Thermodynamics

Isothermal $\rightarrow$ $\Delta T = 0$ Temp. = cons.

Isobaric $\rightarrow$ $\Delta P = 0$ pressure = cons.

Adiabatic $\rightarrow$ $\Delta Q = 0 \rightarrow \dot{Q} = 0$ no heat flow

rigid $\rightarrow$ $\Delta V = 0$ volume = cons.

Steady-state $\rightarrow$ $\frac{dE_{sys}}{dt} = 0$

closed system $\rightarrow$ $\dot{m} = 0$ $\rightarrow$ no mass flow

Open System $\rightarrow$ $\dot{m} \neq 0$

Isentropic $\rightarrow$ (Adiabatic + reversable process) $\rightarrow$ $\Delta S = 0$
$\rightarrow$ no change in the entropy

Thermodynamics

Problem 1.1

	unit	dimention
Force	N	$M \cdot L / t^2 = M L t^{-2}$
Pressure	Pa	$M / L t^2 = M L^{-1} t^{-2}$
Energy	J	$M L^2 t^{-2}$
Power	W	$M L^2 t^{-3}$

Dimentions: Mass: M, Length: L, Time: t

$1 \, Pa = 1 \, N/m^2$

$1 \, J = 1 \, Nm$

$1 \, W = J/s$

Problem 1.4

givens:

$m = 2 \, Kg$

$a - g_{grav} = 5 \, m/s^2$

$g_{grav} = 9.81 \, m/s^2$

req:-

$F_{app} = ?$

Solution:-

$$F_{app} = a \cdot m$$

$$a = 5 \, m/s^2 + g_{grav} = 14.81 \, m/s^2$$

$$\boxed{F_{app} = 2 \, Kg \cdot 14.81 \, m/s^2 = 29.62 \, m/s^2}$$

Problem 1.5

givens:

$m = 1200 \, Kg$

$V_0 = 50 \, Km/h = 13.89 \, m/s$

$V_f = 100 \, Km/h = 27.78 \, m/s$

req:

$E_{Kin} = ?$

$\Delta E_{Kin} = ?$

Solution:-

$$E_{Kin} = \frac{1}{2} m V_0^2 = \frac{1}{2}(1200 \, Kg)(13.89)^2$$

$$\Rightarrow \boxed{E_{Kin} = 115.74 \, KJ}$$

$$\Delta E_{Kin} = \frac{1}{2} m (V_f^2 - V_0^2) = \frac{1}{2}(1200)(27.78^2 - 13.89^2)$$

$$\Rightarrow \boxed{\Delta E_{Kin} = 347.22 \, KJ}$$

Problem 1.6

givens:

$m = 5000\ Kg$

$V = 150\ m/s$

$h = 10\,000\ m$

$g = 9.78\ m/s^2$

req:-

a) E_{K}, E_p

b) if $\Delta E_K = +10000\ KJ$

$V_f = ?$

Solution

a) $E_K = \frac{1}{2} m v^2 = \frac{1}{2}(5000\ Kg)(150\ m/s)^2$

$\Rightarrow \boxed{E_K = 56250\ KJ}$

$E_p = mgh = 5000\ Kg \cdot 9.78\ m/s^2 \cdot 10000\ m$

$\Rightarrow \boxed{E_p = 489000\ KJ}$

b) if $E_{Kf} = E_K + \Delta E_K = 66250\ KJ$

$V_f = \sqrt{\frac{2 E_{Kf}}{m}} = \sqrt{\frac{2(66250\ KJ)}{5000\ Kg}}$

$\Rightarrow \boxed{V_f = 162.8\ m/s}$

Problem 1.7

givens:-

$n = 0.5\ Kmol$

$V = 6\ m^3$

$MW_{NH_3} = 17\ Kg/Kmol$

$g = 9.81\ m/s^2$

req:

a) Weight = ?

b) specific volume = ?

Solution

a)

$m = n \cdot MW_{NH_3} = 0.5\ Kmol \cdot 17\ Kg/Kmol = 8.5\ Kg$

$\boxed{W = m \cdot g = 83.34\ N}$

b) Spec. Vol. = V/n or V/m

$\Rightarrow V/n = 6\ m^3/0.5\ Kmol = 12\ m^3/Kmol$

$\Rightarrow V/m = 6\ m^3/8.5\ Kg = 0.705\ m^3/Kg$

Thermodynamics

Ideal gas Law :

$$P \cdot V = R \cdot T$$

, where $v = \frac{V}{m}$ = [m³/Kg]   (specific volume; V → volume; m → mass)

$T = [K]$

$P = [\frac{N}{m^2} = Pa]$

$V = [m^3]$

$$P \cdot \bar{V} = \bar{R} \cdot T$$

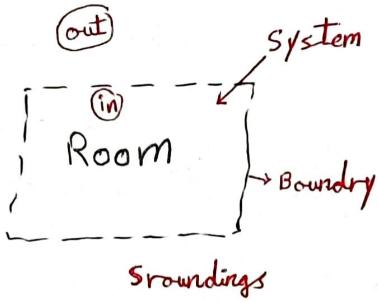
Universal gas Cons.

$$\bar{R} = 8.314 \ J/mol \cdot K$$

$$R_{specific} = \frac{\bar{R}}{M}$$

Ex 2

$\boxed{2.1}$



$V = 6m \cdot 10m \cdot 4m = 240 m^3$

$T = 273 + 25 = 298 K$

$P = 100 \times 10^3 \ Pa$

$\bar{R} = 8.314 \ \frac{J}{mol \cdot K}$

$M_{air} = 28.97 \ g/mol = 28.97 \times 10^{-3} \ Kg/mol$

$\therefore R_{air} = \frac{\bar{R}}{M_{air}} = \frac{8.314 \frac{J}{mol \cdot K}}{28.97 \times 10^{-3} \ Kg/mol} = 286.99 \ \frac{J}{Kg \cdot K}$

Equation of state → Ideal gas

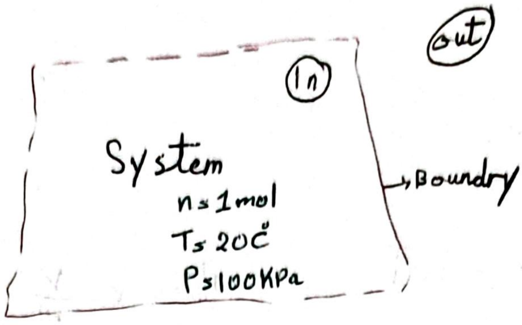
$P \cdot v = R_{air} T$, since $v = \frac{V}{m}$

$\therefore P \cdot \frac{V}{m} = R_{air} \cdot T$

$$\boxed{m = \frac{P \cdot V}{R_{air} \cdot T}}$$ solution

$m = \frac{10^5 \ Pa \cdot 240 \ m^3}{286.99 \frac{J}{Kg \cdot K} \cdot 298 K} = \underline{\underline{280.63 \ Kg}}$

2.2



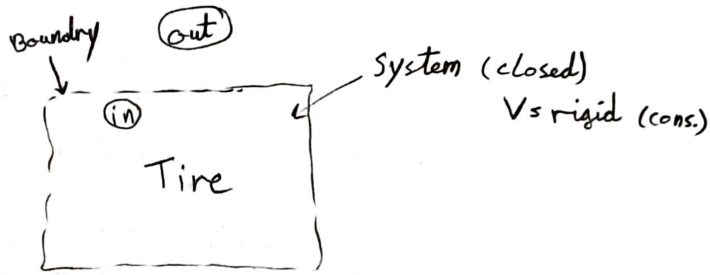
equation of state → Ideal gas law

$PV = nRT$

$V = \frac{1mol \cdot 293K \cdot 8.314 \frac{J}{mol \cdot K}}{10^5 Pa} = 0.02436 m^3$

$V = a^3 \Rightarrow \boxed{a = \sqrt[3]{V} = 0.29 m}$

2.4



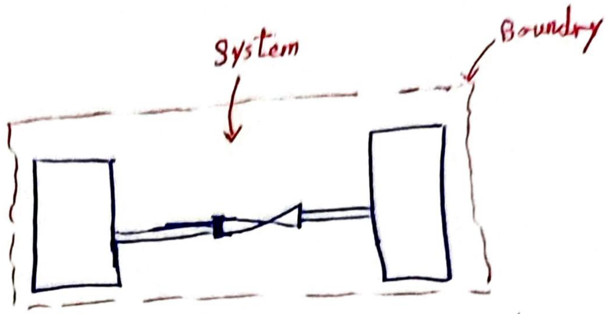
equation of state → Ideal gas

(a) $P_1 \cdot T_2 = P_2 \cdot T_1 \Longrightarrow \boxed{P_2 = \frac{P_1 T_2}{T_1}}$

(b) $P_1 \cdot V_1 = m_1 R T_1$

$P_1 \cdot V_1 = m_2 R T_2 \Rightarrow \boxed{\Delta m = m_1 - m_2}$

Problem 2.3



givens:

Tank 1:

$T_1 = 80\,^\circ C = 353\,K$

$m_1 = 5\,Kg$

$P_1 = 10.5\,bar$

Tank 2:

$T_2 = 30\,^\circ C = 303\,K$

$m_2 = 8\,Kg$

$P_2 = 1.2\,bar$

$T_{eq} = 42\,^\circ C = 315\,K$

$R = 297\,\frac{J}{Kg \cdot K}$

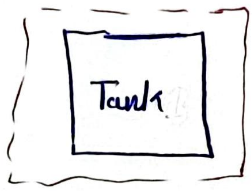
equation of state → ideal gas Law

$$P_{eq} \cdot V_{eq} = m_{eq} R \cdot T_{eq}$$

$$\boxed{P_{eq} = \frac{\overset{?}{m_{eq}} \cdot \overset{\checkmark}{R} \cdot \overset{\checkmark}{T_{eq}}}{?\,V_{eq}}}$$

Since our system is cLosed ⇒ $m_{eq} = m_1 + m_2$

Rigid Tanks ⇒ $V_{eq} = V_1 + V_2$



$P_2 V_2 = m_2 R T_2$

$$\boxed{V_2 = \frac{m_2 R T_2}{P_2}}$$

$P_1 V_1 = m_1 R T_1$

$$\boxed{V_1 = \frac{m_1 R T_1}{P_1}}$$

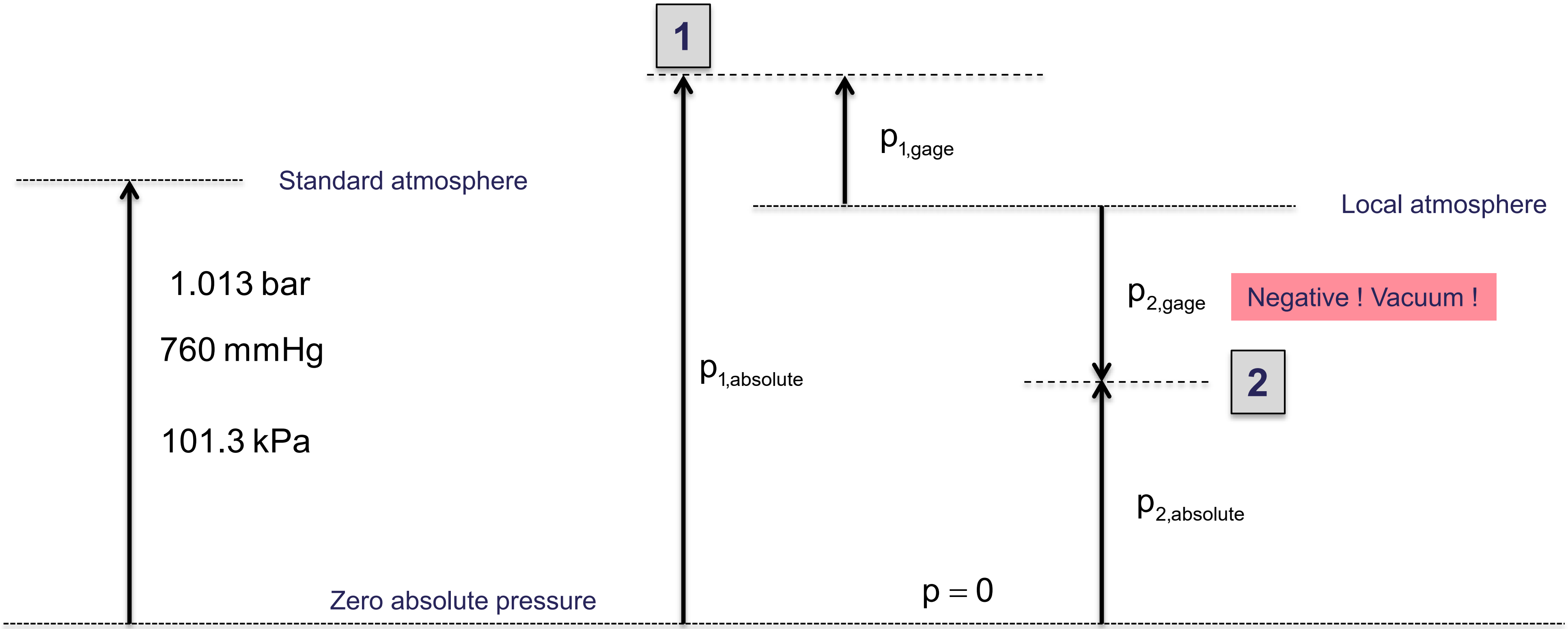
$$P_{eq} = \frac{(m_1+m_2) \cdot \cancel{R} \cdot T_{eq}}{\frac{m_1 \cdot \cancel{R} \cdot T_1}{P_1} + \frac{m_2 \cancel{R} \cdot T_2}{P_2}} = \frac{(5+8)\,\cancel{Kg} \cdot 315\,\cancel{K}}{\left(\frac{5 \cdot 353}{10.5} + \frac{8 \cdot 303}{1.2}\right)\frac{\cancel{Kg \cdot K}}{bar}}$$

$$\boxed{P_{eq} = 1.8715\ bar}$$

Gage pressure and absolute pressure

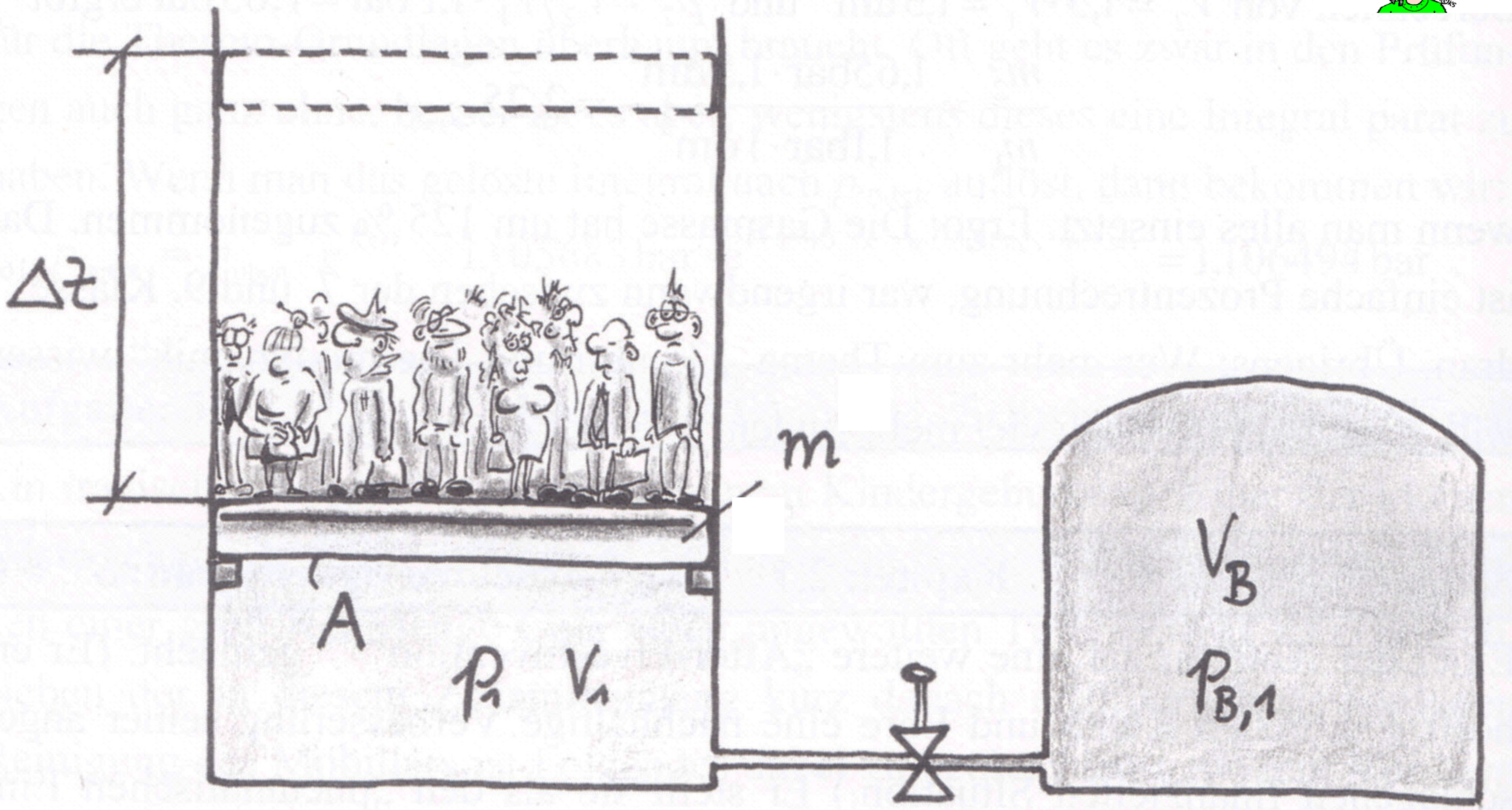
Measuring pressures relative to the local atmospheric pressure: *gage pressure*

$$p_{absolute} = p_{atmospheric} + p_{gage}$$



The absolute pressure reaches zero when an ideal vacuum is achieved. A negative absolute pressure is an impossibility.

Problem 2.5
Pneumatically Driven One-Way Elevator



Problem 2.5
Pneumatically Driven One-Way Elevator

a) What pressure is necessary to elevate people, who weigh 600 kg?

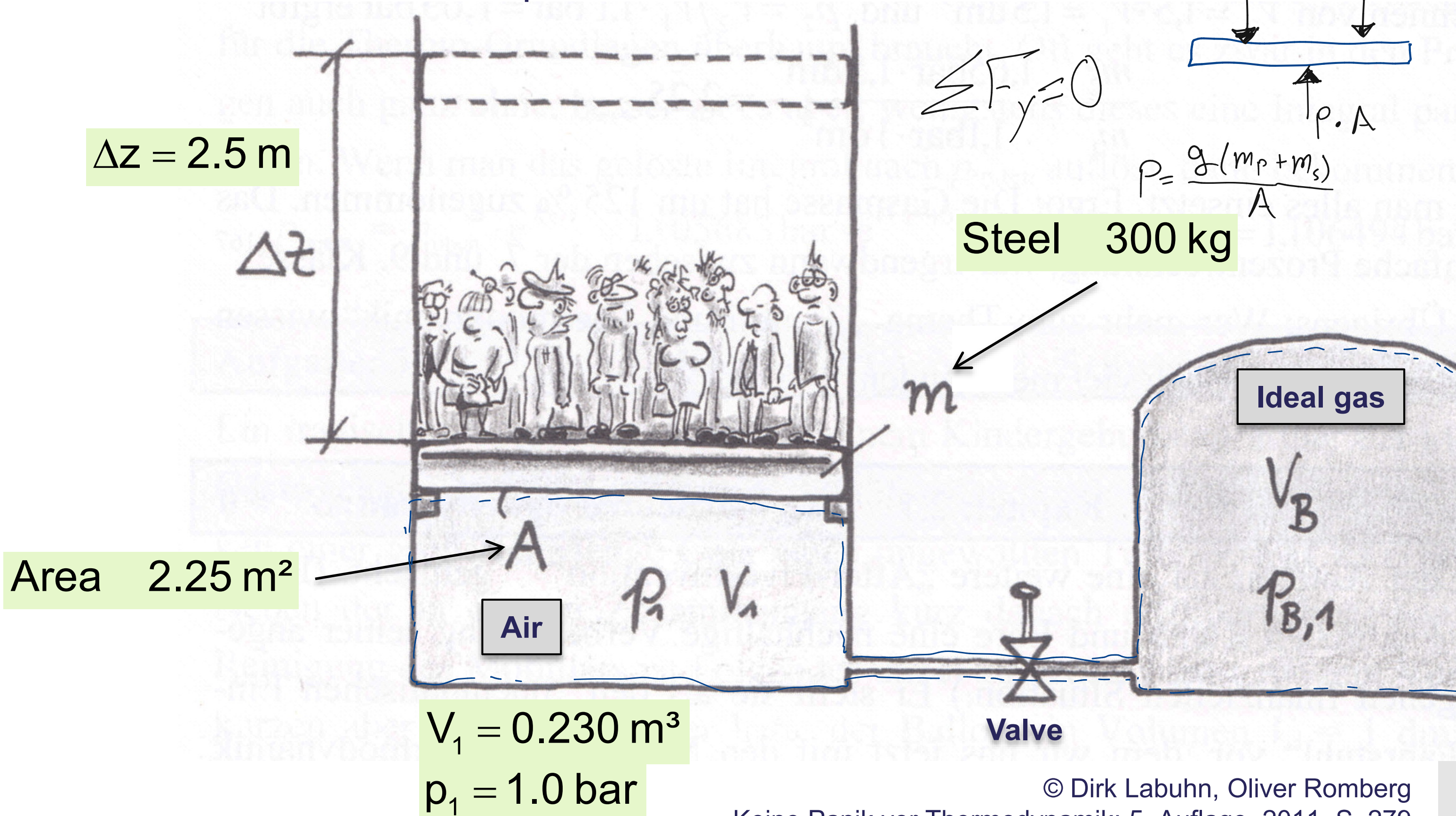
b) What tank pressure $p_{B,1}$ is necessary so that the elevator remains at a position Δz = 2.5 m?

