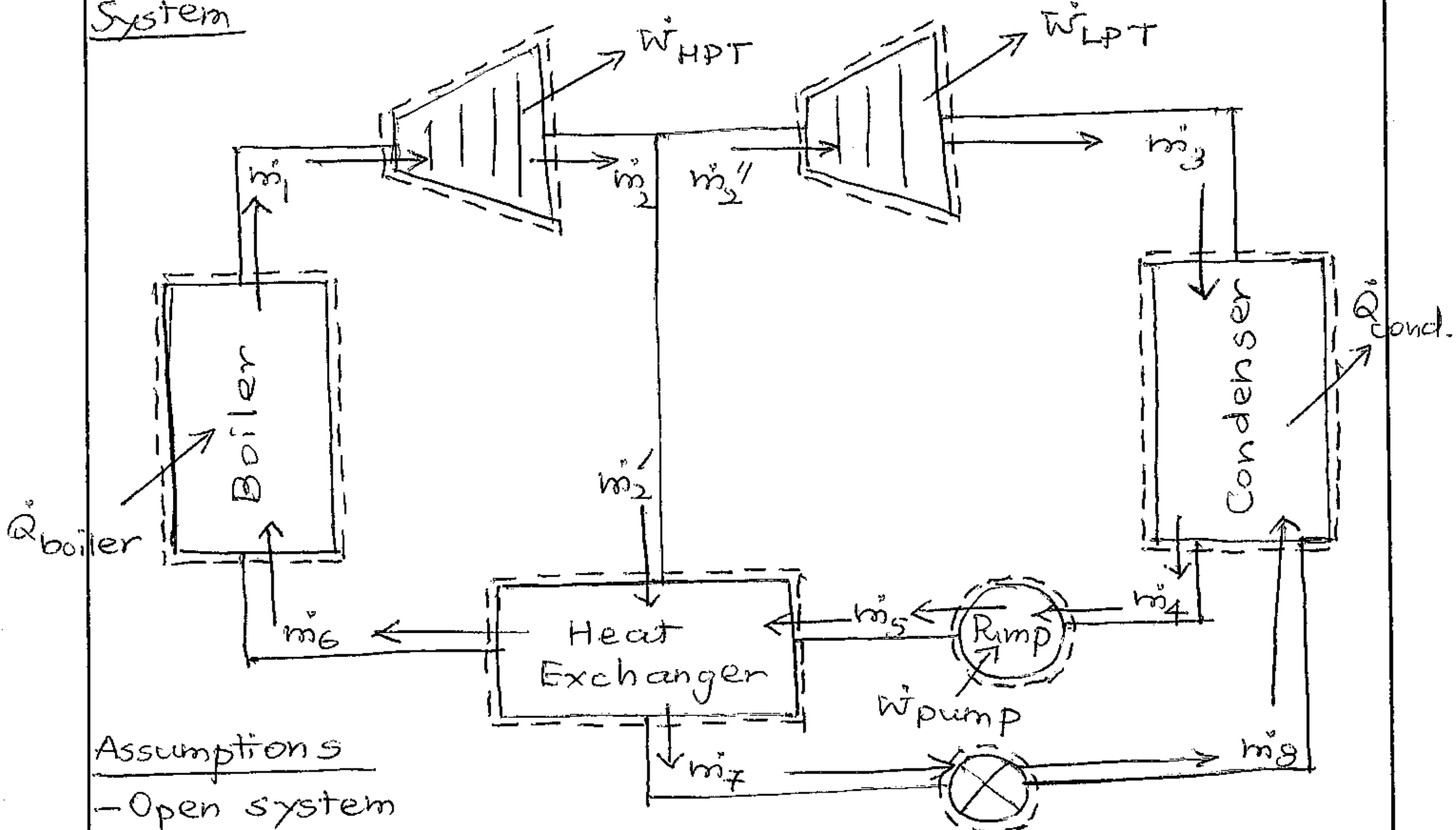
Given
A power cycle operating at steady state

Find
(a) Fraction of steam extracted from HPT
(b) Specific work ($\frac{kJ}{kg}$) for HPT and LPT
(c) Specific work ($\frac{kJ}{kg}$) for pump
(d) Specific heat transfer ($\frac{kJ}{kg}$) for boiler
(e) Specific heat transfer ($\frac{kJ}{kg}$) for condenser

