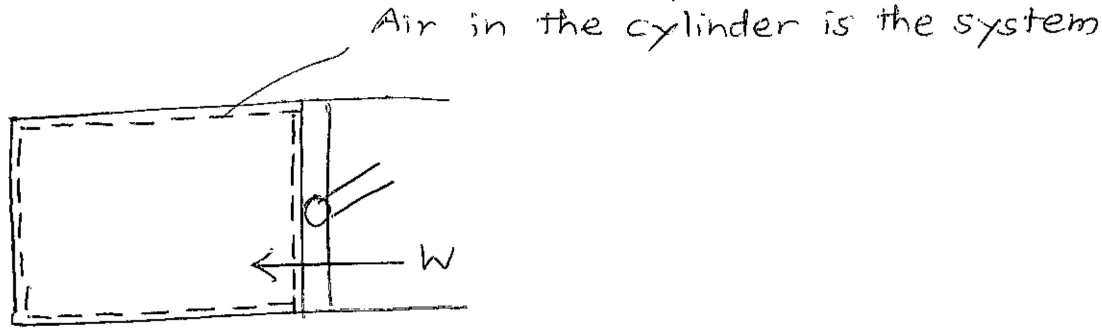
$$\dot{\sigma}_{HE} = -\left(\frac{\dot{Q}_H}{T_H} + \frac{\dot{Q}_c}{T_c}\right) = -\left(\frac{47,557.6 \text{ kW}}{300 \text{ K}} + \frac{-35,668.2 \text{ kW}}{273 \text{ K}}\right)$$

$\dot{\sigma}_{HE} = -27.9 \frac{\text{kW}}{\text{K}} \Rightarrow \dot{\sigma}_{HE} < 0 \Rightarrow$ power cycle (heat engine) is impossible

(e)



System



Assumptions
- Closed system (m = constant)
- Quasi-equilibrium process
- Ignore change in KE and PE
- Air behaves as an ideal gas

Basic Equations

$$\cancel{Q}^{0} - \underbrace{W}_{(W_{boundary} + \cancel{W_{other}}^{0})} = \Delta E = \Delta U + \cancel{\Delta KE}^{\text{no}} + \cancel{\Delta PE}^{\text{no}}$$

$$\cancel{\frac{Q}{T_b}}^{0} + \sigma = \Delta S$$

Solution

(a) Considering energy balance, work during the process: $-W_{12} = (U_2 - U_1) = (m_1 = m_2)(u_2 - u_1)$

Actual specific work during the process:

$$w_{act} = w_{12} = \frac{W_{12}}{m} = u_1 - u_2$$

$$u_1 = u_{air}(T_1) = 214.1\ \frac{kJ}{kg}$$

$$u_2 = u_{air}(T_2) = 396.9\ \frac{kJ}{kg}$$

$$\boxed{w_{act.} = -182.8\ \frac{kJ}{kg}}$$ $w < 0$ work done on air

(b) Considering entropy balance, entropy generation during the process: $\sigma_{12} = (S_2 - S_1) = (m_1 = m_2)(s_2 - s_1)$

Specific entropy generation during the process:

$$\sigma_{12} = \frac{\sigma_{12}}{m} = s_2 - s_1 = s_2^{\circ} - s_1^{\circ} - R_{air} \ln \frac{P_2}{P_1}$$

$$R_{air} = \frac{\bar{R}}{M_{air}} = \frac{8.314\ \frac{kJ}{kmol-K}}{28.97\ \frac{kg}{kmol}} = 0.287\ \frac{kJ}{kg-K}$$

$s_1^o = s_{air}^o(T_1) = 1.703 \frac{kJ}{kg-K}$

$s_2^o = s_{air}^o(T_2) = 2.319 \frac{kJ}{kg-K}$

$\sigma_{12} = \left(2.319 - 1.703 - 0.287 \ln \frac{7\ bar}{1\ bar}\right) \frac{kJ}{kg-K}$

$\boxed{\sigma_{12} = +0.0575 \frac{kJ}{kg-K}}$

(c) Isentropic efficiency of compression process:

$$\eta_{comp.} = \frac{w_s}{w_{act.}} = \frac{u_1 - u_{2s}}{u_1 - u_2}$$

State 2s $\quad P_{2s} = 7\ bar,\ s_{2s} = s_1 \Rightarrow s_{2s} - s_1 = 0$

$$s_{2s}^o - s_1^o - R_{air} \ln \frac{P_{2s}}{P_1} = 0$$

$$s_{2s}^o = s_1^o + R_{air} \ln \frac{P_{2s}}{P_1} = \left(1.703 + 0.287 \ln \frac{7\ bar}{1\ bar}\right) \frac{kJ}{kg-K}$$

$$s_{2s}^o = 2.262 \frac{kJ}{kg-K} \Rightarrow T_{2s} \cong 520\ K,\ u_{2s} \cong 374.4 \frac{kJ}{kg}$$

Alternatively

$$\frac{Pr_{2s}}{Pr_1} = \frac{P_{2s}}{P_1} \Rightarrow Pr_{2s} = 1.386 * \frac{7\ bar}{1\ bar} = 9.702$$

$$\Rightarrow T_{2s} \cong 520\ K,\ u_{2s} \cong 374.4 \frac{kJ}{kg}$$

Isentropic specific work during the process:

$$w_s = u_1 - u_{2s} = -160.3 \frac{kJ}{kg}$$

$$\eta_{comp.} = \frac{160.3 \frac{kJ}{kg}}{182.8 \frac{kJ}{kg}} = 0.877 \Rightarrow \boxed{\eta_{comp.} = 87.7\%}$$

(d)