Assume that the process 1 → 2 is isothermal.

Solution

a) $p = 1.039$ bar

b) $p_{B1} = 6.89$ bar



$V_B = 1.0$ m³

Problem 2.6
Spring – Piston System

Consider air contained within a vertical piston-cylinder assembly. On its top, a 10-kg piston is attached to a spring and exposed to an atmospheric pressure of 1 bar. Initially the bottom of the piston is x = 0, and the spring exerts a negligible force on the piston. The valve is opened and air enters the cylinder from the supply line, causing the volume of air within the cylinder to increase.

Determine the pressure of air within the cylinder, in bar,
a) when the piston is at its **initial** position
b) when the piston is at its **final** position.

Solution

a) $p_1 = 1.126$ bar

b) $p_2 = 1.767$ bar

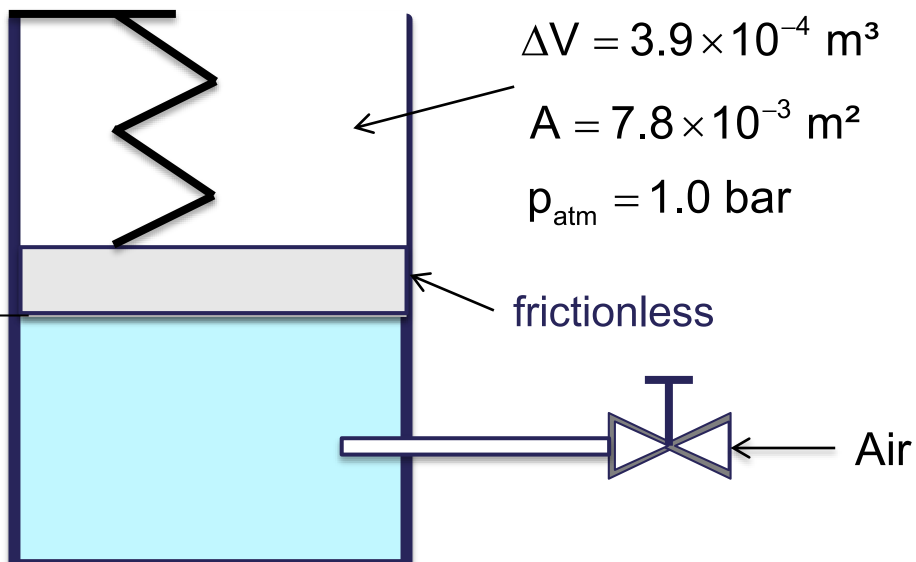
Spring

$k = 10{,}000 \, \frac{N}{m}$

Piston

$m = 10$ kg

$x = 0$



$\Delta V = 3.9 \times 10^{-4}$ m³

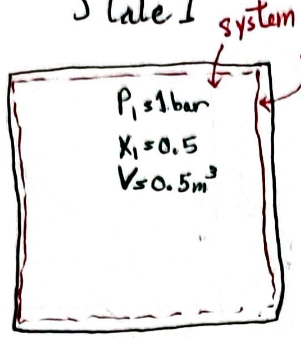
$A = 7.8 \times 10^{-3}$ m²

$p_{atm} = 1.0$ bar

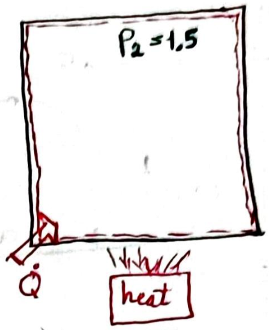
Moran/Shapiro Fundamentals of Engineering Thermodynamics Problem 1.32, p.26

Prob. 3.2

State 1



State 2



Closed system $\Rightarrow m_1 = m_2 = \text{Cons.}$

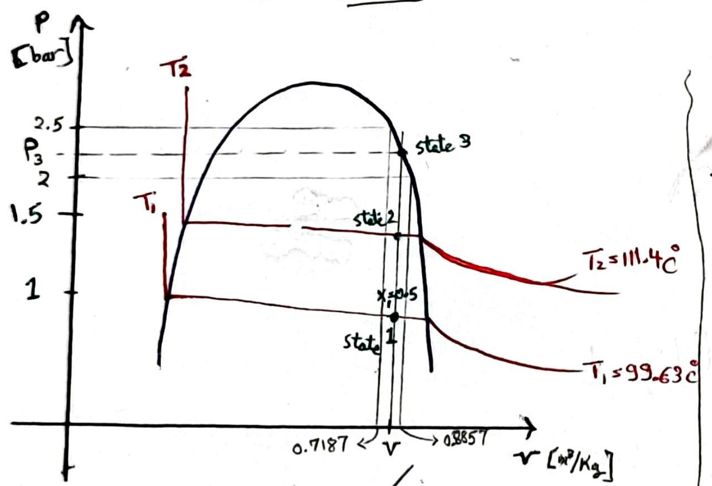
rigid $\Rightarrow V_1 = V_2 = V = 0.5\,m^3$

since $v = \frac{V}{m} \Rightarrow v_1 = v_2$

from the table :-

$P_1 = 1\,bar \Rightarrow \boxed{T_1 = 99.63\,^\circ C}$

$P_2 = 1.5\,bar \Rightarrow \boxed{T_2 = 111.4\,^\circ C}$



v_1: $v_{f_1} = 1.0432 \times 10^{-3}\,m^3/Kg$, $v_{g_1} = 1.694\,m^3/Kg$

$v_1 = v_2 = (1-x_1)\cdot v_{f_1} + x_1 \cdot v_{g_1} = 0.8475\,m^3/Kg$

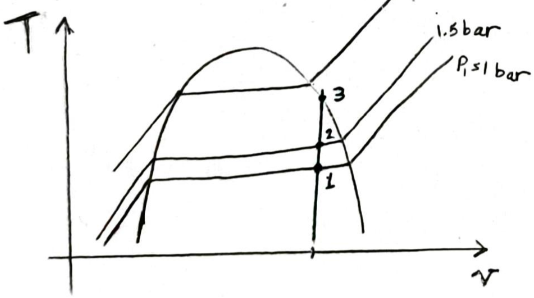
table (A-3) $\Rightarrow v_{f_2} = 1.0528 \times 10^{-3}\,m^3/Kg$, $v_{g_2} = 1.159\,m^3/Kg$

$v_2 = (1-x_2) v_{f_2} + x_2 v_{g_2}$

$\Rightarrow x_2 = \frac{v_2 - v_{f_2}}{v_{g_2} - v_{f_2}} = 0.731$

$v = \frac{V_{tot}}{m_{tot}} \Rightarrow m_{tot} = \frac{V}{v} = \frac{0.5\,m^3}{0.8475\,m^3/Kg}$

$\Rightarrow \boxed{m_t = 0.59\,Kg}$



$x = \frac{m_{vap}}{m_t} \Rightarrow m_{vap_1} = x_1 \cdot m_t = 0.5 \cdot 0.59\,Kg$

$\Rightarrow \boxed{m_{vap_1} = 0.295\,Kg}$

$m_{vap_2} = x_2 \cdot m_t = 0.731 \cdot 0.59\,Kg$

$\Rightarrow \boxed{m_{vap_2} = 0.431\,Kg}$

From table A-3 Interpolation :-

$\frac{2.5\,bar - 2\,bar}{(P_3 - 2)\,bar} = \frac{0.7187 - 0.8857}{0.8475 - 0.8857} \Rightarrow \boxed{P_3 = 2.11\,bar}$

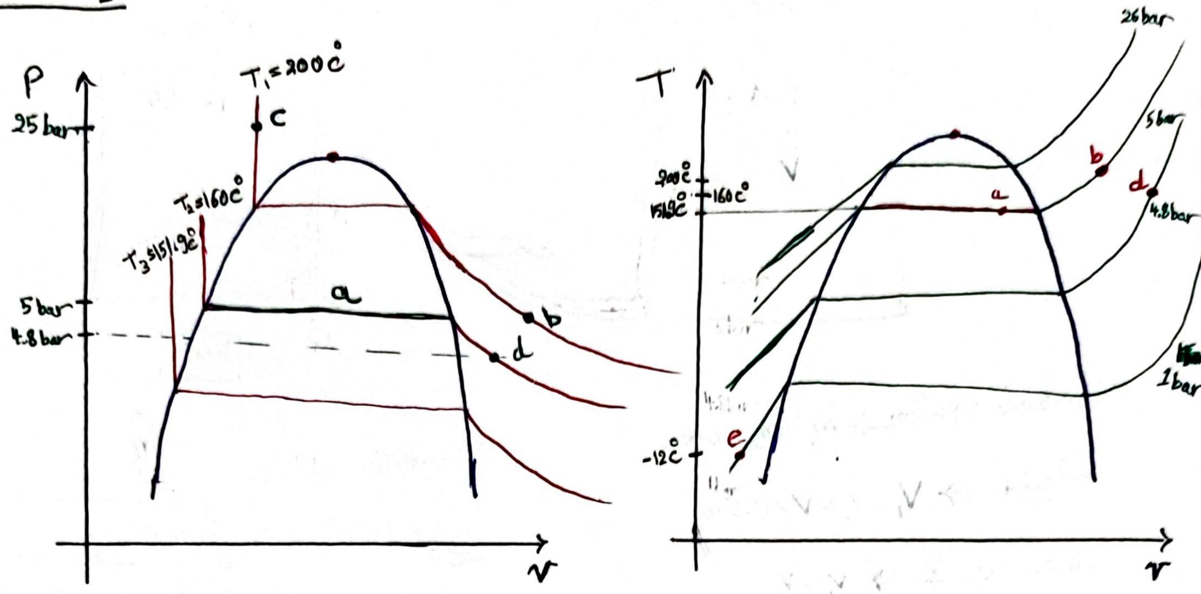
Since all mass is vapour, $x_3 = \frac{m_{vap}}{m_t} = 1$

$\therefore v_3 = v_{vap_3} = 0.8475$

$\boxed{m_{vap_3} = m_t = 0.59\,Kg}$

Problem 3.1

Thermodynamics



a) Saturated water/vapour

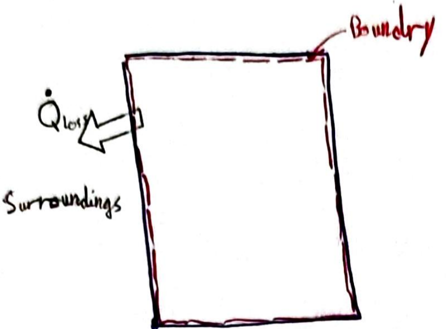
b) Superheated vapour

c) compressed/subcooled liquid

d) Superheated vapour

e) Solid

Problem 3.3 Thermodynamics



givens:

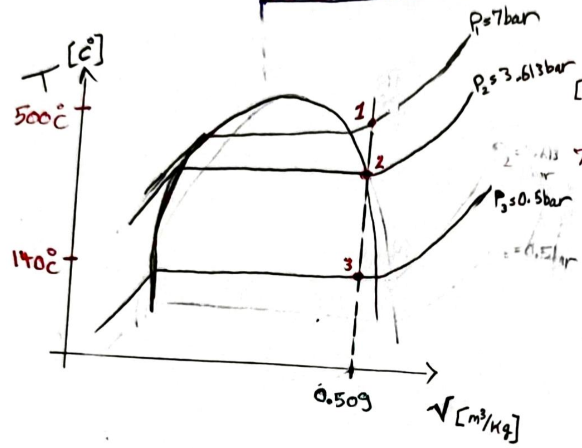
rigid → $V_1 = V_2 = 1\ m^3$

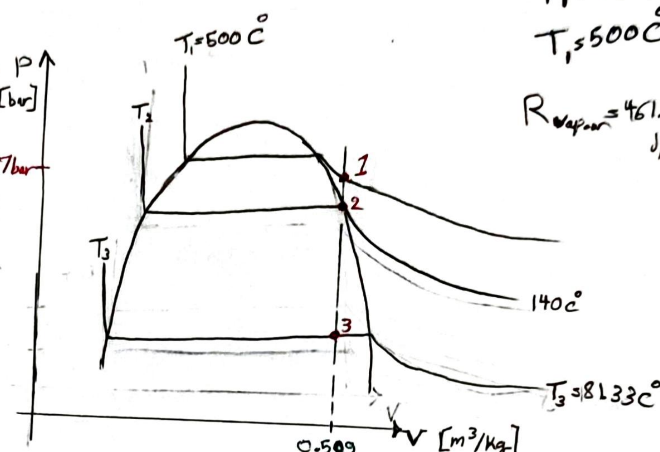
closed system → $\dot{m} = 0$, $m =$ cons.

$P_1 = 7\ bar$

$T_1 = 500°C$

$R_{vapour} = 461.5\ J/kg\cdot K$





Ideal gas Law → $PV = mRT \Rightarrow m = \dfrac{7\times10^5\ N/m^2 \cdot 1\ m^3}{(500+273)\ K \cdot 461.5\ Nm/kg\cdot K}$

$\Rightarrow \boxed{m = 1.962\ kg}$ ∴ $\boxed{v = \dfrac{V}{m} = \dfrac{1\ m^3}{1.962\ kg} \cong 0.509\ m^3/kg}$

Since V = cons. and m = cons.

∴ $v = \dfrac{V}{m} =$ Cons.

from table A-2, we can check for $v_g = 0.509\ m^3/kg$

at $v_g = v_2 = 0.509\ m^3/kg \Rightarrow \boxed{T_2 \cong 140°C}$

b) $P_3 = 0.5\ bar$

in table A-3 at $P_3 = 0.5\ bar \longrightarrow v_{g_3} = 3.24\ m^3/kg$, $v_{f_3} = 1.03\times10^{-3}\ m^3/kg$

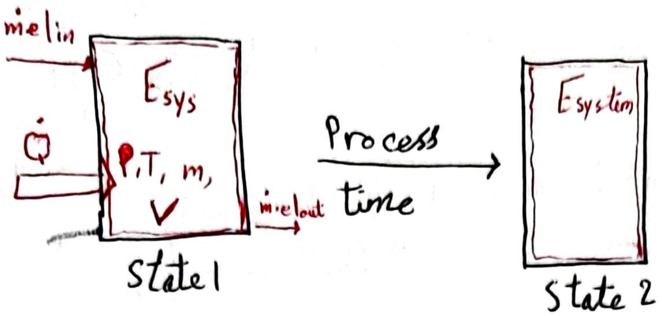
$v = (1-x_3)v_{f_3} + x_3 v_{g_3} \Rightarrow x_3 = \dfrac{v - v_{f_3}}{v_{g_3} - v_{f_3}} = \dfrac{(0.509 - 1.03\times10^{-3})\ \cancel{m^3/kg}}{(3.24 - 1.03\times10^{-3})\ \cancel{m^3/kg}}$

$\Rightarrow \boxed{x_3 = 0.157}$

which means $\boxed{\begin{array}{l} x_3 = 15.7\%\ \text{Vapour} \\ (1-x_3) = 84.3\%\ \text{Liquid} \end{array}}$

c) $v_{f_3} = \dfrac{V_{f_3}}{m_{f_3}} \Rightarrow V_{f_3} = m_{f_3} \cdot v_{f_3} = (1.962 * 0.843)\ kg \cdot (1.03\times10^{-3}\ m^3/kg) \Rightarrow \boxed{V_{liquid_3} = 1.704\times10^{-3}\ m^3}$

Efficiency $\eta = \frac{\text{Benefit}}{\text{Efforts}}$



$$\frac{d}{dt} E_{sys} = \sum \dot{Q} + \sum P + \sum \dot{m} \cdot e$$

$$E_{sys} = E_{Kin} + E_p + U$$

internal energy.

$$\frac{E_{sys_2} - E_{sys_1}}{\Delta t} = \sum \dot{Q} + \sum P + \sum \dot{m} \cdot e$$

$$E_{sys_2} - E_{sys_1} = \underbrace{\sum \dot{Q} \cdot \Delta t}_{\text{watt} \cdot s = J} + \underbrace{\sum P \cdot \Delta t}_{\text{Power} = \dot{W}} + \underbrace{\sum \dot{m} \cdot e \cdot \Delta t}_{\dot{m} \cdot \Delta t = m}$$

$\frac{J}{s} \cdot s = J$

$\dot{W} = \frac{\text{Work}}{\text{time}}$

$\dot{W} \cdot \Delta t = W$

$$E_{sys_2} - E_{sys_1} = \sum Q + \sum W + \sum m \cdot e$$

- Neglect E_{Kin}, E_{pot} → Thermodynamic.

$$\therefore \boxed{U_2 - U_1 = \sum Q + \sum W + \sum m \cdot e}$$

- closed system $\sum me = 0$

$$U_2 - U_1 = \sum Q + \sum W$$

- Closed, and steady state system.

$$\frac{\partial}{\partial t} = 0 \Rightarrow U_2 - U_1 = 0$$

$$\sum Q + \sum W = 0$$

! When ever you introduce work $\boxed{W_{12} = \ominus \int_1^2 P \cdot dV}$ on the system

You have to mention it is (on the system) or (by the system)

دائماً خلي الـ Work positive وبعدين لما تيجي تحطه في الـ energe equ. ، لو كان on the sys. يبقى (+) ، ولو by the sys. يبقى (−)

$$\cancel{\Delta E_{sys}} = \sum Q + \sum W + \sum m \cdot e$$

0

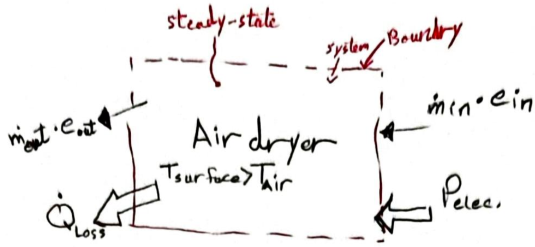
Steady-state

$$0 = Q_{in} - Q_{Loss} + W + m(u_1 - u_2)$$

$$m(u_2 - u_1) = \sum Q + \sum W$$

$$\boxed{du = dq + dw}$$

Nueme acne

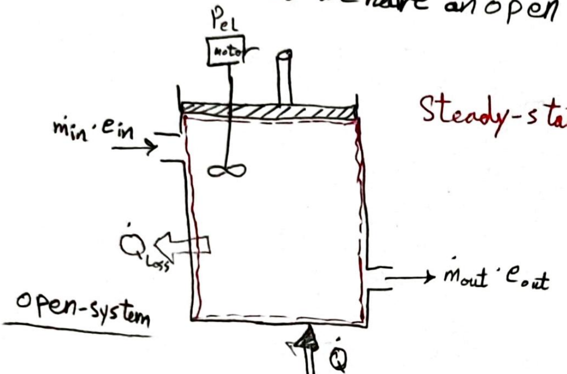


open system

$$P_{el} + \dot{m}_{in} \cdot e_{in} = \dot{Q}_{Loss} + \dot{m}_{out} \cdot e_{out}$$

---

as soon as we have an open system, forget $W = -\cancel{\int} p\,dV$ (volume work)



Steady-state

$$\cancel{\frac{dE_{sys}}{dt}}^{\,0} = \sum \dot{Q} + \sum P + \sum \dot{m} \cdot e$$

$$\dot{Q}_{in} - \dot{Q}_{Loss} + P_{t} + \dot{m} h_{in} - \dot{m} h_{out} = 0$$

$$\dot{m}(\underbrace{h_{out} - h_{in}}) = \dot{Q}_{in} - \dot{Q}_{Loss} + P_{t}$$

$h_2 - h_1 \rightarrow$ Location

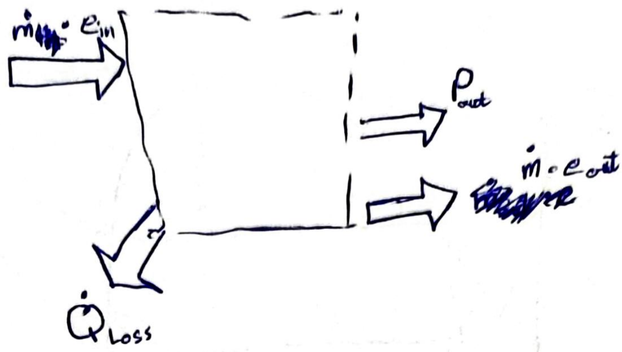
$$e = \underbrace{\overset{(\frac{1}{2}v^2)}{e_{kin}} + \overset{(gh)}{e_{pot}}} + \underbrace{\overset{\text{internal energy}}{u(T,p)} + p \cdot v}_{\text{enthalpy } h \, [kJ/kg]}$$

normally they are neglectable.