System



Assumptions
- Open system
- Steady state, steady flow
- 1-D, uniform flow
- Ignore change in KE and PE
- Boiler and condenser: $\dot{W}=0$
- Turbines and pump: $\dot{Q}=0$
- Heat exchanger: $\dot{Q}=0$, $\dot{W}=0$

Flow of water/steam through various components is the system

Basic Equations

$$\cancelto{0}{\frac{dm}{dt}\Big|_{system}} = \sum_{in} \dot{m}_{in} - \sum_{out} \dot{m}_{out}$$

$$\cancelto{0}{\frac{dE}{dt}\Big|_{system}} = \sum_{in} \dot{m}_{in}(h+\cancel{ke}+\cancel{pe})_{in} - \sum_{out} \dot{m}_{out}(h+\cancel{ke}+\cancel{pe})_{out} + \dot{Q} - \dot{W}$$

Solution

State 1 $P_1 = 100$ bar, $T_1 = 480°C$

$T_1 > T_{sat}(P_1) \Rightarrow$ superheated vapor

$h_1 = 3323.0 \frac{kJ}{kg}$

State 2 $P_2 = 7$ bar, $x_2 = 0.985$

$h_2 = h_f(P_2) + x_2(h_g(P_2) - h_f(P_2))$

$= 697.00 \frac{kJ}{kg} + 0.985 * (2762.8 - 697.0) \frac{kJ}{kg}$

$= 2731.8 \frac{kJ}{kg}$

State 3 $P_3 = 0.06$ bar, $x_3 = 0.82$

$h_3 = h_f(P_3) + x_3(h_g(P_3) - h_f(P_3))$

$= 151.48 \frac{kJ}{kg} + 0.82 * (2566.6 - 151.48) \frac{kJ}{kg}$

$= 2131.9 \frac{kJ}{kg}$

State 4 $P_4 = 0.06$ bar, sat. liquid

$h_4 = h_f(P_4) = 151.48 \frac{kJ}{kg}$

State 5 $P_5 = 100$ bar, $T_5 = 36.8°C$

$T_5 < T_{sat}(P_5) \Rightarrow$ sub-cooled (compressed) liquid

Interpolating: $h_5 = 163.05 \frac{kJ}{kg}$

State 6 $P_6 = 100$ bar, $T_6 = 164.95°C$

$T_6 < T_{sat}(P_6) \Rightarrow$ sub-cooled (compressed) liquid

Interpolating: $h_6 = 702.88 \frac{kJ}{kg}$

State 7 $P_7 = 7$ bar, sat. liquid

$h_7 = h_f(P_7) = 697.00 \frac{kJ}{kg}$

State 8 $P_8 = 0.06$ bar, $h_8 = h_7 = 697.00 \frac{kJ}{kg}$ (Throttling)

Mass balance: $\dot{m}_1 = \dot{m}_2 = \dot{m}_4 = \dot{m}_5 = \dot{m}_6 = \dot{m}$

$\dot{m}_2' = \dot{m}_7 = \dot{m}_8 = y\,\dot{m}$, $\dot{m}_2'' = \dot{m}_3 = (1-y)\,\dot{m}$

(a) Heat exchanger:

Energy balance: $0 = (\dot{m}_2' h_2 + \dot{m}_5 h_5) - (\dot{m}_7 h_7 + \dot{m}_6 h_6) + 0 - 0$

$\cancel{\dot{m}}\, y (h_2 - h_7) = \cancel{\dot{m}} (h_6 - h_5)$

Fraction of stream extracted from HPT:

$$y = \frac{h_6 - h_5}{h_2 - h_7} \Rightarrow \boxed{y = 0.265}$$

(b) HPT

Mass balance: $0 = \dot{m}_1 - \dot{m}_2 \Rightarrow \dot{m}_1 = \dot{m}_2 = \dot{m}$

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

$\dot{W}_{HPT} = \dot{m}(h_1 - h_2)$

Specific work for HPT: $w_{HPT} = \dfrac{\dot{W}_{HPT}}{\dot{m}} = h_1 - h_2$

$\boxed{w_{HPT} = +591.2\ \frac{kJ}{kg}}$ $w > 0$ work output

LPT

Mass balance: $0 = \dot{m}_2'' - \dot{m}_3 \Rightarrow \dot{m}_2'' = \dot{m}_3 = (1-y)\,\dot{m}$

