# Thermodynamics

## Important terms:

- Isothermal $\longrightarrow$ $\Delta T = 0$, Tempreture = cons.
- Isobaric $\longrightarrow$ $\Delta P = 0$, Pressure = cons.
- Isochoric $\longrightarrow$ $\Delta V = 0$, Volume = cons.
- Rigid $\longrightarrow$ $V$ = cons.
- Adiabatic $\longrightarrow$ $\Delta Q = 0$ $(\dot{Q} = 0)$
- Isentropic $\longrightarrow$ $\Delta S = \frac{\Delta Q}{T} = 0$ (Adiabatic + ideal)
- Steady-State $\longrightarrow$ $\frac{dE}{dt} = 0$
- Closed Sys. $\longrightarrow$ $\dot{m} = 0$, $m$ = Cons.
- Open System $\longrightarrow$ $\dot{m} \neq 0$
- Polytropic $\longrightarrow$ $P \cdot v^n$ = constant

## Ideal gas Law

$P \cdot v = R\,T$ → Specific gas cons. (J/kg·K)

$\frac{P \cdot V}{n} = \frac{m\,R\,T}{n}$

$P \cdot \bar{v} = M \cdot R\,T$

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

Universal gas cons. [J/mol·K]

$\bar{R} = M \cdot R$

$\rightarrow R = \frac{\bar{R}}{M}$

$\dot{m} = \rho\, \underbrace{v\, A}_{\dot{V}}$ ($v$: velocity) $\longrightarrow \dot{m} = \rho \cdot \dot{V} \longrightarrow m = \rho\, V$

$v = \frac{V}{m} = \frac{1}{\rho}$

## 1st law: (closed system)

$du = dq + dw$

(Ideal gas): $du = c_v \cdot dT$

$W_v = P\,dV$

## 1st law: (open system)

$dh = dq + dw$

(Ideal gas): $dh = c_p \cdot dT$

$W_t = V \cdot dP$

## Entropy:

$ds = \frac{dQ}{T}$ (Ideal prosses)

(Real process): $ds = \frac{dQ}{T} + \sigma$

$\sigma > 0 \longrightarrow$ Irreversible

$\sigma = 0 \longrightarrow$ reversible

$\sigma < 0 \longrightarrow$ Impossible

## Interpolation:

| T | S |
|---|---|
| $T_1$ | $S_1$ |
| $T_2$ | $S_2$ |
| $T_3$ | $S_3$ |

$$\frac{T_1 - T_3}{S_1 - S_3} = \frac{T_2 - T_3}{S_2 - S_3}$$

# Polytropic processes LC:

## Ideal gas:

slide 4

**Closed system:**

$$\Delta S_{2\to1} = C_v \cdot \ln\left(\frac{T_2}{T_1}\right) + R \cdot \ln\left(\frac{V_2}{V_1}\right)$$

**Open system:**

$$\Delta S_{2\to1} = C_p \cdot \ln\left(\frac{T_2}{T_1}\right) + R \cdot \ln\left(\frac{P_2}{P_1}\right)$$

(Isentropic): $C_v = \frac{R}{K-1}$, $C_p = \frac{K \cdot R}{K-1}$, $K = \frac{C_p}{C_v}$

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{K-1}, \quad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}, \quad \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{K}$$

slide 5

**Polytropic, open system, & Ideal gas:** → slide 8

Technical work: $W_{rev} = \frac{n}{n-1} \cdot (P_2 V_2 - P_1 V_1)$

$PV = RT \longrightarrow W_{rev} = \frac{n \cdot R}{n-1} \cdot (T_2 - T_1)$

$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} \longrightarrow W_{rev} = \frac{n}{n-1} \cdot R T_1 \cdot \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$

special case $(n=1) \longrightarrow P \cdot V = \text{cons.} \longrightarrow T = \text{Cons.}$

$W_{rev} = P_1 V_1 \cdot \ln\left(\frac{P_2}{P_1}\right)$

$W_{rev} = R \cdot T \cdot \ln\left(\frac{P_2}{P_1}\right)$

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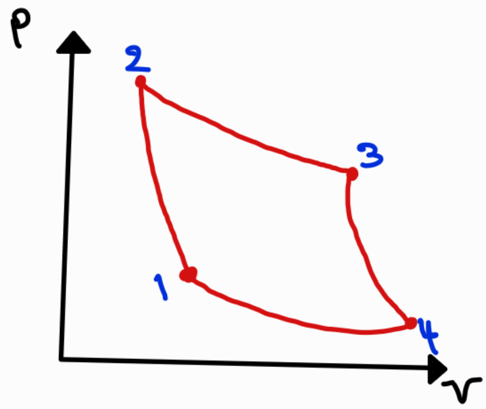
## Carnot cycle:

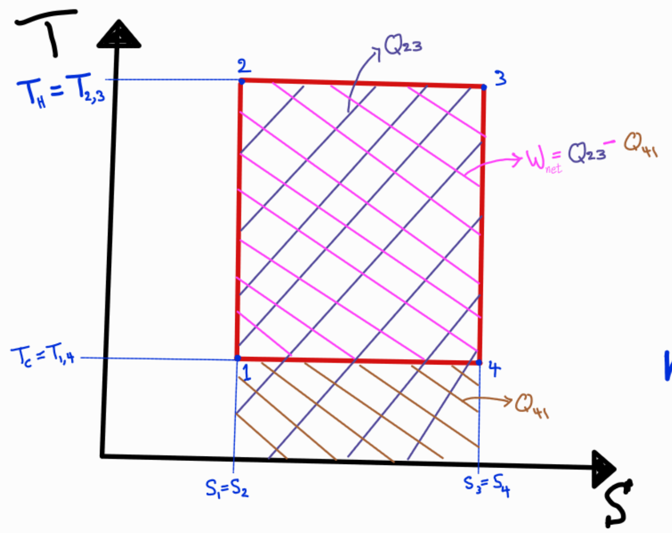



Process $1 \to 2$ (Adiabatic compression)

Process $2 \to 3$ (Isothermal expantion)

Process $3 \to 4$ (Adiabatic expantion)

Process $4 \to 1$ (Isothermal compression)

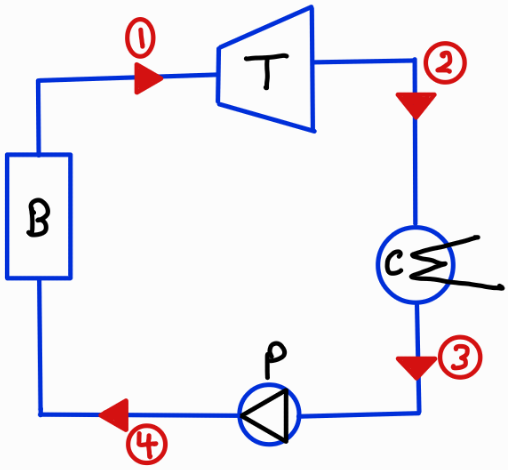


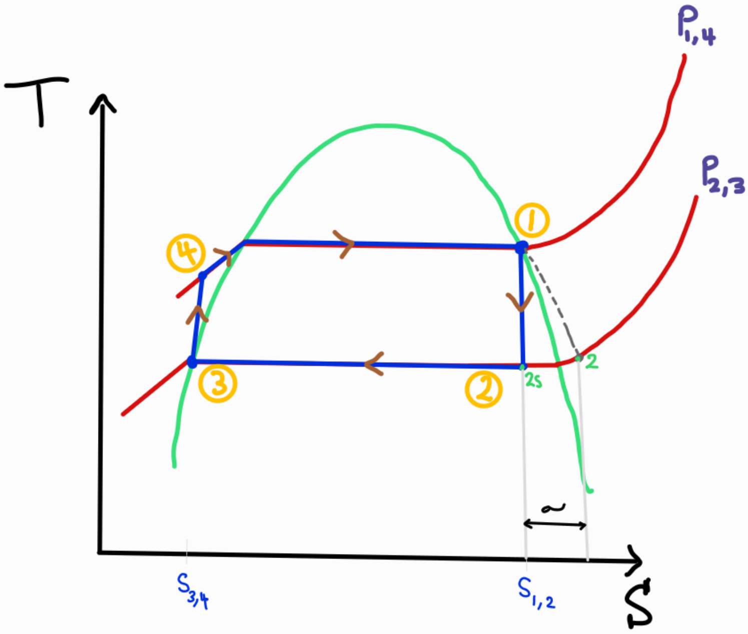

$$\eta_{carnot} = 1 - \frac{T_c}{T_H}$$

$$\eta_{th} = \frac{W_{net}}{Q_{23}} = 1 - \frac{Q_{41}}{Q_{23}} = 1 - \frac{T_c(S_4 - S_1)}{T_H(S_3 - S_2)}$$