Closed System:

$$\underbrace{m(u_2 - u_1) = \sum Q + \sum W}$$

time



Open system

Steady state

$$\overset{0}{\cancel{\frac{E_{sys_2} - E_{sys_1}}{\Delta t}}} = \sum \dot{Q} + \sum P + \sum \dot{m}\cdot e$$

$$e = \underbrace{E_{Kin}}_{\frac{1}{2}V^2} + \underbrace{\cancel{E_{pot}}}_{\text{neglegible}} + \underbrace{U(P,T) + P\cdot v}_{h}$$

$$\dot{m}(e_{out} - e_{in}) = -\dot{Q}_{Loss} - P_{out}$$

solution $\boxed{\dot{Q}_{Loss} = m(e_{in} - e_{out}) - P_{out}}$

$$e_{in} = \frac{1}{2}V_{in}^2 + h_{in}$$

$$e_{out} = \frac{1}{2}V_{out}^2 + h_{out}$$

$$h_{out} = x_2 h_g + (1 - x_2) h_f$$

from table

A-4 → $h_{in} = 3177.2$ KJ/Kg

A-3 → $h_f = 191.83$ KJ/Kg, $h_{fg} = 2392.8$ KJ/Kg, $h_g = 2584.7$ KJ/Kg

Problem 4.1

<u>State 1:</u>

$P_1 = 10\,bar$

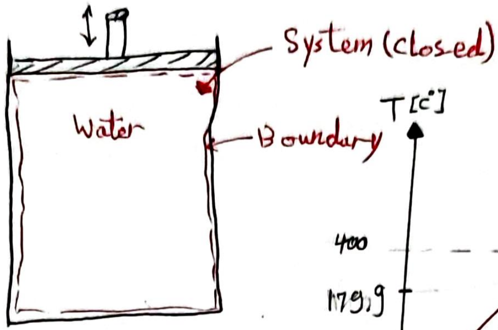
$T_1 = 400°C$

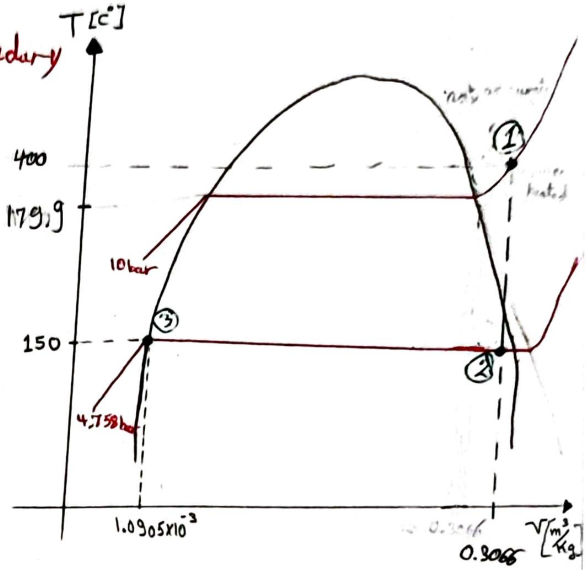
$m = cons.$

<u>State 2:</u>

$V_1 = V_2$

$T_2 = 150°C$





<u>State 3:</u>

$V_3 < V_2$

$T_3 = T_2 = 150°C$ (isothermal)

a)

(at P_1, and T_1)

from table A-4 $\rightarrow V_1 = V_2 = 0.3066\ m^3/Kg$, $u_1 =$

<u>from A-2</u> at $T_2 \longrightarrow V_g > V_1 \longrightarrow V_{g_2} = 0.3928\ m^3/Kg$, $u_{g_2} = 2559.5\ KJ/Kg$

$u_{f_2} = 631.68\ KJ/Kg$

which means its saturated water/vapour

from A-2 at $T_3 \rightarrow V_f = V_3 = 1.0905 \times 10^{-3}\ m^3/Kg$, $u_3 = u_f$

$P_2 = P_3 = 4.758\ bar$

b) $\frac{W}{m} = -\int_2^3 P\,dv = -P_2(V_3 - V_2) = -4.758\ bar * \frac{100\,KPa}{1\,bar}(1.0905 \times 10^{-3}\ m^3/Kg - 0.3066\ m^3/Kg)$

$$\boxed{\frac{W}{m} = 145.4\ KJ/Kg}$$

c)

$V_2 = x_2 V_{g_2} + (1 - x_2) V_{f_2} \Longrightarrow x_2 = \frac{V_2 - V_{f_2}}{V_{g_2} - V_{f_2}} \Longrightarrow x_2 = 0.78 = 78\%$

$u_2 = x_2 u_{g_2} + (1 - x_2) u_{f_2} \Rightarrow \underline{u_2 = 2135.262\ KJ/Kg}$

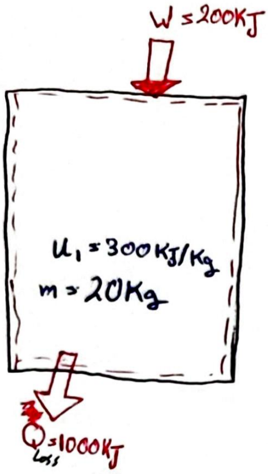
$m(u_3 - u_2) = -Q_{23} + W_{23} \Longrightarrow (u_3 - u_2) = -\frac{Q_{23}}{m} + \frac{W_{23}}{m}$

$\frac{Q_{23}}{m} = \frac{W_{23}}{m} + u_2 - u_3 \Longrightarrow \boxed{\frac{Q_{23}}{m} = 1649\ KJ/Kg}$

We can also bring specific heat capacity $C = \frac{Q}{m\,\Delta T}$

Prob 4.2

Thermodynamics



Closed system $\Rightarrow \dot{m} = 0$

$$m(u_2 - u_1) = \Sigma Q + \Sigma W$$

$$m(u_2 - u_1) = -Q_{Loss} + W$$

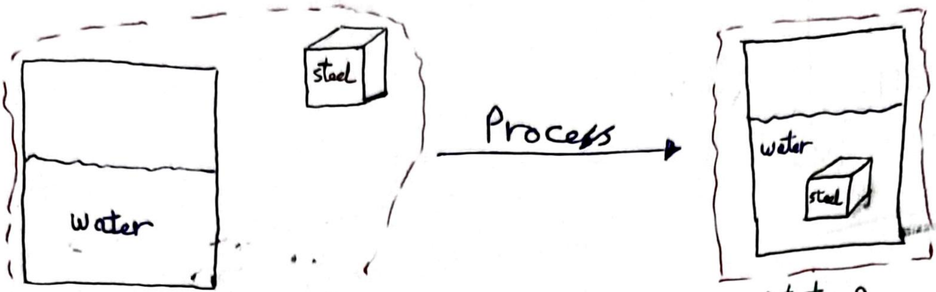
$$\boxed{u_2 = \frac{-Q_{Loss} + W}{m} + u_1}$$

$$u_2 = \frac{-1000\,KJ + 200\,KJ}{20\,Kg} + 300\,KJ/Kg$$

$$\boxed{u_2 = 260\,KJ/Kg}$$

Prob 4.3

Thermodynamics



state 1

state 2

Thermal equilibrium

Closed system $\rightarrow \dot{m} = 0$

Steady-state $\rightarrow \frac{d}{dt} E_{sys} = 0$

givens

$m_w = 10 L = 10 Kg$

$T_w = 15 \mathring{C} = 288 K$

$\bar{C}_w = 4.19 KJ/Kg \cdot K$

$m_s = 0.5 Kg$

$T_s = 800 \mathring{C} = 1073 K$

$\bar{C}_s = 0.716 KJ/Kg \cdot K$

$T_{eq} = ?$

1st Law of thermodynamics:

$$u_2 - u_1 = \cancel{\Sigma q}^{0} + \cancel{\Sigma W}^{0} = 0$$

$$du = c_v \, dT$$

$$\bar{C} = C_v = Cons.$$

$$u_2 - u_1 = 0 \Longrightarrow u_2 = u_1$$

$$m_w \bar{C}_w T_{eq} + m_s \bar{C}_s T_{eq} = m_w \bar{C}_w T_w + m_s \bar{C}_s T_s$$

$$\therefore \boxed{T_{eq} = \frac{m_w \bar{C}_w T_w + m_s \bar{C}_s T_s}{m_w \bar{C}_w + m_s \bar{C}_s}}$$ solution

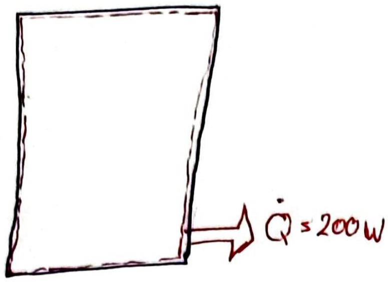
Equilibrium Temperature

$$T_{eq} = \frac{10\,Kg \cdot 4.19\,KJ/Kg \cdot K \cdot 288K + 0.5\,Kg \cdot 0.716\,KJ/Kg \cdot K \cdot 1073K}{10\,Kg \cdot 4.19\,KJ/Kg \cdot K + 0.5\,Kg \cdot 0.716\,KJ/Kg \cdot K} = 294.65\ K$$

$$\boxed{T_{eq} = 21.65\ \mathring{C}}$$

Problem 4.4

Closed $\Rightarrow \dot{m} = 0$



$T_1 = 25^\circ C = 298\ K$

$T_2 = 8^\circ C = 281\ K$

$$m_{liq} = \frac{V_{liq}}{v_{liq}} = \frac{0.5L \cdot \frac{10^{-3} m^3}{L} \cdot 20\,\text{bottles}}{0.9852 \times 10^{-3} \frac{m^3}{Kg}} = 10.15\ Kg$$

$$P_{air} V_{air} = m_{air} R T_{air} \Rightarrow m_{air} = \frac{1.01\,bar \cdot \frac{10^5 N/m^2}{bar} \cdot 1.2\,m^3}{287\,Nm/Kg{\cdot}K\ (25+273)K} = 1.403\ Kg$$

With $T_2 \rightarrow m_{air} = 1.488\ Kg$

1st law of thermodynamics:

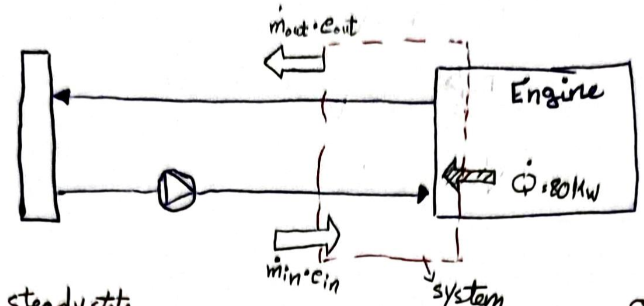
$$\frac{m(u_2 - u_1)}{dt} = \sum \dot{Q} + \sum \dot{W} + \dots$$

$$dt = \frac{m(u_2 - u_1)}{-\dot{Q}} = 57.094\ min$$

$$U_1 = m_{bot} \cdot \bar{c}_{glass} T_1 \times 20 + m_{liq} \cdot \bar{c}_{liq} \cdot T_1 \times 20 + m_{air} \bar{c}_{air} T_1$$

$$m_{bot} \cdot \bar{c}_{glass} \cdot 20 + m_{liq} \cdot \bar{c}_{liq} = 39295.5$$

Problem 5.1



steady state

open system

$$\cancel{\frac{d}{dt}} E_{sys} = \sum \dot Q + \sum P + \sum \dot m e$$

$$e = \underbrace{\cancel{e_{Kin}}^{0} + \cancel{e_{pot}}^{0}}_{\text{neglegtable}} + \underbrace{u + pv}_{h}$$

$\dot m_{in} = \dot m_{out}$

$$\dot m (h_{out} - h_{in}) = + \dot Q$$

$$dh = c_p \int_{T_{in}}^{T_{out}} dT$$

$c_p = \bar c_{p,ref} = \text{Cons.}$

$$\Longrightarrow \dot m \cdot \bar c_{p,ref} (T_{out} - T_{in}) = 80 \frac{KJ}{s}$$

$$\boxed{T_{in} = T_{out} - \frac{\dot Q}{\dot m_{ref} \cdot \bar c_{p,ref}}}$$ Solution

$\dot{m} = \rho \underset{\text{velocity}}{v} A$

or $\dot{m} = \rho \dot{V}$ → volume flow

$\dot{m} = \frac{\dot{V}}{v}$

$\dot{V} = \underset{\text{velocity}}{v} \cdot A$

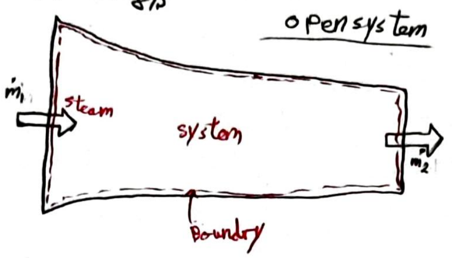
Problem 5.3

$\dot{V}_1 = 0.14692$

$\dot{m} = 2\ Kg/s$

open system

$P_1 = 40\ bar$
$T_1 = 400\ °C$
$V_1 = 10\ m/s$



$P_2 = 15\ bar$
$V_2 = 665\ m/s$

From A-4 at P_1, and T_1 → $h_1 = 3213.6\ KJ/Kg$

assumptions:
- steady-state process
- open system
- $\dot{m}_1 = \dot{m}_2$
- The system is isolated (no heat transfer with the surroundings, $\dot{Q} = 0$)
- reversable processes (no friction)
- Potential energy neglected.

1st Law of thermodynamics:

$$\underbrace{\cancel{\frac{d}{dt} E_{sys}}}_{\text{steady-state } 0} = \underbrace{\cancel{\sum \dot{Q}}}_{0} + \underbrace{\cancel{\sum \dot{P}}}_{0} + \sum \dot{m} \cdot e$$

$$e = \underbrace{e_{Kin}}_{\frac{1}{2}v^2} + \underbrace{\cancel{e_{Pot}}}_{0} + \underbrace{u + Pv}_{h}$$

(take care $(\frac{1}{2}v^2) = [\frac{Jole}{Kg}]$ when $v = [m/s]$)

$$\dot{m}(h_1 + \frac{1}{2}V_1^2 + h_2 + \frac{1}{2}V_2^2) = 0 \Rightarrow h_2 = h_1 + \frac{1}{2}V_1^2 - \frac{1}{2}V_2^2$$

$$= 3213.6\ KJ/Kg \cdot \frac{10^3 J}{KJ} + \frac{1}{2}(10\ m/s)^2 - (665\ m/s)^2$$

$$\Rightarrow h_2 = 2992537.5\ J/Kg = 2992.5\ KJ/Kg$$

$\boxed{h_2, P_2}$ → A3 ⇒ $h_2 > h_g$ ⇒ state is super-heated vapour

$\boxed{h_2, P_2}$ → A-4 ⇒ $v = 0.1627\ m^3/Kg$

since $\dot{m} = \rho v A$, and $\rho = \frac{1}{v}$ ⇒ $\boxed{A_2 = \frac{\dot{m} \cdot v_2}{V_2}}$ solution

$A_2 = \pi \frac{d_2^2}{4}$

$\boxed{A_2 = 4.8932331 \times 10^{-4}\ m^2}$

$\therefore \boxed{d_2 = 24.9605\ mm}$

Thermodynamics

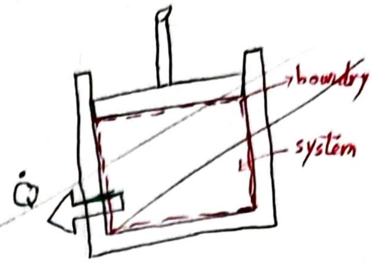
Prob. 4.1

givens

state 1

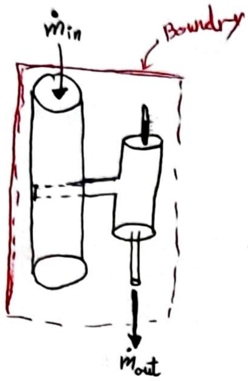
$P_1 = 10$ bar

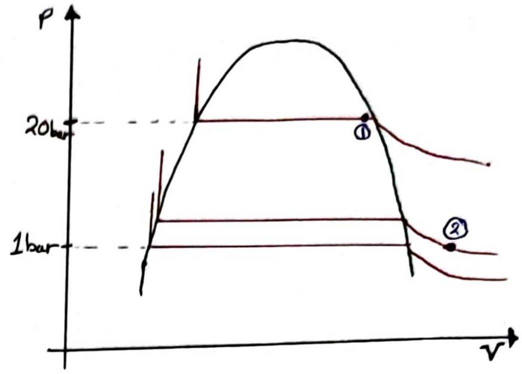
$T_1 = 400°C$



Prob. 5.4

open-system





assumtions:

- steady-state
- reversable processes
- Potenial and kinetic energies are neglitable.

$$\underbrace{\frac{dE_{sys}}{dt}}_{0 \text{ (steadystate)}} = \underbrace{\sum \dot{Q}}_{0} + \underbrace{\sum \dot{P}}_{0} + \sum \dot{m}\, e$$

$$e = \underbrace{e_{kin} + e_{pot}}_{\substack{0 \\ \text{neglegted}}} + \underbrace{u + pv}_{h}$$

$\dot{m}(h_1 - h_2) = 0$

$\therefore \boxed{h_1 = h_2}$

Since state 1 is saturated liq/vap.

$$\therefore h_1 = x_1 h_{g_1} + (1 - x_1) h_{f_1} \Rightarrow x_1 = \frac{h_1 - h_{f_1}}{h_{g_1} - h_{f_1}}$$

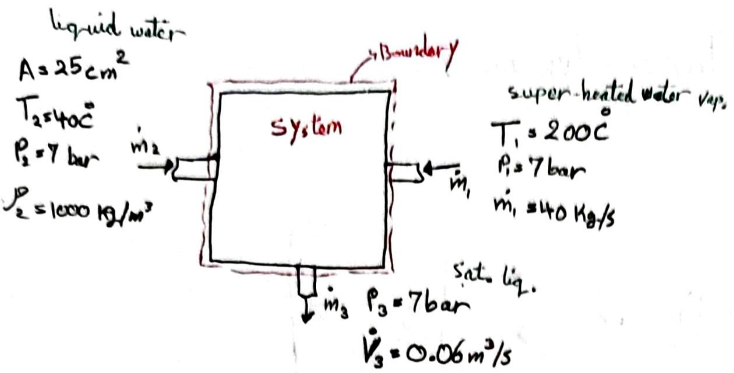
since $h_1 = h_2 \Rightarrow \boxed{x_1 = \frac{h_2 - h_{f_1}}{h_{g_1} - h_{f_1}}}$ Solution

at $\boxed{P_1 = 20 \text{bars}} \rightarrow \boxed{A\text{-}3} \rightarrow h_{g_1} = 2799.5$ KJ/Kg , $h_{f_1} = 908.79$ KJ/Kg

at $\boxed{P_2, T_2} \rightarrow \boxed{A\text{-}4} \rightarrow h_2 = 2716.6$ KJ/Kg

$\boxed{x_1 = 0.956}$

Prob. 5.5



assumptions:

- open system
- Steady-state
- potenial energy neglected
- reversable process (no friction)

continuity equation $\rightarrow \dot m_3 = \dot m_1 + \dot m_2$

$\Rightarrow \boxed{\dot m_2 = \dot m_3 - \dot m_1}$ solution

at $\boxed{P_3 = 7\,bar} \rightarrow \underline{A\text{-}3} \rightarrow v_3 = v_{f_3} = 1.108\times10^{-3}\,m^3/Kg$

$$\dot m_3 = \frac{\dot V_3}{v_3} = \frac{0.06\,\cancel{m^3}/s}{1.108\times10^{-3}\,\cancel{m^3}/Kg} = 54.152\,Kg/s$$

$$\therefore \boxed{\dot m_2 = \dot m_3 - \dot m_1 = 14.152\,Kg/s}$$

$$\dot m_2 = \rho_2 V_2 A_2 \Rightarrow V_2 = \frac{\dot m_2}{\rho_2 \cdot A_2} = \frac{14.15\,\cancel{Kg}/s}{1000\,\cancel{Kg}/m^3 \cdot 25\,\cancel{cm^2} \cdot \frac{m^2}{10^4\,\cancel{cm^2}}}$$

$$\Rightarrow \boxed{V_2 = 5.661\,m/s}$$

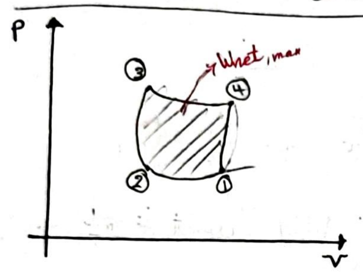
Thermodynamics 6/12/2021

Carnot Cycle

Ideal cycle $\rightarrow$ no irreversibilities (reversibile)

$$\eta_{carnot} = 1 - \frac{T_C}{T_H}$$

maximum possible efficiency



$$\eta_{thermal} = \frac{W_{net}}{Q_{in}} = \frac{P_{net}}{\dot{Q}_{in}}$$

$$= \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$\eta_{carnot} = \eta_{thermal}$$

$$\cancel{1} - \frac{T_C}{T_H} = \cancel{1} - \frac{Q_{out}}{Q_{in}} \Rightarrow \frac{T_C}{T_H} = \frac{Q_{out}}{Q_{in}}$$

$$\boxed{\frac{Q_{in}}{T_H} = \frac{Q_{out}}{T_C}}$$

Clausius introduced entropy (S)

$S = \frac{Q}{T}$ $\quad [S] = \frac{J}{K}$, $[s] = \left[\frac{J}{Kg \cdot K}\right]$

$dS = \frac{dQ}{T}$

Const

With Irreversibilities (real process)

From Carnot $\xrightarrow{to}$ real process
ideal process

$$\frac{Q_{in}}{T_H} - \frac{Q_{out}}{T_C} = 0$$

$$S_{in} - S_{out} = 0$$

no change in entropy (S)

$$dS = 0$$

For the system it's a gain, for us it's a loss, because we need more power

Sigma (a name)

$$\frac{Q_{in}}{T_H} - \frac{Q_{out}}{T_C} + \sigma = 0$$

irreversibility

$$\frac{Q_{in}}{T_H} - \frac{Q_{out}}{T_C} = -\sigma \quad \hookrightarrow \left[\frac{J}{K}\right]$$

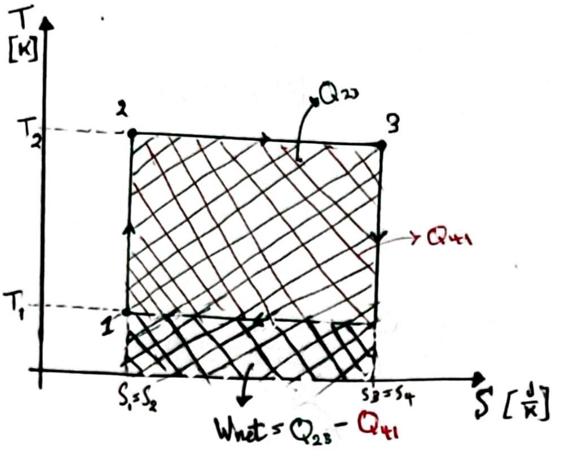
$\sigma > 0$ (irreversibility present Possible!)