Energy balance: $0 = \dot{m}_2'' h_2 - \dot{m}_3 h_3 + 0 - \dot{W}_{LPT}$

$\dot{W}_{LPT} = \dot{m}(1-y)(h_2 - h_3)$

Specific work for LPT: $w_{LPT} = \dfrac{\dot{W}_{LPT}}{\dot{m}} = (1-y)(h_2 - h_3)$

$\boxed{w_{LPT} = +440.9\ \frac{kJ}{kg}}$ $w > 0$ work output

(c) Pump

Mass balance: $0 = \dot{m}_4 - \dot{m}_5 \Rightarrow \dot{m}_4 = \dot{m}_5 = \dot{m}$

Energy balance: $0 = \dot{m}_4 h_4 - \dot{m}_5 h_5 + 0 - \dot{W}_{pump}$

$\dot{W}_{pump} = \dot{m}(h_4 - h_5)$

Specific work for pump: $w_{pump} = \dfrac{\dot{W}_{pump}}{\dot{m}} = h_4 - h_5$

$\boxed{w_{pump} = -11.6\ \frac{kJ}{kg}}$ $w < 0$ work input

(d) Boiler:

Mass balance: $0 = \dot{m}_6 - \dot{m}_1 \Rightarrow \dot{m}_1 = \dot{m}_6 = \dot{m}$

Energy balance: $0 = \dot{m}_6 h_6 - \dot{m}_1 h_1 + \dot{Q}_{boiler} - \cancel{0}$

$\dot{Q}_{boiler} = \dot{m}(h_1 - h_6)$

Specific heat transfer for boiler: $q_{boiler} = \dfrac{\dot{Q}_{boiler}}{\dot{m}} = h_1 - h_6$

$$\boxed{q_{boiler} = +2620.1 \frac{kJ}{kg}}$$

$q > 0$ heat transfer into the system

(e) Condenser

Mass balance: $0 = (\dot{m}_3 + \dot{m}_8) - \dot{m}_4$

$\dot{m}_3 = (1-y)\dot{m}$, $\dot{m}_8 = y\dot{m}$, $\dot{m}_4 = \dot{m}$

Energy balance: $0 = (\dot{m}_3 h_3 + \dot{m}_8 h_8) - \dot{m}_4 h_4 + \dot{Q}_{condenser} - \cancel{0}$

$\dot{Q}_{condenser} = \dot{m} h_4 - \dot{m}(1-y) h_3 - \dot{m} y h_8$

Specific heat transfer for condenser:

$q_{condenser} = \dfrac{\dot{Q}_{condenser}}{\dot{m}} = h_4 - (1-y) h_3 - y h_8$

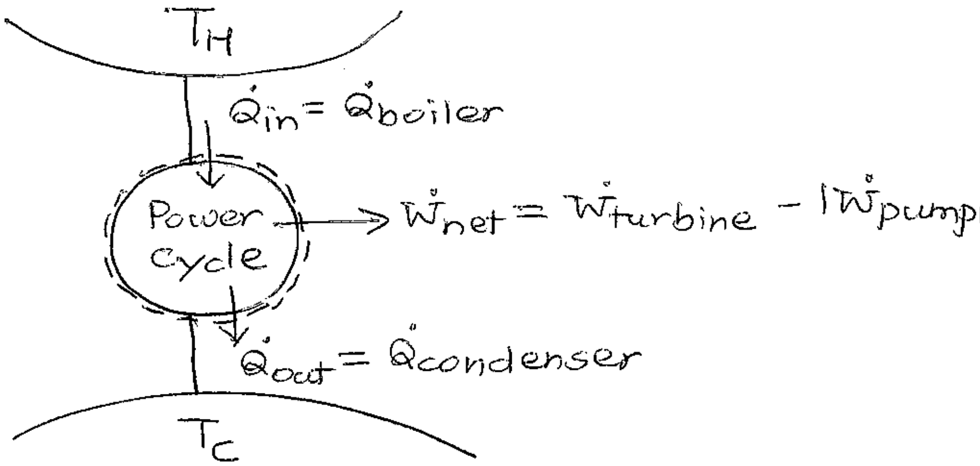
$$\boxed{q_{condenser} = -1600.1 \frac{kJ}{kg}}$$