# Rankine cycle

## Ideal cycle




$1 \rightarrow 2$ (Turbin) Isentropic expantion (saturated vapour)

$(\Delta S = 0 \rightarrow \dot{Q} = 0)$ , $\left(\frac{P_T}{\dot{m}}\right) = h_1 - h_2$ , $x = 1$ , $P_1 = P_4$

$2 \rightarrow 3$ (condenser) Isobaric & Isothermal condensation (saturated mixture)

$(\Delta T = 0 \ \& \ \Delta P = 0) \longrightarrow (P_2 = P_3 \ , T_2 = T_3)$

out

$\frac{\dot{Q}_c}{\dot{m}} = h_2 - h_3$ , $0 < x < 1$

Cooling water (cw): $(x = 0)$

$\dot{m}_{cw} = \frac{\dot{Q}_c}{\underbrace{h_{out} - h_{in}}_{\text{Shapiro table at } T_{in} \ \& \ T_{out}}}$ or $dh = C_p \cdot dT$ , $C_{p,cw} = Cons. = 4.2 \ KJ/Kg \cdot K$

$\Rightarrow \dot{m}_{cw} = \frac{\dot{Q}_c}{C_p (T_{out} - T_{in})}$

$3 \rightarrow 4$ (Pump) Isentropic compression (saturated Liquid) $\rightarrow x = 0$

$(\Delta S = 0 \rightarrow \dot{Q} = 0)$ , $\frac{P_p}{\dot{m}} = h_4 - h_3$

(assumptions: water is incompressible $\rightarrow v = cons.$) $\longrightarrow \frac{P_p}{\dot{m}} = W_t = v_3 \cdot (P_4 - P_3)$

$4 \rightarrow 1$ (Boiler) Isobaric compression (Compressed liquid)

$(\Delta P = 0)$ , $\frac{\dot{Q}_B}{\dot{m}} = h_1 - h_4$

$P_4 = P_1$

in

$$\eta_{th} = \frac{P_T - P_p}{Q_B} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4} = 1 - \frac{h_2 - h_3}{h_1 - h_4}$$

$$P_{net} = P_T - P_p = \dot{m}(h_1 - h_2) - \dot{m}(h_4 - h_3)$$

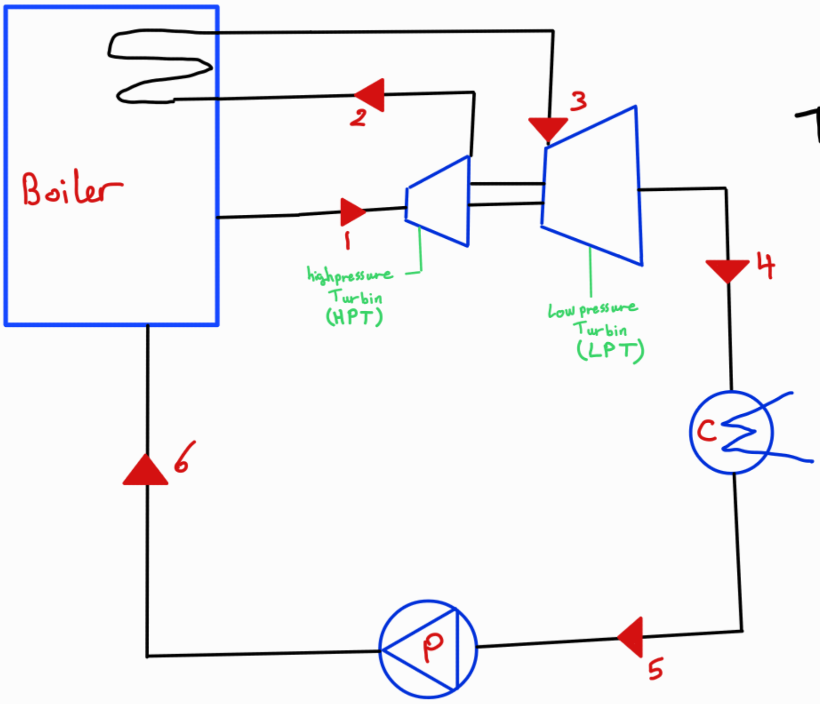
$$\Rightarrow \dot{m} = \frac{P_{net}}{(h_1 - h_2) - (h_4 - h_3)}$$