$\sigma = 0$ (ideal case) reversible

$\sigma < 0 \rightarrow$ impossible!

$$S_{in} - S_{out} + \sigma = 0$$

$$\text{Cycle: } \oint dS = -\sigma$$



$1 \to 2$ adiabatic compression

S = Cons.

isentropic

$2 \to 3$

$$T_H (S_3 - S_1) = Q_{23}$$

area under $\underline{2 \to 3 \text{ line}}$

$3 \to 4$ adiabatic expan.

S = cons.

isentrobic

$4 \to 1$

$$T_C (S_4 - S_1) = Q_{41}$$

$$W_{net} = \text{area} = Q_{23} - Q_{41}$$

$$\eta_{thermal} = 1 - \frac{Q_{41}}{Q_{23}} = 1 - \frac{T_C (S_4 - S_1)}{T_H (S_3 - S_1)}$$

$$\eta_{thermal} = 1 - \frac{T_C}{T_H} = \eta_{carnot}$$

Entropy S

Air

(1) Ideal gas law $Pv = RT$

(2) internal energy $du = c_v \cdot dT$

(3) Enthalpy $dh = c_p \cdot dT$

$ds = \frac{dq}{T}$ 1st rule: $du = dq + dw$

$dq = T\,ds \rightarrow$ 2nd rule: $du = T\,ds + dw$

work on the system $\rightarrow dw = -P\,dv$

$\therefore du = T\,ds - P\,dv$

$c_v\,dT$

$$\rightarrow ds = \frac{du}{T} + \frac{P}{T}\,dv \qquad \frac{P}{T} = \frac{R}{v}$$

$$\int_1^2 ds = \int_1^2 \frac{c_v\,dT}{T} + \int_1^2 \frac{R}{v}\,dv$$

assumptions:
$R =$ cons.
$C_v =$ cons.

$$S_2 - S_1 = c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{V_2}{V_1}\right)$$

Entropy change of an ideal gas

Ideal gas $$p \cdot v = R \cdot T$$

$$du = c_V \, dT \qquad dh = c_P \, dT$$

$$du = T\,ds - p \cdot dv \qquad dh = T\,ds + v\,dp$$

$$ds = \frac{du}{T} + \frac{p}{T} dv \qquad ds = \frac{dh}{T} - \frac{v}{T} dp$$

$$ds = c_V(T) \cdot \frac{dT}{T} + R \cdot \frac{dv}{v} \qquad ds = c_P(T) \cdot \frac{dT}{T} - R \cdot \frac{dp}{p}$$

Assumption: $c_V = \text{const.}$ $\qquad c_P = \text{const.}$

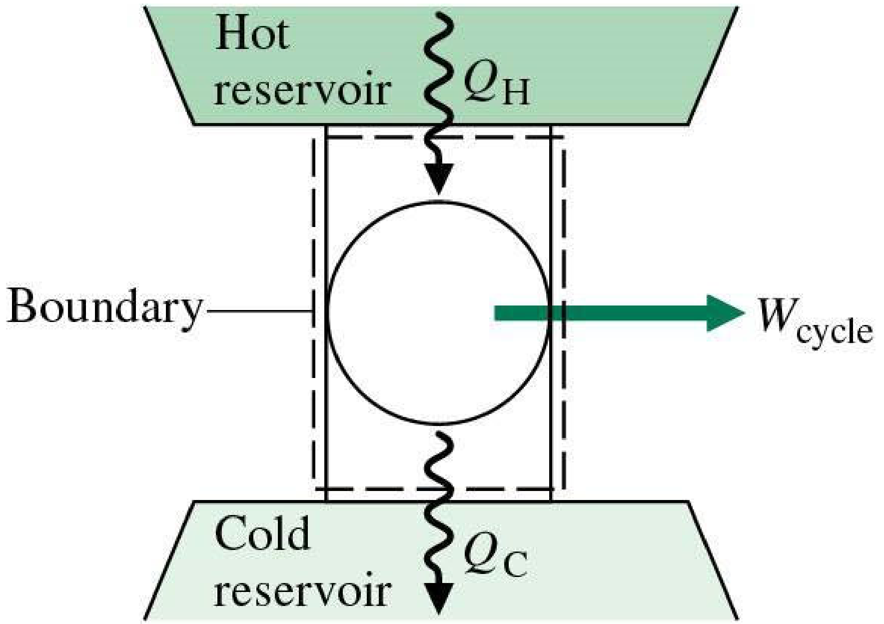
$$\Delta s_{2\to 1} = c_V \cdot \ln \frac{T_2}{T_1} + R \cdot \ln \frac{v_2}{v_1} \qquad \Delta s_{2\to 1} = c_P \cdot \ln \frac{T_2}{T_1} - R \cdot \ln \frac{p_2}{p_1}$$

Problem 6.1
Efficiency versus Clausius inequality

A system executes a power cycle while receiving 1,000 kJ by heat transfer at a temperature of 500 K and discharging energy by heat transfer at a temperature of 300 K. There are no other heat transfers. Determine σ_{cycle} if the thermal efficiency is

(a) 60%
(b) 40%
(c) 20%

Identify the cases (if any) that are internally reversible, irreversible or impossible.



Problem 6.1
Efficiency versus Clausius inequality

Solution

$$\oint dS = \oint \frac{dQ}{T} = -\sigma_{cycle}$$

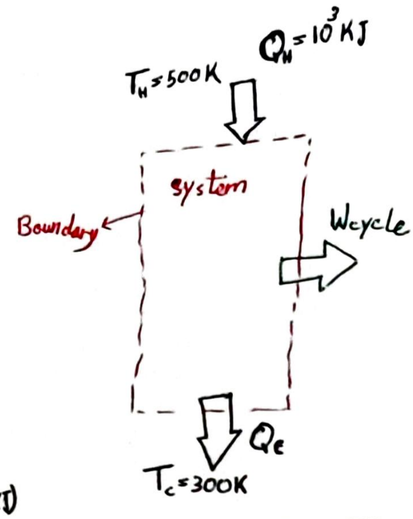
(a) $\sigma_{cycle} = -0.667\ \frac{kJ}{K}$ impossible

(b) $\sigma_{cycle} = 0$ reversible / maximum efficiency

(c) $\sigma_{cycle} = +0.667\ \frac{kJ}{K}$ irreversible

Prob. 6.1 — Thermodynamics

Determine σ = ?



* closed system → $\dot{m} = 0$
* steady-state → $\frac{dE_{sys}}{dt} = 0$

$$\oint dS = \oint \frac{dQ}{T} = -\sigma_{cycle}$$

a) if $\eta_{thermal} = 60\% = 0.6$

$$\eta_{thermal} = 1 - \frac{Q_c}{Q_H} = 0.6 \Rightarrow \frac{Q_c}{Q_H} = 1 - 0.6 = 0.4$$

$$\Rightarrow Q_c = 0.4(10^3 KJ) = 400 KJ$$

2nd rule of thermo!

$$\frac{Q_H}{T_H} - \frac{Q_c}{T_c} = -\sigma \Rightarrow S_{in} - S_{out} = -\sigma$$

$$\frac{10^3 KJ}{500K} - \frac{400 KJ}{300K} = -\sigma \Rightarrow \boxed{\sigma = -\frac{2}{3}} < 0$$

impossible units!

b) if $\eta_{th} = 0.4 \Rightarrow Q_c = (1 - \eta_{th}) Q_H = 600 KJ$

$$\frac{Q_H}{T_H} - \frac{Q_c}{T_c} = -\sigma \Rightarrow \frac{10^3 KJ}{500K} - \frac{600 KJ}{300 K} = \boxed{0 = \sigma}$$ reversible processes.

c) if $\eta_{th} = 0.2 \Rightarrow Q_c = (1 - \eta_{th}) Q_H = 800 KJ$

$$\frac{10^3 KJ}{500K} - \frac{800 KJ}{300K} = -\sigma \Rightarrow -\sigma = -\frac{2}{3} \Rightarrow \boxed{\sigma = \frac{2}{3}} > 0$$

irreversibile processes.

Problem 6.2

Heat transformer and Clausius inequality

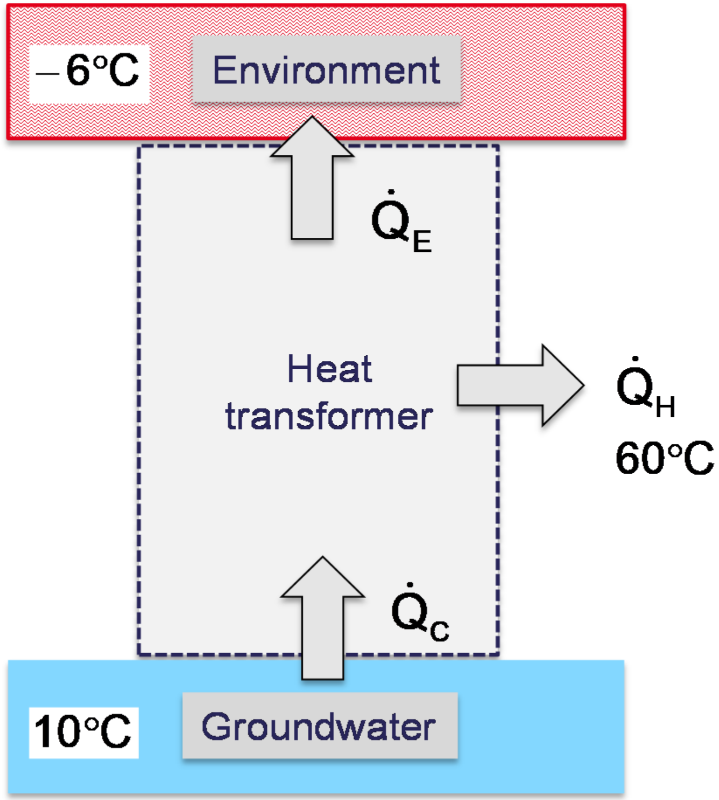
A heat transformer extracts heat from a large groundwater reservoir at a temperature of 10°C. The extracted heat flow amounts to 100 kW.

Operating at steady-state conditions, a heat flow of 15 kW is provided for heating purposes at a temperature of 60°C, while a heat flow of 85 kW is released to the environment.

The temperature of the environment can be assumed as - 6°C.

Is it possible to operate a real transformer under these conditions?

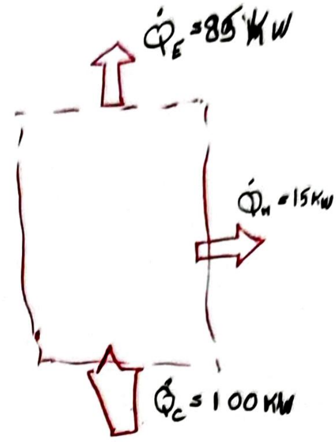
Provide proof by applying the 1st and 2nd rule of thermodynamics.



Prob. 6.2

1st Law :

Closed , steady-state system



$$\cancelto{0}{\frac{dE_{sys}}{dt}} = \sum \dot{Q} + \cancelto{0}{\sum \dot{W}} + \cancelto{0}{\sum \dot{m} \cdot e}$$

$$\dot{Q}_C = \dot{Q}_H + \dot{Q}_E \checkmark$$

2nd rule :

$$\frac{Q_{in}}{T_{hot}} - \frac{Q_{out}}{T_{cold}} = -\sigma$$

$$\frac{100\,KW}{(10+273)K} - \frac{\cancel{100\,KW}\ 15\,Kw}{(60+273)K} - \frac{85\,Kw}{(273-6)K} = -\sigma$$

$\sigma = 0.01 \frac{KW}{K}$ $\quad$ $\sigma > 0$ possible

or $10 \frac{W}{K} > 0$

Entropy change of an ideal gas

Mention num. of Lecture, and page then, use the equation directly

Ideal gas $$p \cdot v = R \cdot T$$

$$du = c_V \, dT \qquad dh = c_P \, dT$$

$$du = T\,ds - p \cdot dv \qquad dh = T\,ds + v\,dp$$

$$ds = \frac{du}{T} + \frac{p}{T} dv \qquad ds = \frac{dh}{T} - \frac{v}{T} dp$$

$$ds = c_V(T) \cdot \frac{dT}{T} + R \cdot \frac{dv}{v} \qquad ds = c_P(T) \cdot \frac{dT}{T} - R \cdot \frac{dp}{p}$$

Assumption: $c_V = \text{const.}$ $\qquad c_P = \text{const.}$

$$\Delta s_{2\to1} = c_V \cdot \ln \frac{T_2}{T_1} + R \cdot \ln \frac{v_2}{v_1} \qquad \Delta s_{2\to1} = c_P \cdot \ln \frac{T_2}{T_1} - R \cdot \ln \frac{p_2}{p_1}$$

Problem 6.3
Carnot cycle using air

One (1) kilogram of air as an ideal gas executes a Carnot power cycle having a thermal efficiency of 60%. The heat transfer to the air during the isothermal expansion is 40 kJ. At the end of the isothermal expansion, the pressure is 5.6 bar and the volume is 0.3 m³.

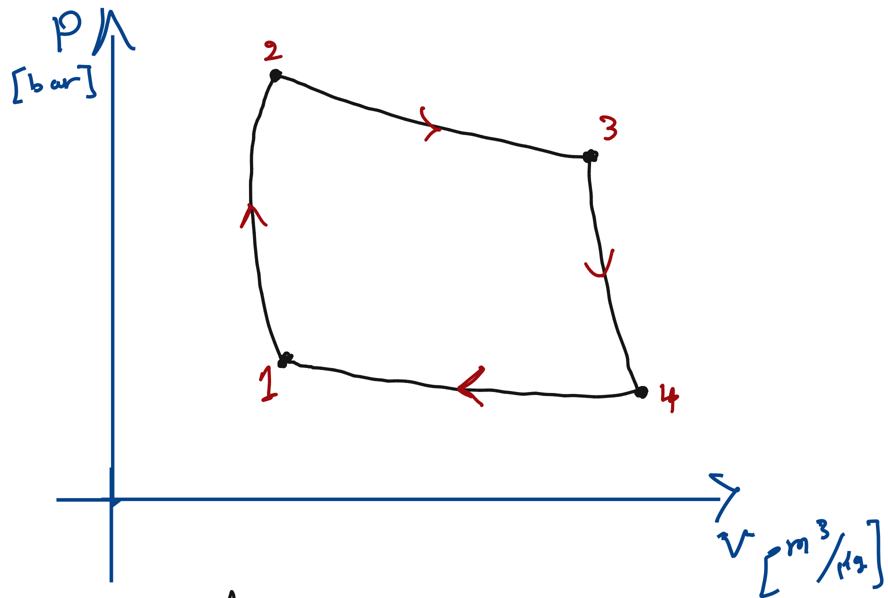
(a) Sketch the cycle on p-v coordinates.

(b) Determine the maximum and minimum temperatures for the cycle, in K.

(c) Determine the pressure and volume at the beginning of the isothermal expansion in bar and m³, respectively.

(d) Determine the work and heat transfer for each of the four processes, in kJ.

a)



assumptions:
* closed system $\rightarrow \dot{m} = 0$
* steady-state processes $\rightarrow \frac{dE_{sys}}{dt} = 0$
* c_v, c_p = cons.
* $R_{air} = 287\ J/kg.K$

Fundamentals of Engineering Thermodynamics; 6e, SI Version, 2010, p. 203

Problem 6.3

$1 \to 2$ Adiabatic comp.

$2 \to 3$ Isothermal exp.

$3 \to 4$ Adiabatic exp.

$4 \to 1$ Isothermal comp.

State	P [bar]	T [K]	V [m^3/Kg]	u
1		234.2		
2	7.12	585.4	0.236	
3	5.6	585.4	0.3	
4		234.2		

Process	Q [KJ]	W [KJ]
$1 \to 2$	0	252.2
$2 \to 3$	40	40
$3 \to 4$	0	252.2
$4 \to 1$	16	16

at state 3

$$P_3 V_3 = R T_3 \Rightarrow T_3 = \frac{PV}{R} = \frac{5.6\,\cancel{bar} * \frac{10^5\,\cancel{N/m^2}}{\cancel{bar}} \cdot 0.3\,\frac{m^3}{1\,\cancel{Kg}}}{287\,\cancel{J}/\cancel{Kg}\cdot K} \quad Nm = J$$

$$\Rightarrow T_3 = 585.4\ K = T_2 \longrightarrow \text{Isothermal process}$$

Process $1 \to 2$ or $3 \to 4$

$$\eta_{th} = \eta_{carnot} = 0.6$$

$$\Rightarrow 1 - \frac{T_c}{T_H} = 0.6 \Rightarrow T_c = T_H (1 - 0.6)$$

$$\Rightarrow T_H = 585.4K \cdot 0.4 = 234.2K \Rightarrow \underline{T_H = T_1 = T_4}$$

At state 2

ideal gas Law $\to P_2 V_2 = R T_2 \Rightarrow P_2 = \frac{R T_2}{V_2}$

$$P_2 = \frac{287\,\cancel{J}/\cancel{Kg}\cdot\cancel{K} * 585.4\,\cancel{K}}{0.236\,m^3/\cancel{Kg}} \times 10^{-5}\,\frac{bar}{N/m^2} = 7.12\ bar \quad Nm$$

Process $2 \to 3$ Isothermal exp.

$$S_{23} = \underbrace{\cancel{C_v \ln\left(\frac{T_3}{T_2}\right)}}_{0} + R \ln\left(\frac{V_3}{V_2}\right)$$

$$\frac{Q_{23}}{T} = R \ln\left(\frac{V_3}{V_2}\right)$$

$$\Rightarrow V_2 = V_3 / e^{\frac{Q_{23}}{T \cdot R}} \Rightarrow V_2 = 0.236\ m^3/Kg$$

$$V_2 = V_2 \cdot m = 0.236\ m^3$$

Process $1 \rightarrow 2$

Adiabatic comp.

$$m(u_2 - u_1) = \cancel{Q_{12}}^{\,0} + W_{12}$$

on the system

$$W_{12} = m \cdot c_v (T_2 - T_1) = 1\,\cancel{kg}\,(0.718\ kJ/\cancel{kg}\cdot\cancel{K})(585.4 - 234.2)\,\cancel{K}$$

$$\Rightarrow W_{12} = 252.2\ kJ$$

Process $2 \rightarrow 3$

Isothermal exp.

by the system

$$\cancel{du}^{\,0} = dq_{23} - dw_{23}$$

$$\cancel{du}^{\,0} = c_v\,\cancel{\Delta T}^{\,0}$$

$$\therefore Q_{23} = W_{23} = 40\ kJ$$

Process $3 \rightarrow 4$

Adiabatic exp.

$$m(u_4 - u_1) = \cancel{Q_{34}}^{\,0} - W_{34}$$

work done by the system

$$W_{34} = -m c_v (T_4 - T_3) = -1\,\cancel{kg}\,(0.718\ kJ/\cancel{kg}\cdot\cancel{K})(234.2 - 585.4)\,\cancel{K}$$

$$\Rightarrow W_{34} = 252.2\ kJ$$

Process $4 \rightarrow 1$

Isothermal comp.