$q < 0$ heat transfer out of the system

Given
A power cycle operating at steady state

Find
(a) Thermal efficiency (%) of the cycle using net specific work
(b) Thermal efficiency (%) of the cycle using net specific heat transfer

System



Assumptions
- Steady state

Basic Equations

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

Solution
See HW-17

$$w_{turbine} = w_{HPT} + w_{LPT} = (591.2 + 440.9)\ \frac{kJ}{kg}$$
$$= +1032.1\ \frac{kJ}{kg}$$

$$w_{pump} = -11.6\ \frac{kJ}{kg}$$

$$q_{boiler} = +2620.1\ \frac{kJ}{kg}$$

$$q_{condenser} = -1600.1\ \frac{kJ}{kg}$$

Considering energy balance for the cycle:

$$\dot{Q}_{in} - |\dot{Q}_{out}| = \dot{W}_{out} - |\dot{W}_{in}| \quad \text{i.e. } \dot{Q}_{net} = \dot{W}_{net}$$

$$w_{net} = w_{turbine} - |w_{pump}| = +1020.5\ \frac{kJ}{kg}$$

$$q_{net} = q_{boiler} - |q_{condenser}| = +1020.0\ \frac{kJ}{kg}$$

Note

$q_{net} = w_{net}$ (within round-off) This is a "cyclic" system

(a) Thermal efficiency of the cycle: $\eta_{th} = \dfrac{w_{net}}{q_H = q_{boiler}}$

$$\eta_{th} = \frac{1020.5\ \frac{kJ}{kg}}{2620.1\ \frac{kJ}{kg}} = 0.389 \Rightarrow \boxed{\eta_{th} = 38.9\%}$$

(b) Thermal efficiency of the cycle: $\eta_{th} = \dfrac{w_{net} = q_{net}}{q_H = q_{boiler}}$

$$\eta_{th} = \frac{1020.0\ \frac{kJ}{kg}}{2620.1\ \frac{kJ}{kg}} = 0.389 \Rightarrow \boxed{\eta_{th} = 38.9\%}$$

Given

A gas inside a closed piston-cylinder device undergoing three processes

Find

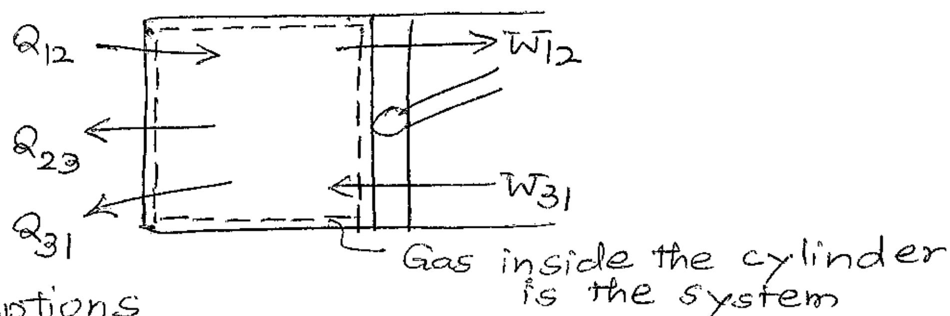
(a) P-V diagram

(b) Work (kJ) for each process

(c) Heat transfer (kJ) for each process

(d) Thermal efficiency (%) of the cycle

System



Assumptions

- Closed system (m = constant)
- Quasi-equilibrium process
- Ignore KE and PE change