(Back-work ratio) $\eta_{bwr} = \frac{P_p}{P_T} = \frac{h_4 - h_3}{h_1 - h_2}$

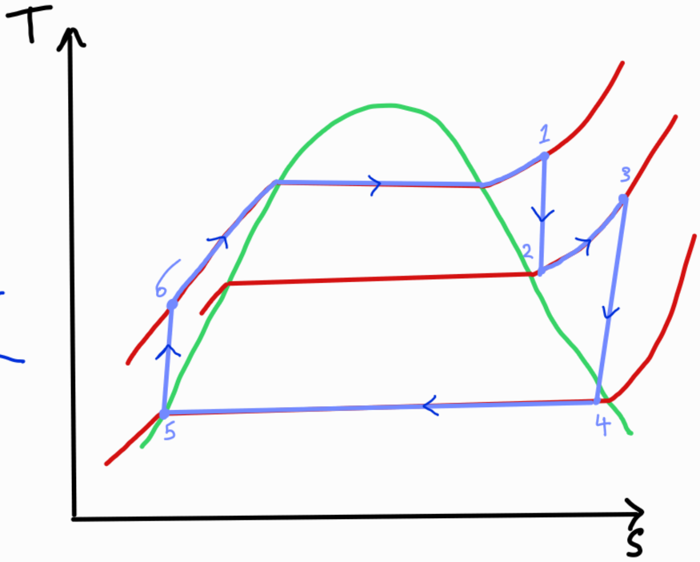
Isentropic (Ideal): $P_{Ts} = \dot{m}(h_1 - h_{2s})$

Isentropic (real, $\sigma > 0$): $P_T = \dot{m}(h_1 - h_2)$

Isentropic efficiency: $\eta_{is} = \frac{P_T}{P_{Ts}} = \frac{h_1 - h_2}{h_1 - h_{2s}} < 1$




• state(2) can be after or under the Dome



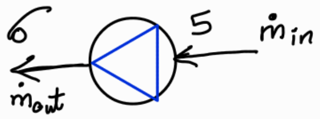

$$\eta_{th} = \frac{\overbrace{(h_1-h_2)}^{HPT}+\overbrace{(h_3-h_4)}^{LPT}-\overbrace{(h_6-h_5)}^{Pump}}{\underbrace{(h_1-h_6)}_{\substack{\text{Boiler}\\(\text{evapouration \& super-heating})}}+\underbrace{(h_3-h_2)}_{\text{reheating}}} \quad , \quad \dot{m} = \frac{\dot{W}_{cycle/net} \rightarrow P_{net}}{(h_1-h_2)+(h_3-h_4)-(h_6-h_5)} \quad , \quad \dot{Q}_c = \dot{m}(h_4-h_5)$$

1st step: Calculate $x_2$ (if under dome), & $x_4$.

$$x_2 = \frac{S_2 - S_{f_2}}{S_{g_2} - S_{f_2}} \quad \Bigg| \quad x_4 = \frac{S_4 - S_{f_4}}{S_{g_4} - S_{f_4}}$$

2nd step: caculate $h_2$ & $h_4$.

3rd step: after bringing $h_5 = h_{f_5}$ (because $x=0$), we need to find $h_6 = ?$




$$P_p = \dot{m}(h_6 - h_5) \longrightarrow \frac{P_p}{\dot{m}} = w_t = (h_6 - h_5)$$

↳ technical work

$$(v = cons.) \longrightarrow w_t = \int_5^6 v\,dP = v_5(P_6 - P_5) \Longrightarrow h_6 = w_t + h_5$$

4th step: calculate the $\eta_{th}$, and then the mass flow rate $\dot{m}$:

$$\eta_{th} = \frac{\overbrace{(h_1-h_2)}^{HPT}+\overbrace{(h_3-h_4)}^{LPT}-\overbrace{(h_6-h_5)}^{Pump}}{\underbrace{(h_1-h_6)}_{\substack{\text{Boiler}\\(\text{evapouration \& super-heating})}}+\underbrace{(h_3-h_2)}_{\text{reheating}}} \quad , \quad P_{net} = P_{T_1} + P_{T_2} - P_p$$

$$\Longrightarrow \dot{m} = \frac{P_{net}}{(h_1-h_2)+(h_3-h_4)-(h_6-h_5)}$$