$$\eta_{th} = 1 - \frac{Q_C}{Q_H} = 1 - \frac{Q_{41}}{Q_{23}} = 60\% \Rightarrow Q_{41} = Q_{23}(1 - 0.6) = 16\ kJ$$

1st Law: $m\,\cancel{du}^{\,0} = -Q_{41} + W_{41}$ $\Rightarrow$ $W_{41} = Q_{41} = 16\ kJ$

because $\Delta T = 0$

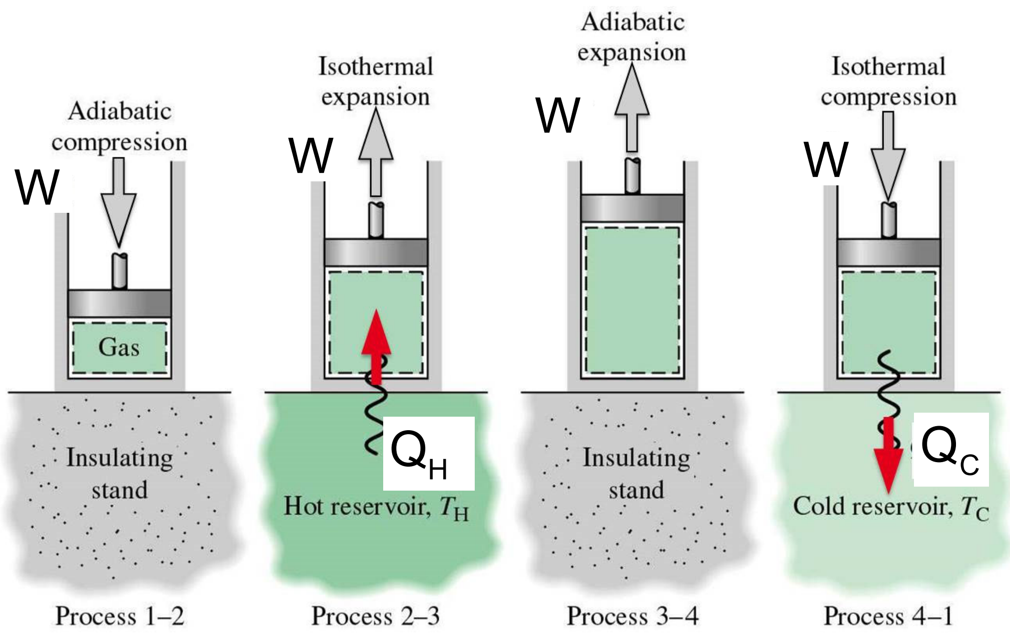
Loss heat

on the system

Problem 6.3
Carnot cycle using air

Solution	Q [kJ]	W [kJ]
1 → 2	0.0	256.7
2 → 3	40	40
3 → 4	0.0	256.7
4 → 1	16.0	16.0

Sign convention



Problem 6.4

Carnot cycle using water

Two kilograms of water execute a Carnot power cycle. During the isothermal expansion, the water is heated until it is a saturated vapor from an initial state there the pressure is 40 bar and the quality is 15%. The vapor expands adiabatically to a pressure of 1.5 bar while doing 491.5 kJ/kg of work.

(a) Sketch the cycle on a p-v diagram and on a T-s diagram.

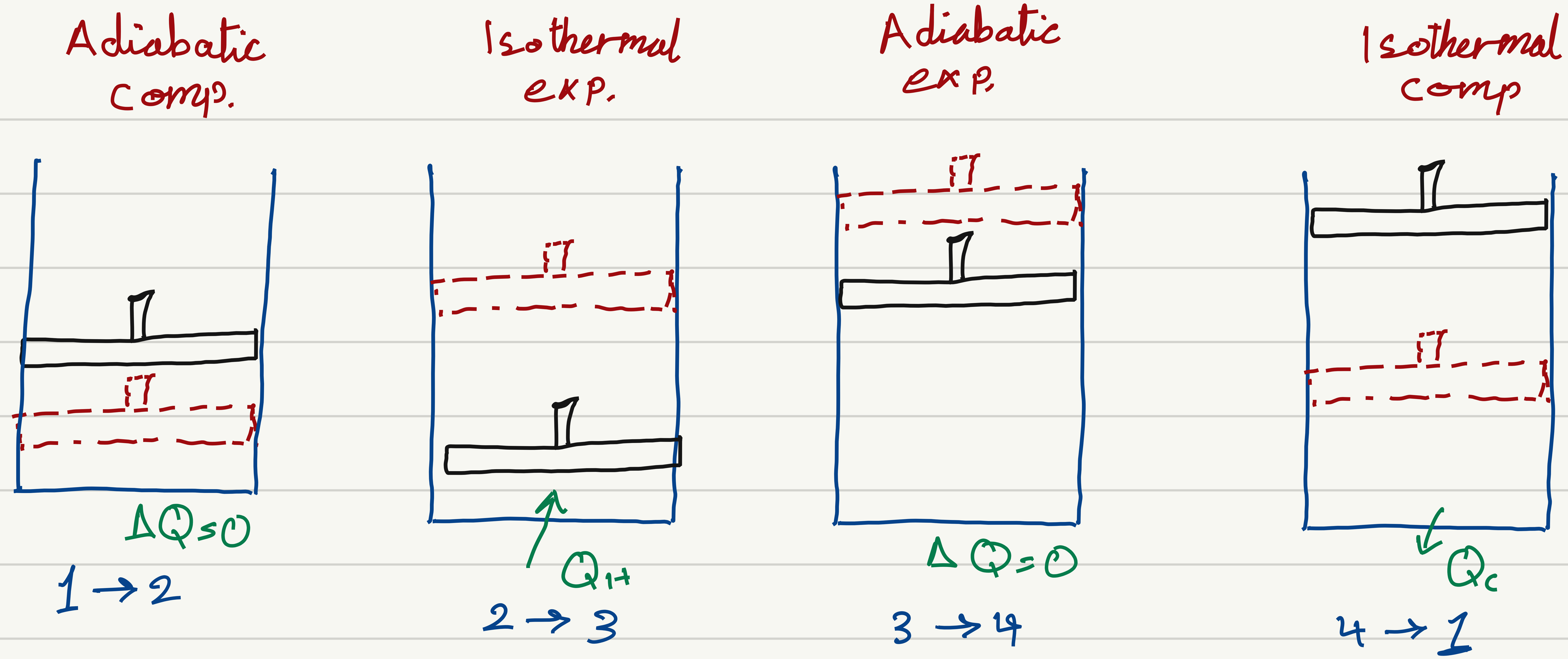
(b) Evaluate the heat and work for each process, in kJ.

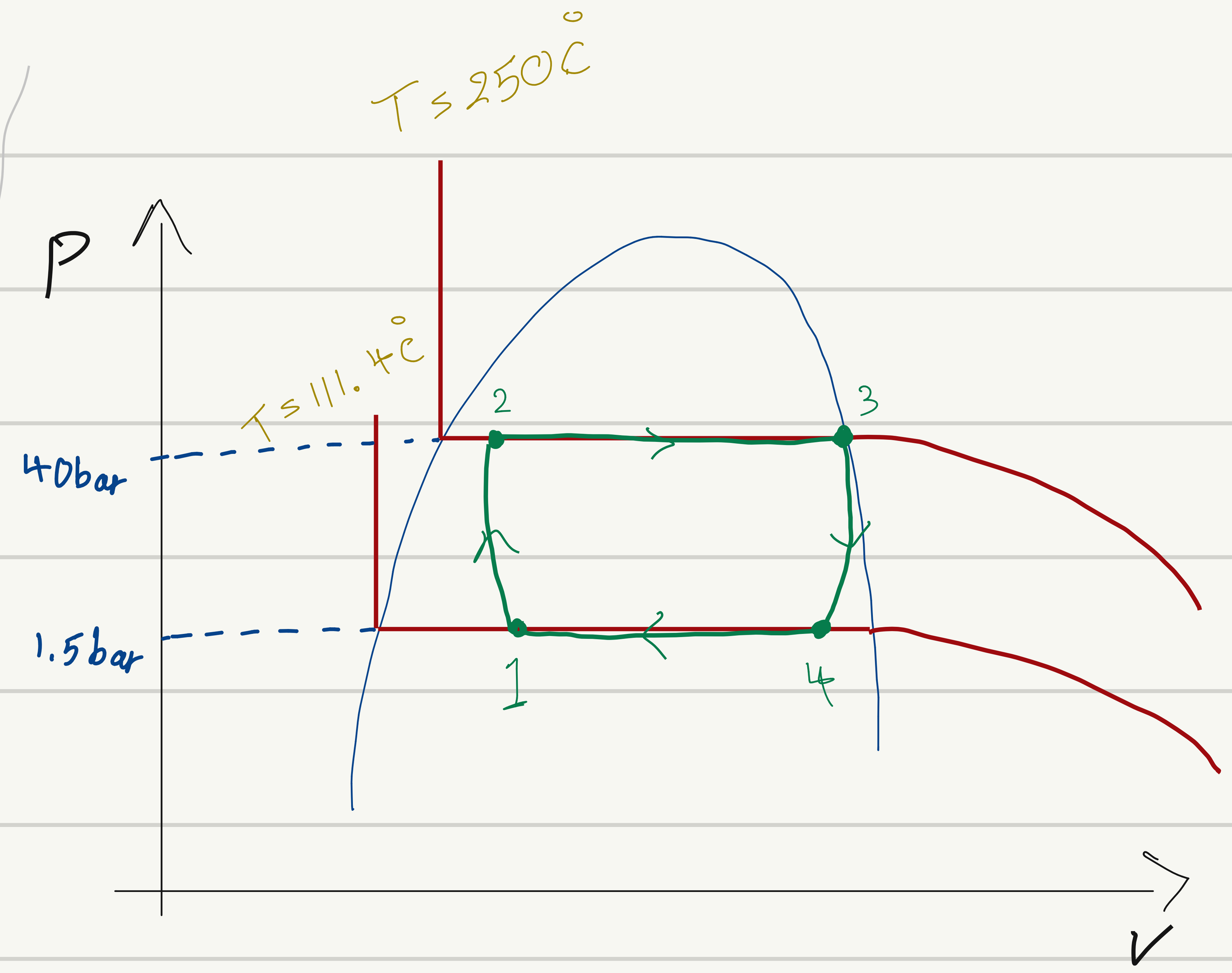
(c) Evaluate the thermal efficiency.

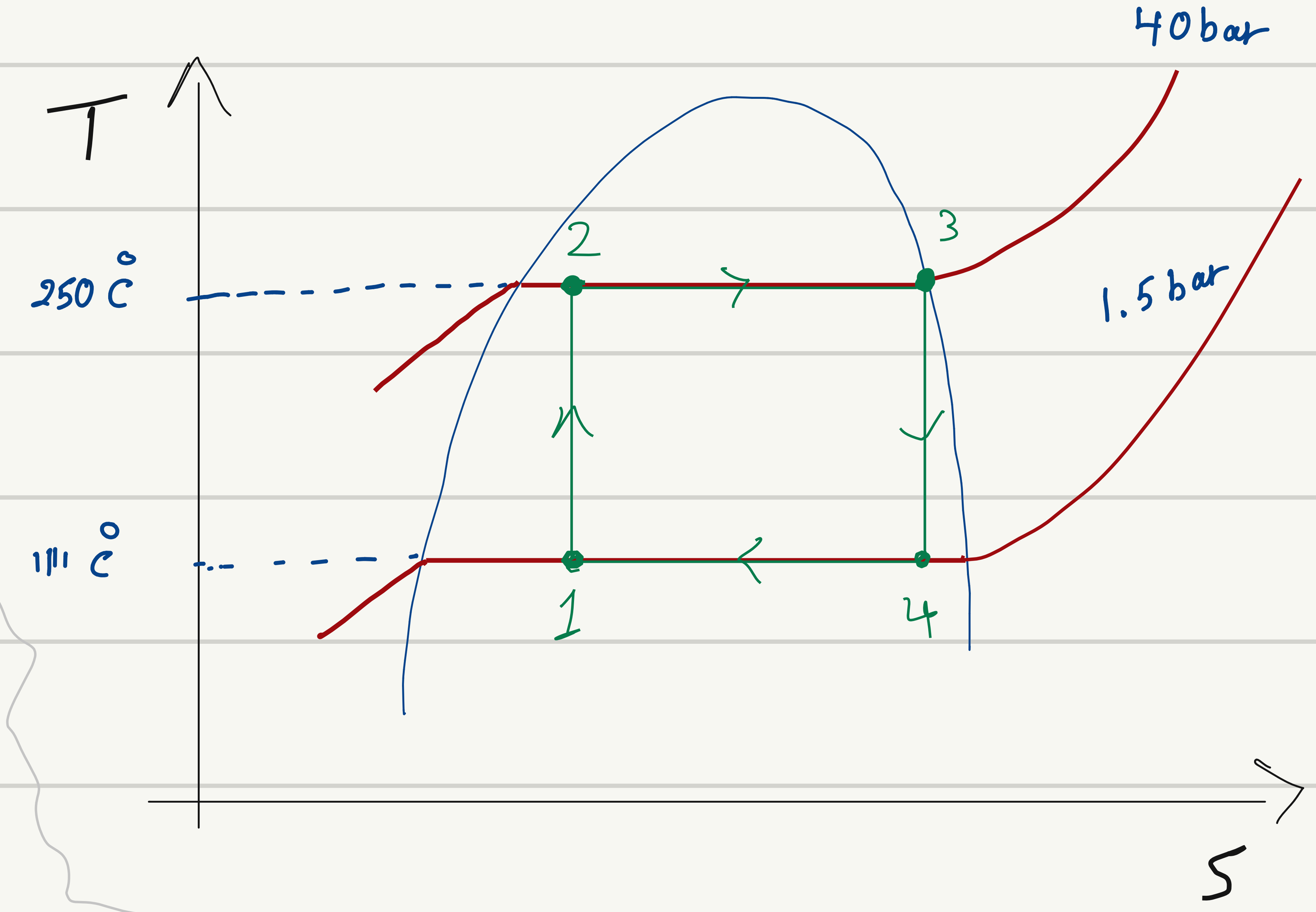
State	p [bar]	T [C°]	v [m^3/kg]	x	u [kJ/kg]	s [kJ/kg·K]	
1	1.5	111		0.32	1124	$= s_2$	↓ isentrobic
2	40	250		0.15	1310.3	3.287	
3	40	250	0.04978	1	2602.3	6.0701	↓ Isentrobic
4	1.5	111		0.8	2110.8	$= s_3$	

Process	Q [kJ]	W [kJ]
1 → 2	0	372.5
2 → 3	2913.35	329.35
3 → 4	0	983
4 → 1	2193.65	4113

Assumptions:-
* closed system → $\dot{m} = 0$
* steady-state
*







Process 2 → 3

Isothermal exp.

$P_2 = 40\,\text{bar}$, $x_2 = 0.15 \rightarrow$ A-3 table $\rightarrow T_2 = 250\,^\circ C$

$s_{g_2} = 6.0701\ \text{KJ/Kg·K}$, $s_{f_2} = 2.7964\ \text{KJ/Kg·K}$, $u_{g_2} = 2602.3\ \text{KJ/Kg}$, $u_{f_2} = 1082.3\ \text{KJ/Kg}$

$s_2 = x_2 s_{g_2} + (1-x_2) s_{f_2} = 3.287\ \text{KJ/Kg·K}$

$u_2 = x_2 u_{g_2} + (1-x_2) u_{f_2} = 1310.3\ \text{KJ/Kg}$

Since $x_3 = 1$ (saturated vapour) $\rightarrow P_2 = P_3 = 40$ bar, $T_2 = T_3 = 250\,^\circ C$ → isothermal $\Delta T = 0$

$s_3 = s_{g_3} = 6.0701\ \text{KJ/Kg·K}$, $u_3 = u_{g_3} = 2602.3\ \text{KJ/Kg}$

2nd Law of thermodynamics

$$\int_2^3 ds = \int_2^3 \frac{dQ}{T}, \quad T = \text{cons}$$

$$\therefore m(s_3 - s_2) = \frac{Q_{23}}{T_H} \Rightarrow 2\,\text{Kg}\,(6.0701 - 3.287)\,\text{KJ/Kg·K}\,(250+273)\,\text{K} = Q_{23}$$

$Q_{23} = 2913.35\ \text{KJ}$

1st Law of thermodynamics: $du = dq + dw$

$$m(u_3 - u_2) = Q_{23} \underset{\text{by the system}}{-} W_{23} \longrightarrow W_{23} = 2913.35\,\text{KJ} - 2\,\text{Kg}\,(2602.3 - 1310.3)\,\text{KJ/Kg}$$

$\Rightarrow W_{23} = 329.35\ \text{KJ}$

work done by the system

Process $3 \to 4$ Adiabatic exp.

$P_4 = 1.5$ bar , saturated $x_4 = ?$ (from the diagrams) $\longrightarrow$ A-3 $\longrightarrow T_4 = 111\,°C$

since the process is Adiabatic + reversable = Isentropic ($\Delta S = 0$) $\longrightarrow s_4 = s_3 = 6.0701$ KJ/Kg·K

from (A-3) $\longrightarrow$ $S_{g_4} = 7.2233$ KJ/Kg·K , $S_{f_4} = 1.4336$ KJ/Kg·K , $u_{g_4} = 2519.7$ KJ/Kg , $u_{f_4} = 466.94$ KJ/Kg

$$x_4 = \frac{s_4 - s_{f_4}}{s_{g_4} - s_{f_4}} = \frac{(6.0701 - 1.4336)\,\cancel{KJ/Kg\cdot K}}{(7.2233 - 1.4336)\,\cancel{KJ/Kg\cdot K}} = 0.8 \quad , \quad u_4 = u_{g_4} x_4 + (1 - x_4)\, u_{f_4} = 2110.83\ KJ/Kg$$

$$\text{1st Law: } m(u_4 - u_3) = \underset{\text{adiabatic}}{\underbrace{Q_{34}}_{0}} \overset{\text{by the system}}{-} W_{34} \Longrightarrow W_{34} = -2\,\cancel{Kg}\,(2110.83 - 2602.3)\ KJ/\cancel{Kg} = 982.943\ KJ$$

Process $1 \to 2$ Adiabatic comp.

from the diagrams we can see $T_1 = T_4 = 111\,°C$, $P_1 = P_4 = 1.5$ bar , and since the process is Isentropic $\longrightarrow S_1 = S_2 = 3.287$ KJ/Kg·K

from A-3 table at $P_1 = P_4 \longrightarrow S_{g_1} = S_{g_4}$, $S_{f_1} = S_{f_4}$, $u_{g_1} = u_{g_4}$, $u_{f_1} = u_{f_4}$

$$X_1 = \frac{S_1 - S_{f_1}}{S_{g_1} - S_{f_1}} = \frac{(3.287 - 1.4336)\,\cancel{KJ/Kg\cdot K}}{(7.2233 - 1.4336)\,\cancel{KJ/Kg\cdot K}} = 0.32$$

$$u_1 = x_1 u_{g_1} + (1 - x_1)\, u_{f_1} = 1124.07\ KJ/Kg$$

$$\text{1st Law: } m(u_2 - u_1) = \overset{0}{\cancel{Q_{12}}} \overset{\text{work done on the system}}{+} W_{12} \Longrightarrow W_{12} = 2\,\cancel{Kg}\,(1310.3 - 1124.07)\ KJ/\cancel{Kg} = 372.5\ KJ$$

Process $4 \rightarrow 1$ Isothermal comp.