Basic Equations

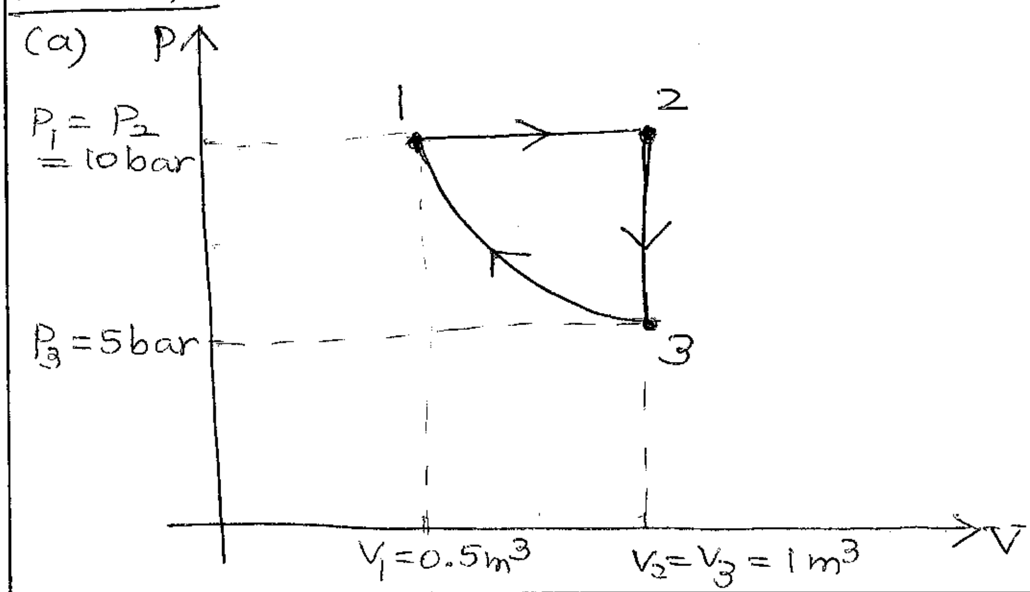
$$W_{boundary} = \int P\,dV$$

$$Q - W = \Delta E = \Delta U + \cancel{\Delta KE}^{\sim 0} + \cancel{\Delta PE}^{\sim 0}$$

$$W \to (W_{boundary} + \cancel{W_{other}}^{0})$$

Solution

(a)



(b) Boundary work for each process:

$$W_{12} = \int_{V_1}^{V_2} P\,dV = (P_1 = P_2)(V_2 - V_1) = (10 \times 100)\,\text{kPa} * (1 - 0.5)\,m^3$$

$$\Rightarrow \boxed{W_{12} = +500\ \text{kJ}}$$ W > 0 work done by the gas

$$W_{23} = \int_{V_2}^{V_3} P\,\cancel{dV}^{\,0} \Rightarrow \boxed{W_{23} = 0}$$

$$W_{31} = \int_{V_3}^{V_1} P\,dV = \int_{V_3}^{V_1} \frac{\text{constant}}{V}\,dV = \text{constant}\ \ln \frac{V_1}{V_3}$$

$$\text{constant} = P_1 V_1 = P_3 V_3 = (10 \times 100)\,\text{kPa} * 0.5\,m^3 = 500\ \text{kJ}$$

$$W_{31} = 500\ \text{kJ}\ \ln \frac{0.5\ m^3}{1.0\ m^3} \Rightarrow \boxed{W_{31} = -346.6\ \text{kJ}}$$

W < 0 work done on the gas

(c) Considering energy balance: $Q = W + \Delta U$

$$Q_{12} = W_{12} + (U_2 - U_1) = +500\ \text{kJ} + (400 - 200)\ \text{kJ}$$

$$\Rightarrow \boxed{Q_{12} = +700\ \text{kJ}}$$ Q > 0 heat transfer into the gas

$$Q_{23} = \cancel{W_{23}}^{\,0} + (U_3 - U_2) = (200 - 400)\ \text{kJ}$$

$$\Rightarrow \boxed{Q_{23} = -200\ \text{kJ}}$$ Q < 0 heat transfer out of the gas

$$Q_{31} = W_{31} + \cancel{(U_1 - U_3)}^{\,0} \Rightarrow \boxed{Q_{31} = -346.6\ \text{kJ}}$$

Q < 0 heat transfer out of the gas

Note

$$W_{net} = W_{12} + W_{23} + W_{31} = +153.4\ \text{kJ}$$

$$Q_{net} = Q_{12} + Q_{23} + Q_{31} = +153.4\ \text{kJ}$$

$$\Delta U_{net} = \Delta U_{12} + \Delta U_{23} + \Delta U_{31} = 0$$

$$Q_{net} - W_{net} = \cancel{\Delta U_{net}}^{\,0} \Rightarrow Q_{net} = W_{net}$$

This is a "cyclic" system

(d) Thermal efficiency of the cycle: $\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_{net}}{Q_{12}}$

$\eta_{th} = \frac{153.4\ kJ}{700\ kJ} = 0.219 \Rightarrow \boxed{\eta_{th} = 21.9\%}$