2nd law of thermodynamics: $m\int_4^1 ds = \int_4^1 \frac{dQ}{T_4}$

$$m(s_4 - s_1) = \frac{Q_{41}}{T_4} \Rightarrow Q_{41} = 2\cancel{Kg}\cdot(6.0701 - 3.287)\, KJ/\cancel{Kg}\cdot\cancel{K}\ (111+273)\,\cancel{K} \Rightarrow \boxed{Q_{41} = 2139.65\, KJ}$$

Heat Loss on the system

1st Law: $m(u_4 - u_1) = -Q_{41} + W_{41} \Rightarrow W_{41} = 2\cancel{Kg}(2110.83 - 1124.07)\, KJ/\cancel{Kg} + 2139.65\, KJ$

$\Rightarrow \boxed{W_{41} = 4113.16}$

c)

$$\eta_{th} = 1 - \frac{Q_{41}}{Q_{23}} = 1 - \frac{2139.65\,\cancel{KJ}}{2913.35\,\cancel{KJ}} = \boxed{0.265}$$

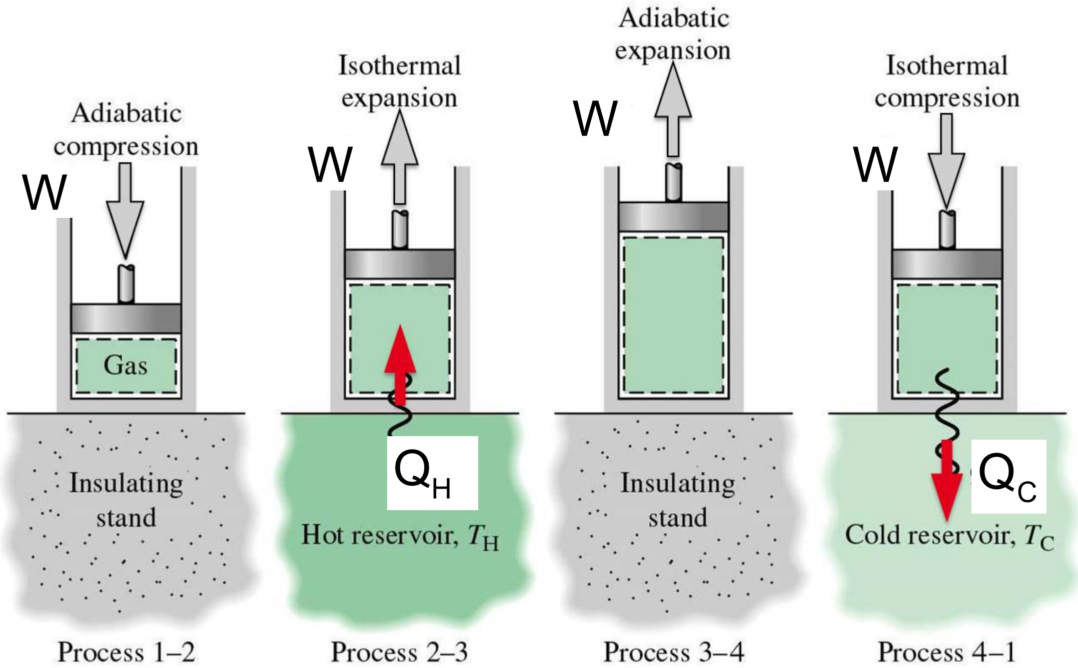
$$\boxed{\eta_{th} = 26.5\%}$$

Problem 6.4
Carnot cycle using water

Solution	Q [kJ]	W [kJ]
1 → 2	0.0	373.0
2 → 3	2,914.0	330.0
3 → 4	0.0	983.0
4 → 1	2,140.2	167.1

$$\eta_{th} = 0.265$$

Sign convention

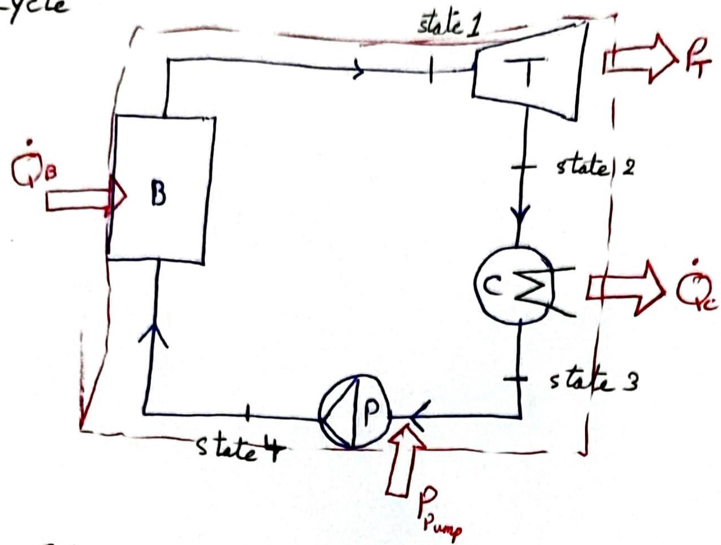


"Rankine cycle"

Ideal cycle

You have to interduce Your states in the exam:-

State 1: fluid turbine in (saturated vapour/steam)



Closed System

1s Law of thermodynamics:

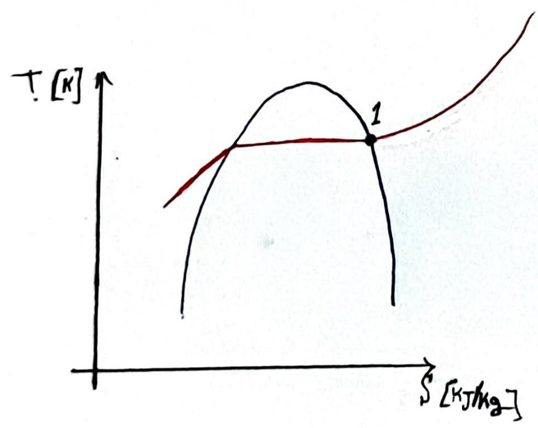
$$\underbrace{\cancel{\frac{dE_{sys}}{dt}}}_{\text{steady state}\ 0} = \sum \dot{Q} + \sum P + \underbrace{\sum \cancel{\dot{m}e}}_{0\ \text{closed system}}$$

$$0 = \dot{Q}_B - \dot{Q}_C + P_P - P_T$$

$$\eta_{thermal} = \frac{\text{Benefits}}{\text{Efforts}} = \frac{\overbrace{P_T - P_P}^{P_{net}}}{\dot{Q}_B} = \frac{\dot{Q}_B - \dot{Q}_C}{\dot{Q}_B} = 1 - \frac{\dot{Q}_C}{\dot{Q}_B}$$

$$= \cancel{1 - \frac{T_C}{T_H}}$$

This Carnot cycle, not valid with "Rankine cycle"



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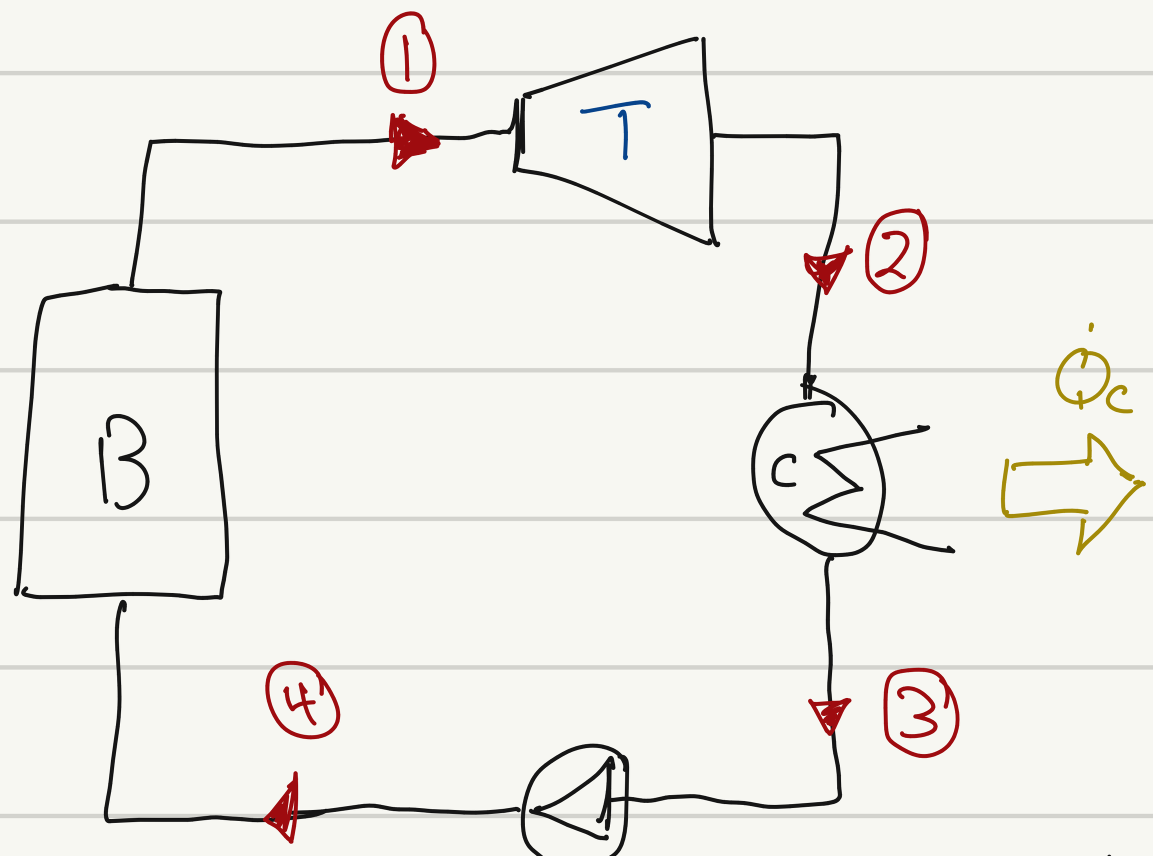
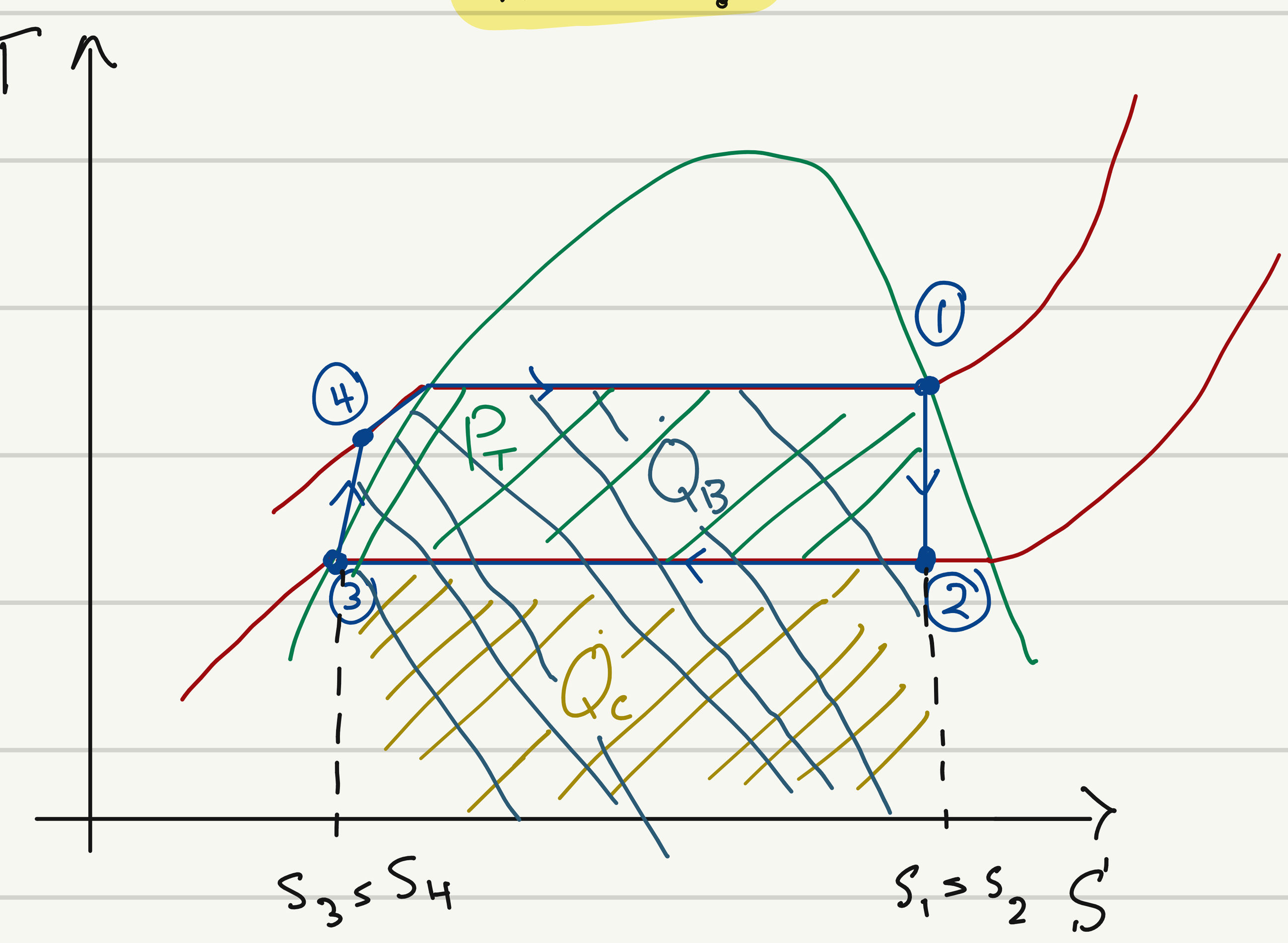
LC 3/1/2022

Vapor power Systems
Rankine Cycle
Isentropic efficiency

Use a ruler to draw strait lines in exam!



Ideal cycle



$0 = -P_T + \dot{Q}_B - \dot{Q}_c$

$P_T = \dot{Q}_B - \dot{Q}_c$

$P_p << P_T$

Process 1 → 2 (output Boiler, inlet Turbine) (saturated vapor) → Isentrobic expantion

Process 2 → 3 → Isobaric condensation

Process 3 → 4 (inlet pump) (saturated Liqued) → Isentrobic compression

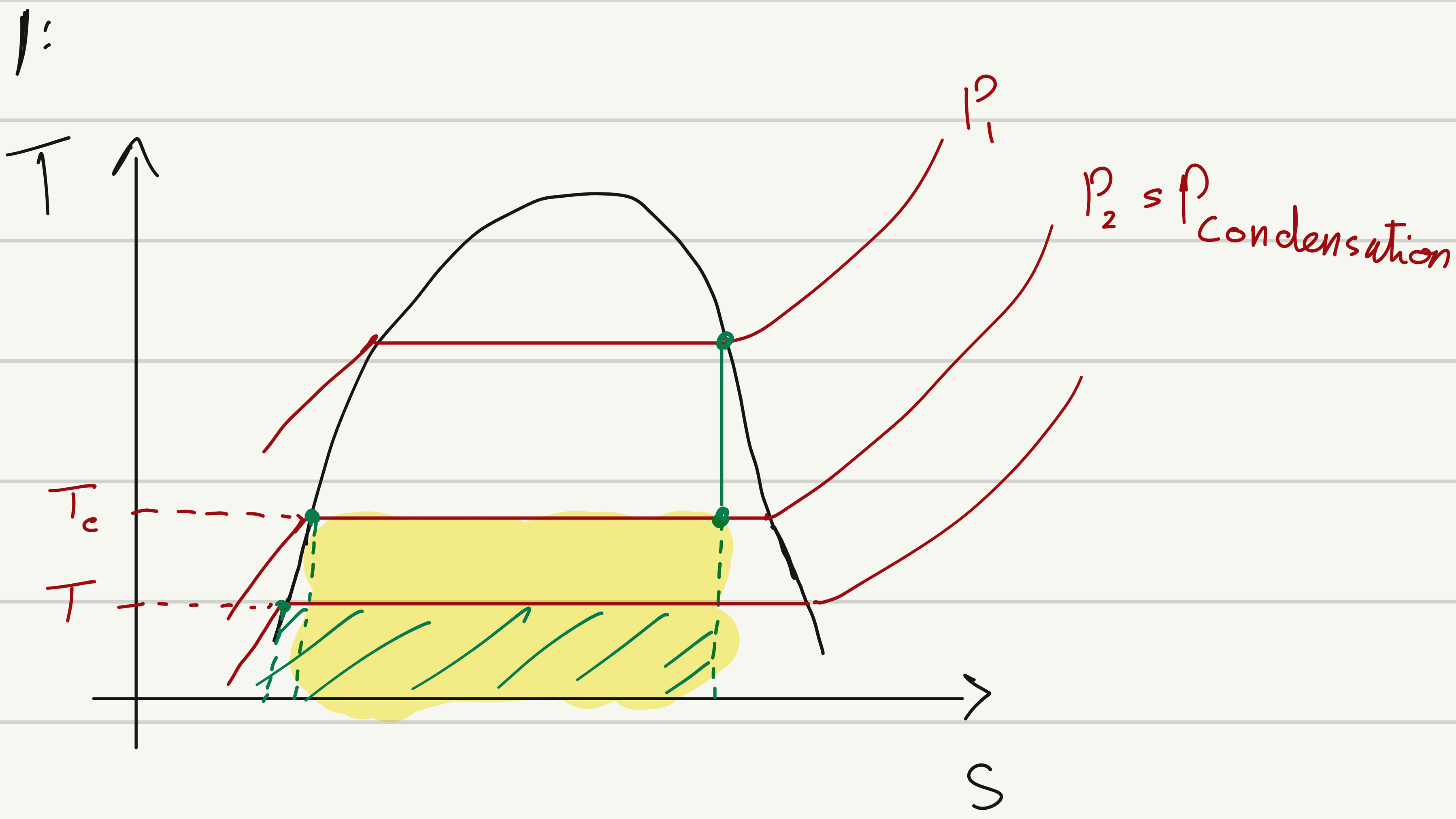
Process 4 → 1 (outlet pump) (compressed liq.) → Isobaric heating

$$\eta_{th} = \frac{P_T}{\dot{Q}_B} = \frac{\dot{Q}_B - \dot{Q}_c}{\dot{Q}_B} = 1 - \frac{\dot{Q}_c}{\dot{Q}_B}$$

option 1 : $\dot{Q}_c \downarrow$, option 2: $\dot{Q}_B \uparrow$

---

option 1:

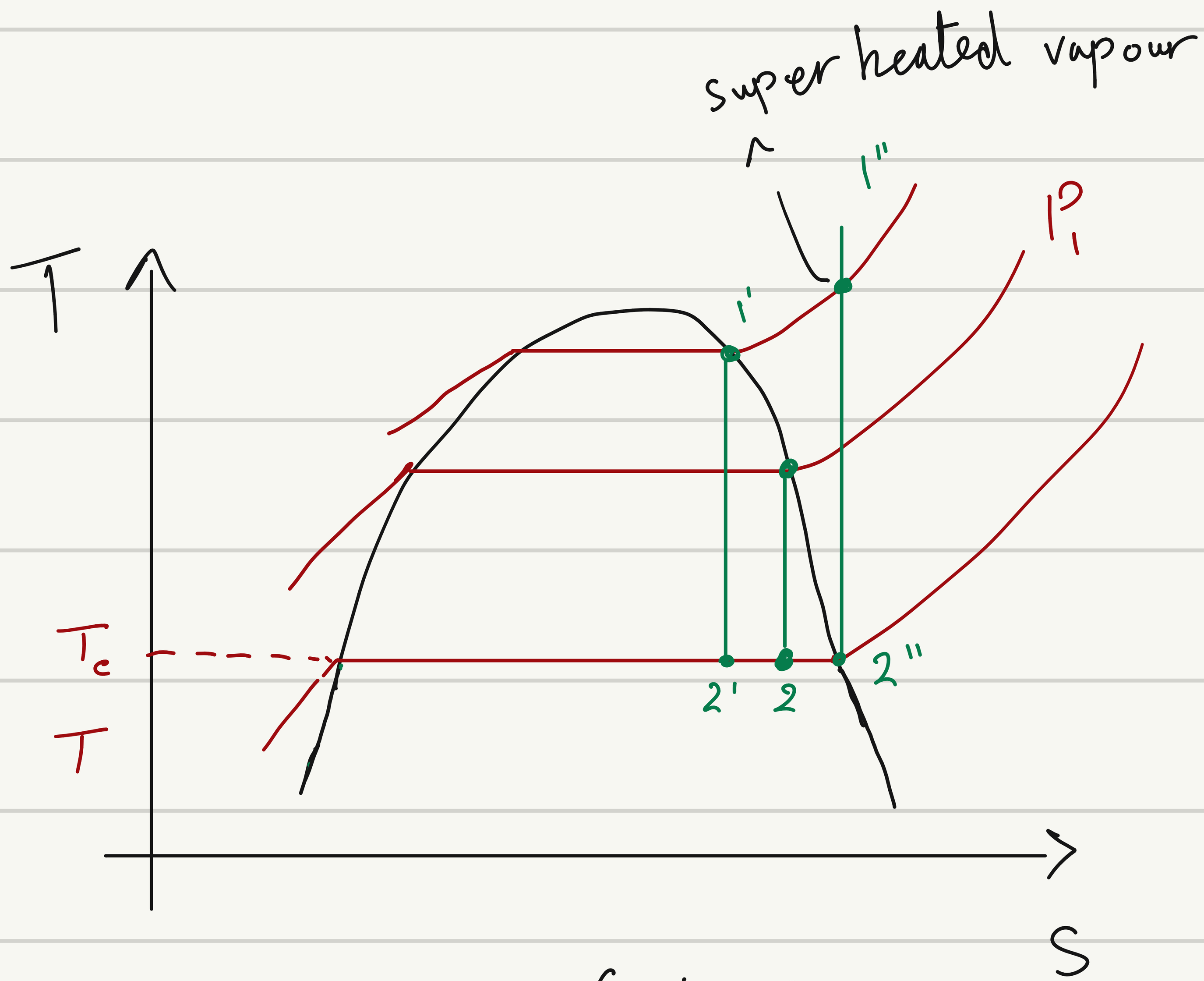


Improvement, How to decrease the yellow area ($\dot{Q}_c$)?

by decreasing P_2

How to decrease P_2 ?

by decreasing Tempreture (cooling the system) (we are limited to the surroundings) option 2 :



$$x_{2'} > x_2$$

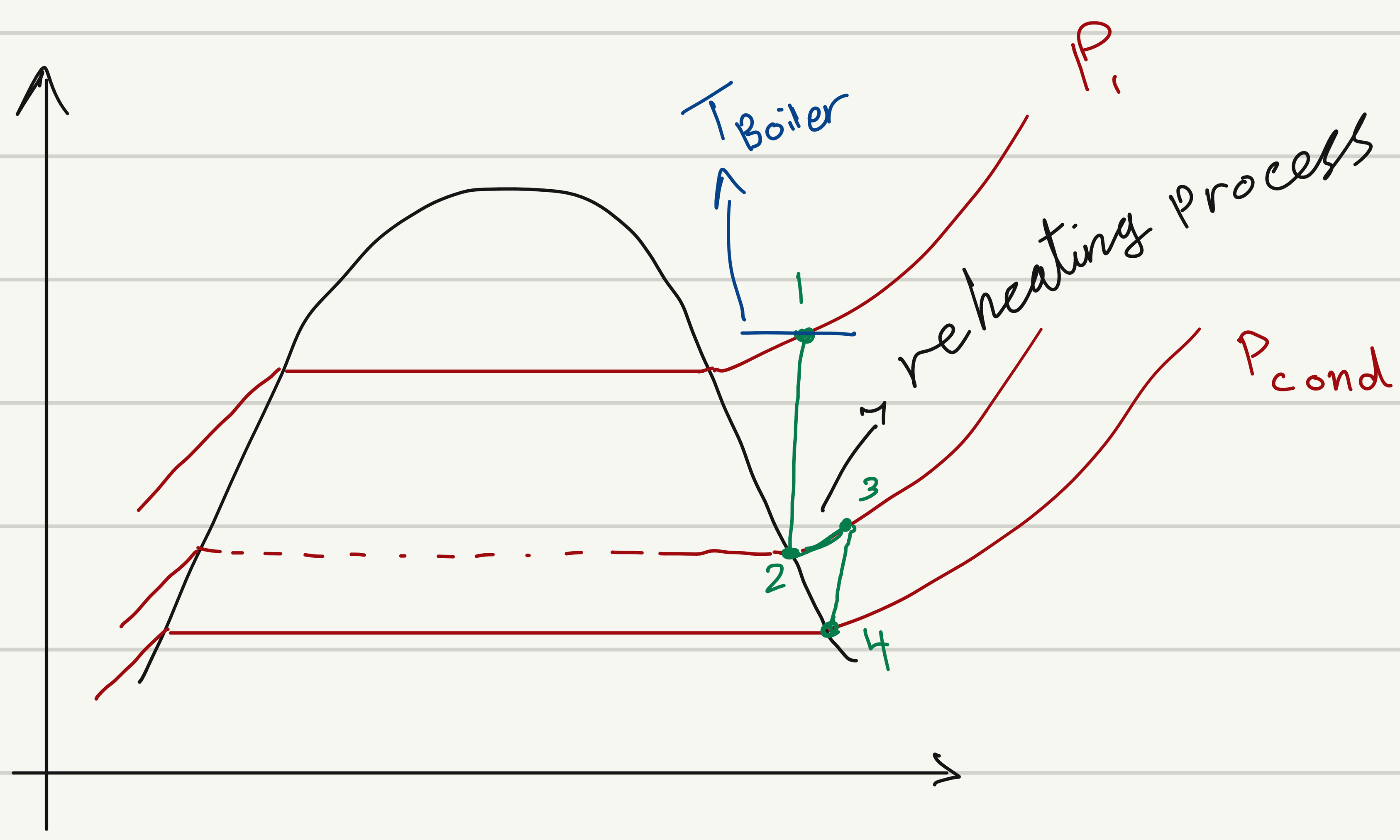
→ more liq. which would damage the turbine.

Summary :

$$\eta_{th} = 1 - \frac{\dot{Q}_c}{\dot{Q}_B}$$

$\dot{Q}_c \rightarrow T_c \rightarrow$ Cold reservoir, Surroundings, $T_{ombient}$ } limits

$\dot{Q}_B \rightarrow T_H \rightarrow T_{Boil}$ (Material)



There is high pressure Turbine.
and low pressure Turbine.

Thermodynamics
WS 2021/22

Exercise 7

Today

Ideal Rankine Cycle
Ideal Superheat and Reheat Cycle

next week

Problem 7.1
Ideal Rankine Cycle

Steam is the working fluid in an ideal Rankine cycle. Saturated vapor enters the turbine at 8.0 MPa and saturated liquid exits the condenser at a pressure of 0.008 MPa. The net power output of the cycle is 100 MW.

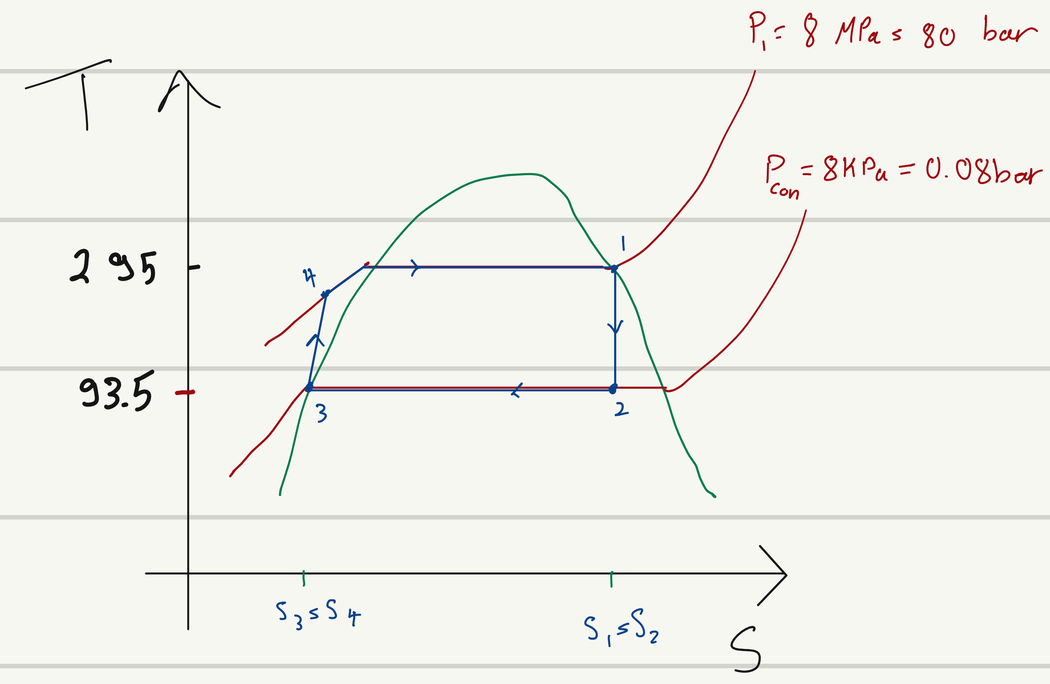
Sketch the process on a T-s diagram.

Determine for the cycle

(a) the thermal efficiency
(b) the back work ratio
(c) the mass flow rate of steam, in kg/h
(d) the rate of heat transfer into the working fluid as it passes through the boiler, in MW
(e) the rate of heat transfer from the condensing steam as it passes through the condenser, in MW
(f) the mass flow rate of the condenser cooling water, in kg/h, if the cooling water enters the condenser at 15°C and exists at 35°C.

Ex. 3/1/2022

State	T (°C)	p (bar)	v (m³/kg)	u (kJ/kg)	s (kJ/kg·K)	h (kJ/kg)	x
1	295	80			5.743	2758	1
2	41.51	0.08			5.743	1794.8	0.6745
3	41.51	0.08	1.0084×10^{-3}		0.5926	173.88	0
4		80				173.961	ND



$P_{net} = 100$ MW

$$\eta_{th} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

put in cheat-sheet!

Process 1 -> 2 Isentrobic

$$s_2 = s_{g_2} x_2 + (1 - x_2) s_{f_2} \Rightarrow x_2 = \frac{s_2 - s_{f_2}}{s_{g_2} - s_{f_2}}$$

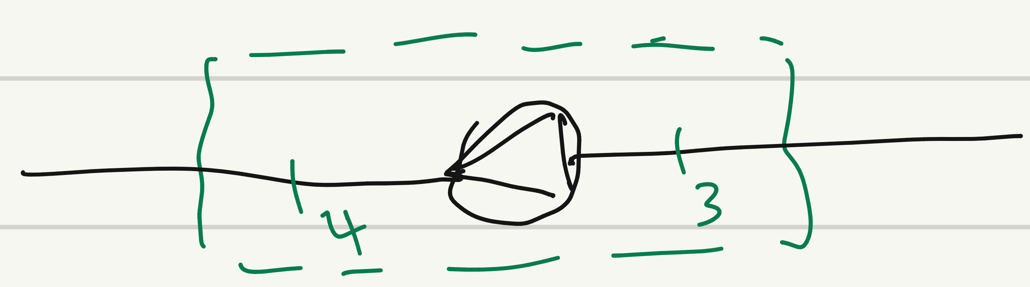
Table A-3 $\longrightarrow s_{f_2} = 0.5926$ KJ/Kg·K , $s_{g_2} = 8.2287$ KJ/Kg·K

$h_{f_2} = 173.88$ KJ/Kg , $h_{g_2} = 2577$ KJ/Kg

$$x_2 = \frac{(5.743 - 0.5926)}{(8.2287 - 0.5926)} = 0.6745$$

$$h_2 = x_2 h_{g_2} + (1 - x_2) h_{f_2} = 1794.8 \text{ KJ/Kg}$$

Process 3 – 4



1st Law

$$H_{out} - H_{in} = \sum \cancel{Q} + \sum P$$

0

adiabatic

$$\dot{m}(h_4 - h_3) = + P_p$$

Technical work: $W_t = + \int_3^4 v \, dp$

(open system)

liquid $\rightarrow$ incompressible $\rightarrow$ V = cons

$$\frac{P_p}{\dot{m}} = W_t = v_3 (P_4 - P_3) = 80.6 \text{ J/Kg}$$

$$h_4 = \frac{80.6}{10^3} \text{ KJ/Kg} + 173.88$$

$\eta_{th} = 0.373$

b) $bwr = \dfrac{P_p}{P_T} = \dfrac{h_4 - h_3}{h_1 - h_2}$

c) $\dot{m} = ?$

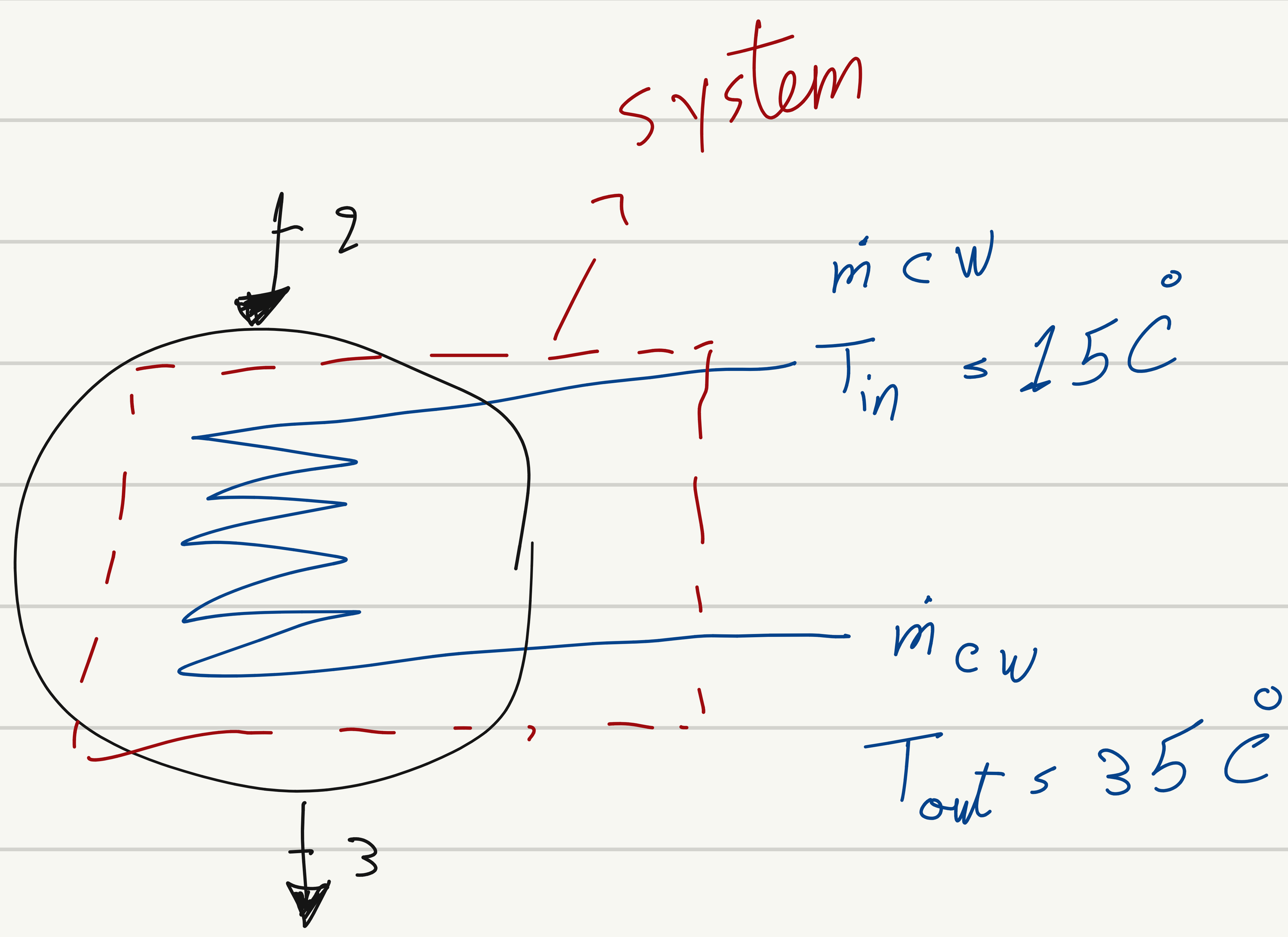
$$P_{net} = 100 \text{ MW} = \underbrace{\dot{m}(h_1 - h_2)}_{P_T} - \underbrace{\dot{m}(h_4 - h_3)}_{P_p}$$

$$\dot{m} = \frac{P_{net}}{P_T - P_p} = \frac{P_{net}}{(h_1 - h_2) - (h_4 - h_3)} = 103.83 \text{ Kg/s} = 3.74 \times 10^5 \text{ Kg/h}$$

d) $\dot{Q}_B = \dot{m}(h_1 - h_4) = 263.77$ MW

e) $\dot{Q}_c = \dot{m}(h_2 - h_3) = 169.71$ MW

f)



$$H_{out} - H_{in} = \sum \dot{Q} + \underbrace{\cancel{\sum \dot{P}}}_{0}$$

no pump

$$\dot{m}_{cw} h_{out} - \dot{m}_{cw} h_{in} = +\dot{Q}_c$$

$$\boxed{\dot{m}_{cw} = \frac{\dot{Q}_c}{\underbrace{h_{out} - h_{in}}_{\text{cooling water}}}}$$

option 1: Moran/shapiro $x = 0$

at $T_{in} =$

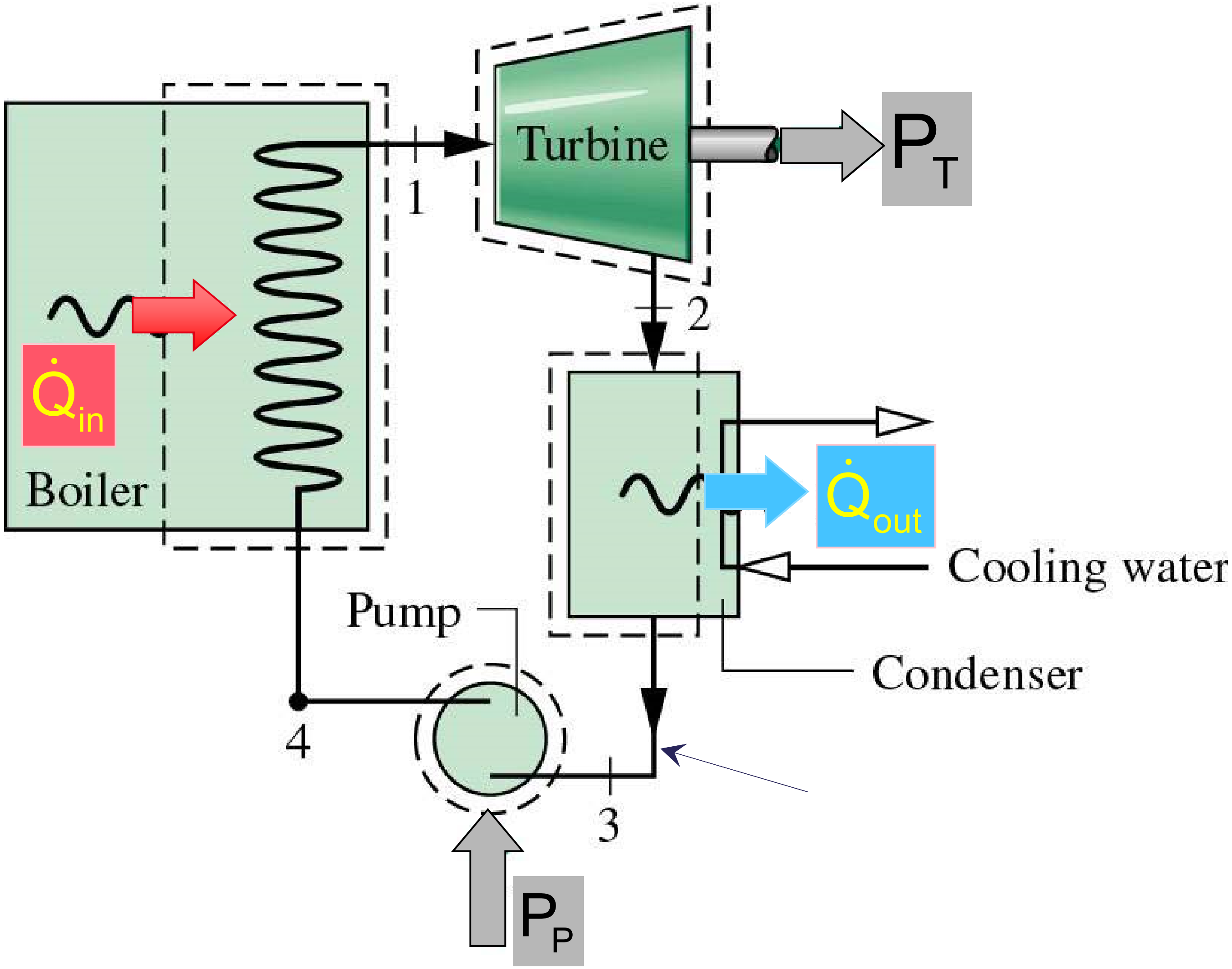
and $T_{out} =$

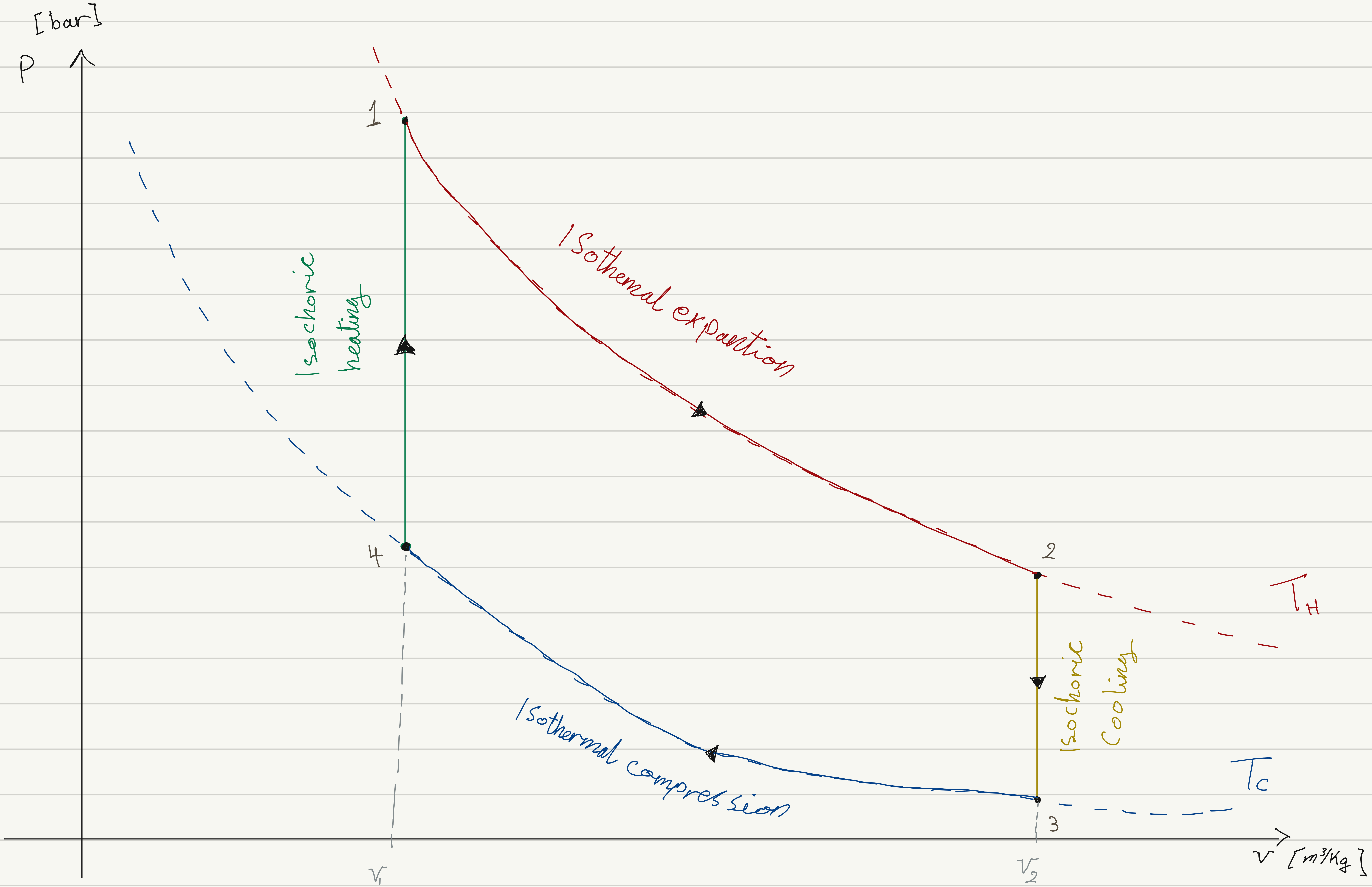
option 2: $dh = C_p \cdot dT$ liquid.

$$h_{out} - h_{in} = \bar{C}_p (T_{out} - T_{in}) \quad , \bar{C}_p = \text{Cons.} \quad , \bar{C}_p = 4.2 \text{ KJ/Kg.K}$$

$$\therefore \dot{m}_{cw} = \frac{\dot{Q}_c}{\bar{C}_p (T_{out} - T_{in})}$$

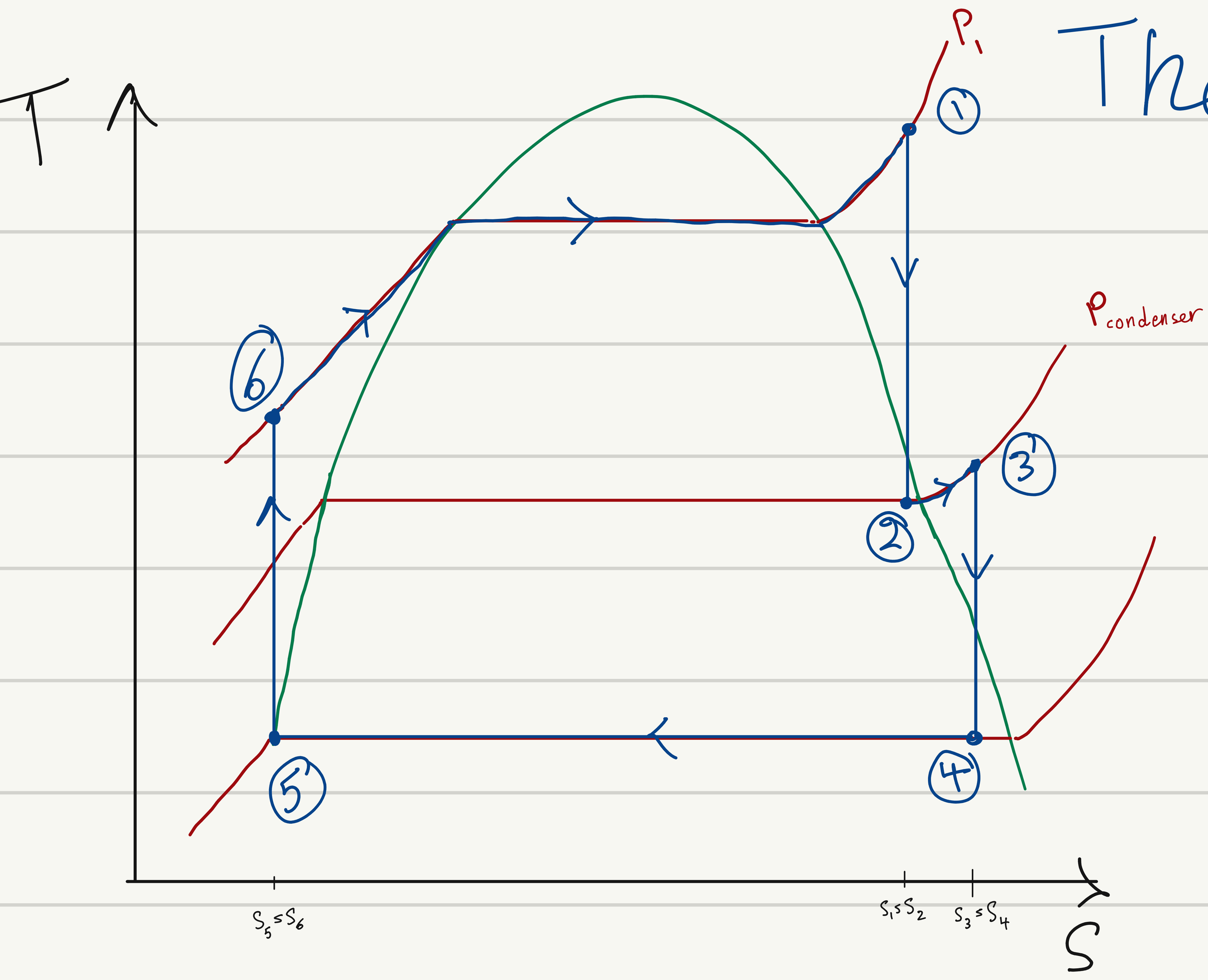
Problem 7.1
Ideal Rankine Cycle

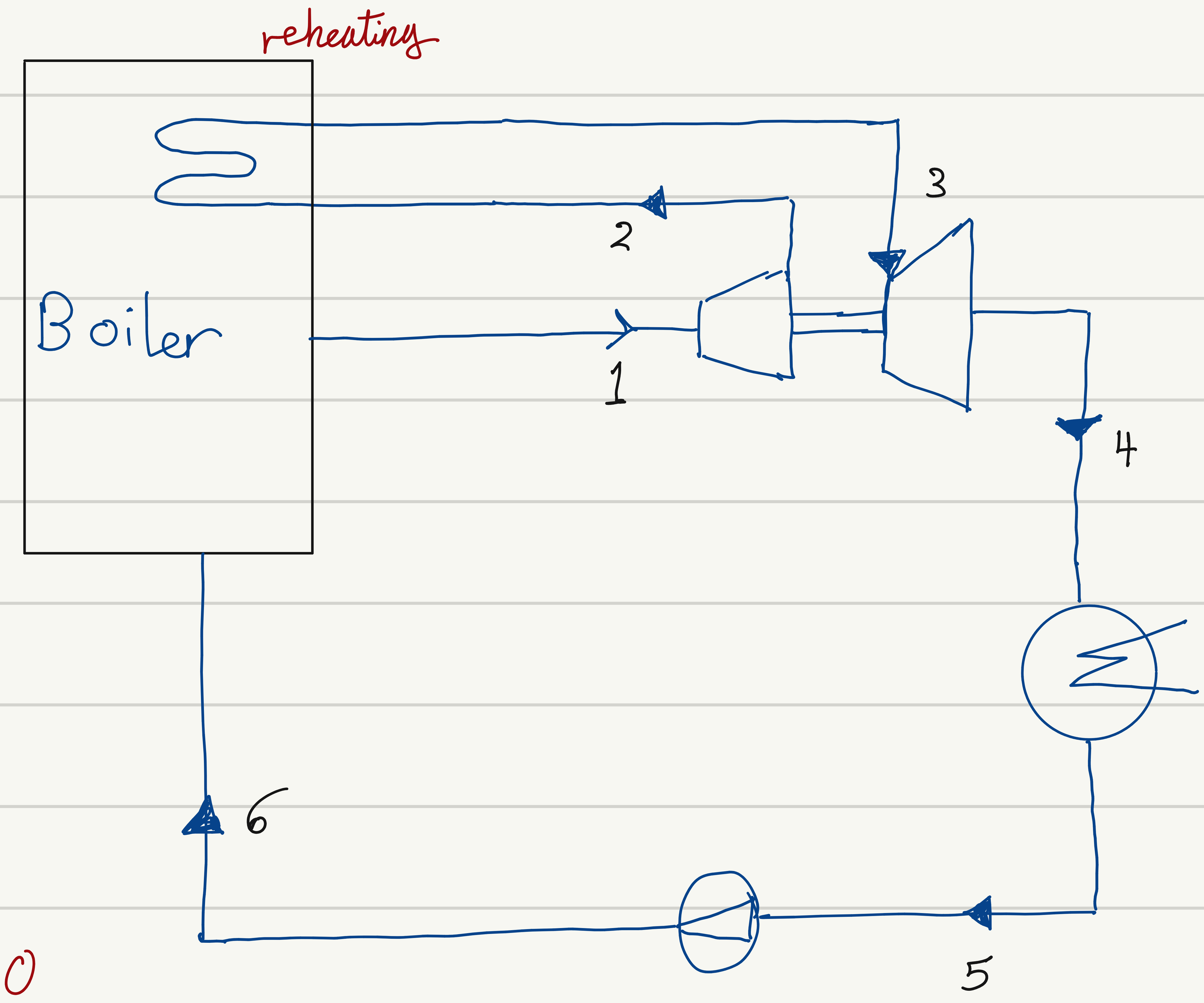




[bar]
P
1
2
3
4
Isothemal expantion
Isochoric heating
Isochoric cooling
Isothermal compression
T_H
T_C
v_1
v_2
v [m³/Kg]

Thermo LC 10.01.2022





Real cycle → irreversibility

$\sigma \neq 0$; $\sigma \ngtr 0$ can't be

Turbine : adiabatic → $s_2 - s_1 = \frac{\cancel{dQ}}{T} + \sigma$ because of 0

LC, 10.1.2022

Isentropic case (Ideal): $P_{Ts} = \dot{m}(h_1 - h_{2s})$

Real case ($\sigma > 0$): $P_T = \dot{m}(h_1 - h_2)$

efficiency: $\eta_{is} = \frac{P_T}{P_{Ts}} < 1$

$$\boxed{\eta_{is} = \frac{h_1 - h_2}{h_1 - h_{2s}}}$$

isentropic

Comes from manufacturer (example: Siemens) Data Sheet

$\eta_{is} \rightarrow$ given always or ~

Any problem must have an assumption at the begging $\rightarrow \eta_{is} = 0.7 - 0.8$

$$\eta_{is} \cdot (h_1 - h_{2s}) = h_1 - h_2 \Rightarrow \boxed{h_2 = h_1 - \eta_{is} \cdot (h_1 - h_{2s})}$$

	h_s	S	h_{actual}
1	3500		
2	3000!		3100

(h-S) diagram

(Mollier diagram)

Entropy change of an ideal gas

$\hookrightarrow P \cdot v = RT$

$du = c_v \, dT \quad , \quad dh = c_p \cdot dT$

$$ds = \frac{dq}{T} + \cancel{\sigma} \quad \text{reversible}$$

1st rule: $du = dq + dw$

work done <u>on</u> the system $\quad dw = -P\,dv$

2nd rule: $du = T \cdot ds - P\,dv$

$$ds = \frac{du}{T} - \frac{P}{T} dv \qquad \frac{P}{T} = \frac{R}{v}$$

$$\int_1^2 ds = \int_1^2 \frac{c_v \cdot dT}{T} - \int_1^2 \frac{R}{v} dv$$

$$\boxed{S_2 - S_1 = c_v \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{v_2}{v_1}\right)}$$

Isentropic exponent $k = \frac{C_v}{C_p}$

(Isentropic processes)

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} \qquad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

$P \cdot v^k = \text{Cons}$

Thermodynamics
WS 2021/22

Exercise 7

Ideal Rankine Cycle
Ideal Superheat and Reheat Cycle

Problem 7.2

Ideal Superheat and Reheat Cycle

Steam is the working fluid in an ideal Rankine cycle with superheat and reheat. Steam enters the first-stage (high pressure) turbine at 8.0 MPa, 480°C, and expands to 0.7 MPa. It is then reheated to 440°C before entering the second-stage (low pressure) turbine, where it expands to the condenser pressure of 0.008 MPa. The net power output of the cycle is 100 MW.

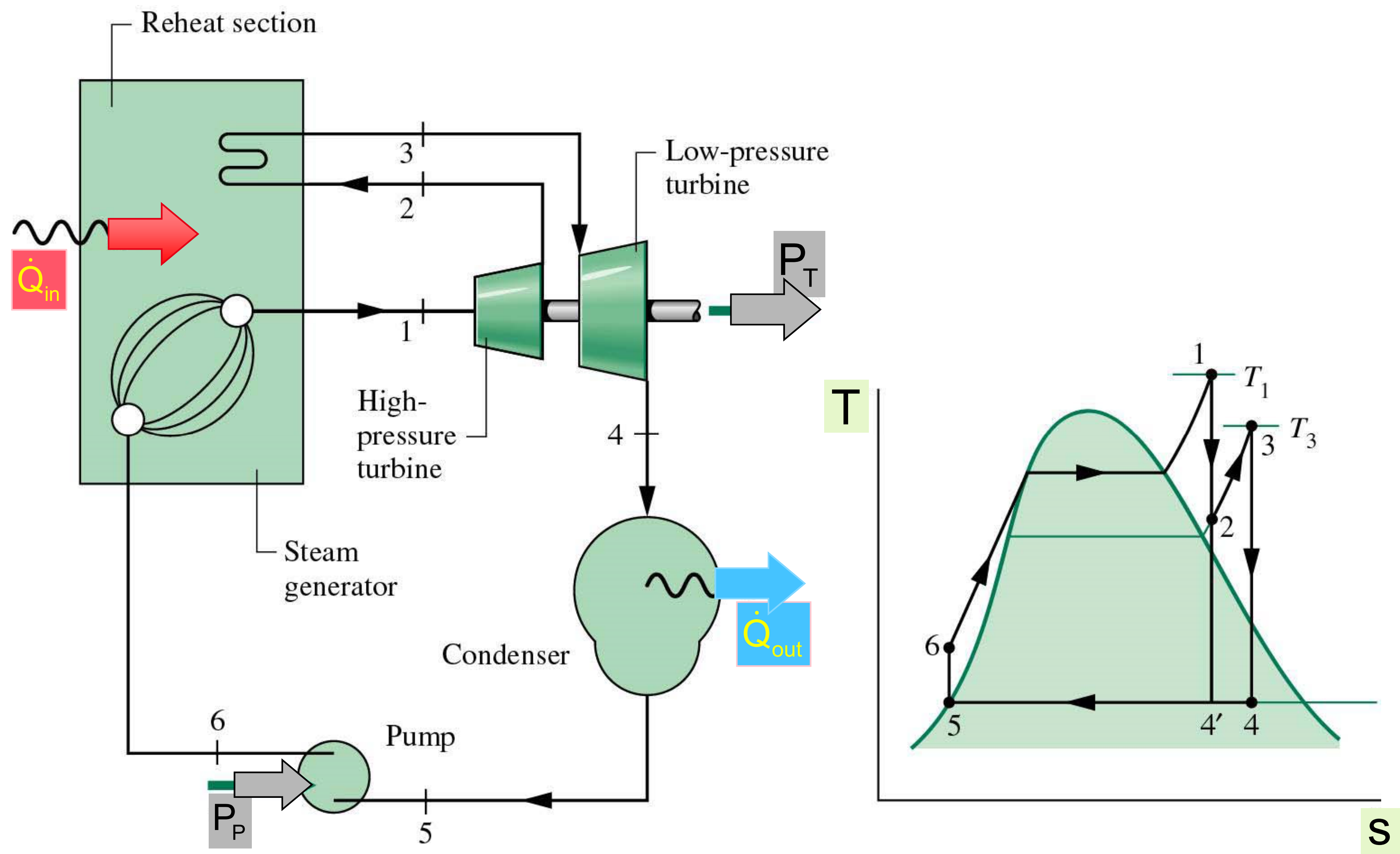
Draw a process flow sheet and sketch the cycle on T-s coordinates.

	T [C°]	p [bar]	h [KJ/Kg]	S [KJ/Kg·K]	X
1	480	80	3348.4	6.6586	—
2		7		6.6586	
3	440	7	3353.3	7.7571	—
4		0.08		7.7571	
5	41.51	0.08	173.88	0.5926	0
6		80		0.5926	—

Determine for the cycle

a) the thermal efficiency
b) the mass flow rate of steam, in kg/h
c) the rate of heat transfer from the condensing steam as it passes through the condenser, in MW
d) Analyse the Rankine cycle without and with reheating by comparing the results of the solution of Problem 7.1 with the results of Problem 7.2.

Problem 7.2
Ideal Superheat and Reheat Cycle



Fundamentals of Engineering Thermodynamics; 6e, SI Version, 2010, p. 342

Problem 7.2
Ideal Superheat and Reheat Cycle

	p [bar]	T [°C]	h [kJ/kg]	s [kJ/kgK]	x [–]
1	80	480	3,348	6.6586	superheated
2	7	165	2,742	6.6586	0.99
3	7	440	3,353	7.7571	superheated
4	0.08	41	2,428	7.7571	0.94
5	0.08	41	174		0
6	80		182		liquid

Problem 7.2
Ideal Superheat and Reheat Cycle

(a) $$\eta_{th} = \frac{(h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)}{(h_1 - h_6) + (h_3 - h_2)}$$

(b) $$\dot{m} = \frac{\dot{W}_{Cycle}}{(h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)}$$

(c) $$\dot{Q}_{out} = \dot{m}\,(h_4 - h_5)$$

Solution

(a) $\eta_{th} = 40.3\ \%$

(b) $\dot{m} = 2.363 \times 10^5\ \frac{kg}{h}$

(c) $\dot{Q}_{out} = 148\ \text{MW}$

See Problem 7.1
Ideal Rankine Cycle

Solution

(a) $\eta_{th} = 37.1\%$

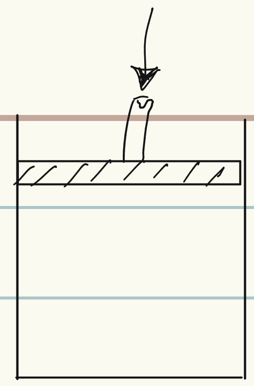
(c) $\dot{m} = 3.77 \times 10^5\ \frac{kg}{h}$

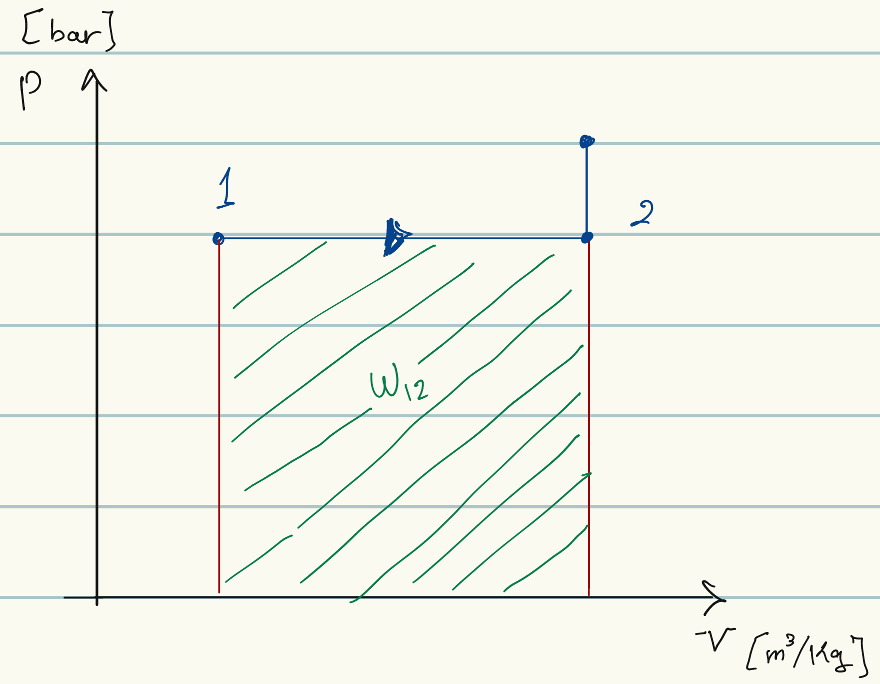
(e) $\dot{Q}_{out} = 169.75\ \text{MW}$

Tu

10.01.2022

	T [C°]	p [bar]	h [KJ/Kg]	S [KJ/Kg·K]	X
1	480	80	3348.4	6.6586	–
2		7		6.6586	
3	440	7	3353.3	7.7571	–
4		0.08		7.7571	
5	41.51	0.08	173.88	0.5926	0
6		80		0.5926	–





1 → 2 Isobaric expantion.

$$W_{12} = \overset{on}{\ominus} \int_1^2 p\,dV = \overset{by}{\oplus} P_{1,2} \overbrace{(V_2 - V_1)}^{>0}$$

2 → 3 isochoric Process

$$W_{23} = 0$$