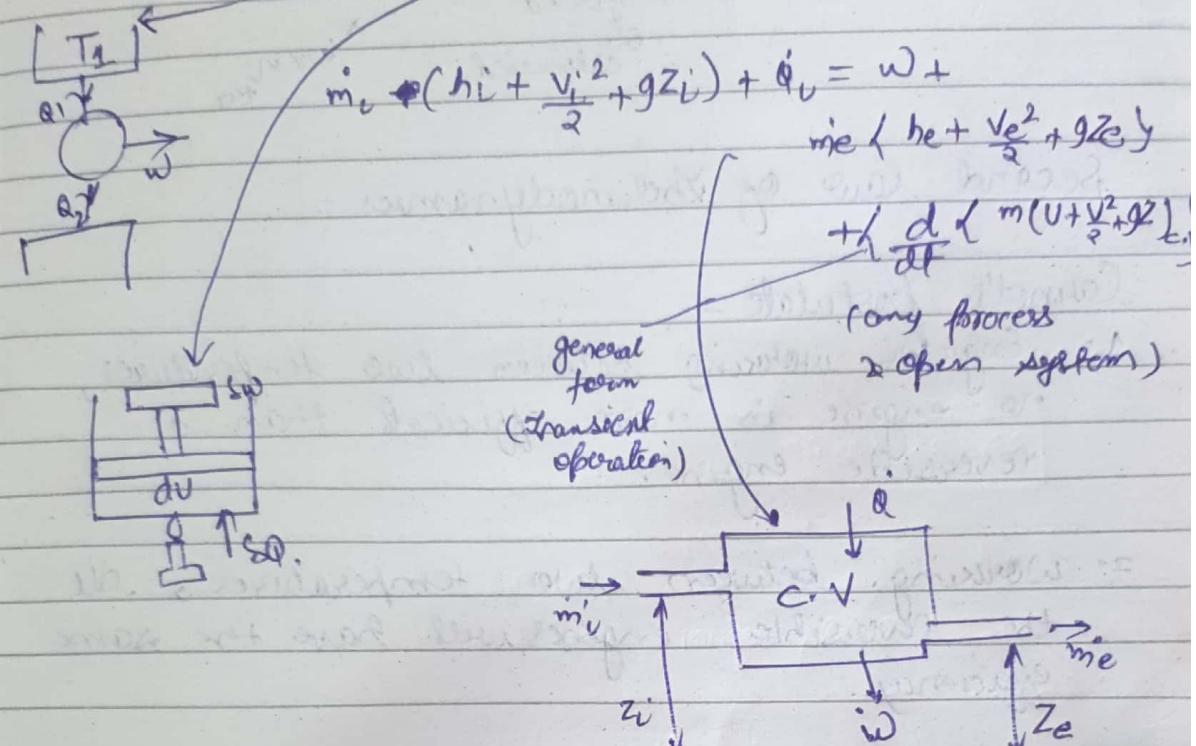


Engineering Thermodynamics -

1st law of thermodynamics } $\oint \delta Q = \oint \delta W$ (cycle)

$$\delta Q = \delta W + dU \quad (\text{any process & closed system})$$



general form
(transient operation)

(any process
in open system)

$$m(h_i + gZ_i + \frac{V_i^2}{2}) + \dot{Q} = \dot{W} + m(h_e + \frac{V_e^2}{2} + gZ_e)$$

$$h_i + \frac{V_i^2}{2} + gZ_i + q = w + h_e + \frac{V_e^2}{2} + gZ_e$$

(SSSF Energy eqn)

Turbine of a SPP at any instant -

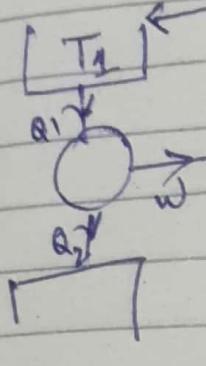
The engineer wants to know the rate of power generation.

Engineering Thermodynamics -

1st law
of thermodynamics

$$\oint \delta Q = \oint \delta W \text{ (cycle)}$$

$$\delta Q = \delta W + dU \text{ (any process & closed system)}$$



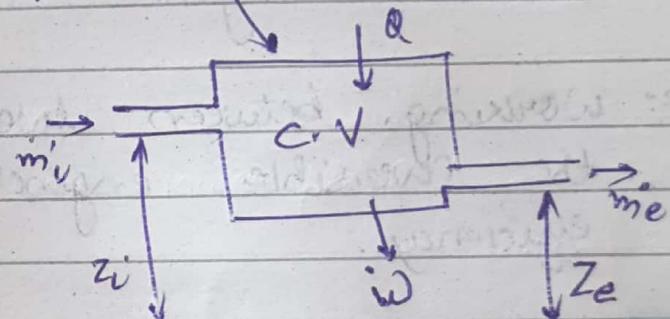
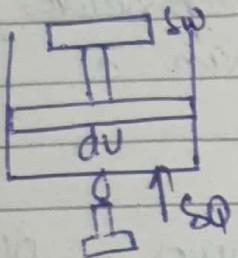
$$m_i (h_i + \frac{V_i^2}{2} + gZ_i) + q_i = w_i +$$

$$m_e (h_e + \frac{V_e^2}{2} + gZ_e)$$

$$+ \frac{d}{dt} \{ m(U + \frac{V^2}{2} + gz) \}$$

(any process
& open system)

general
form
(transient
operation)



$$\dot{m} (h_i + gZ_i + \frac{V_i^2}{2}) + \dot{q} = \dot{w} + \dot{m} (h_e + \frac{V_e^2}{2} + gZ_e)$$

$$h_i + \frac{V_i^2}{2} + gZ_i + q = w + h_e + \frac{V_e^2}{2} + gZ_e$$

(SSSF Energy
eqn)

Turbine of a SPP at any instant -

The engineer wants to know the rate of power generation.

m_{steam} , n_{turbine} , h_i , h_e

$$h_i + \frac{v_i^2}{2} + g z_i + q = \textcircled{w} + h_e + \frac{v_e^2}{2} + g z_e$$

can be neglected
or estimated

$w \times n_{\text{turb.}}$

Second law of Thermodynamics -

Carnot's postulate -

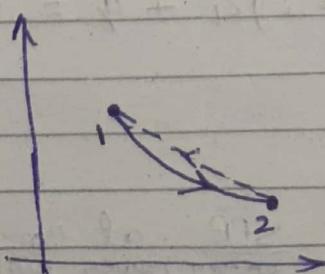
1. ~~Engines~~ working between two temperatures, no engine is more efficient than a reversible engine.
2. Working between two temperatures, all the reversible engines will have the same efficiency.

How to design a "reversible engine" ?

→ Engine which operates in a reversible cycle.

(Case)

All the processes are reversible.



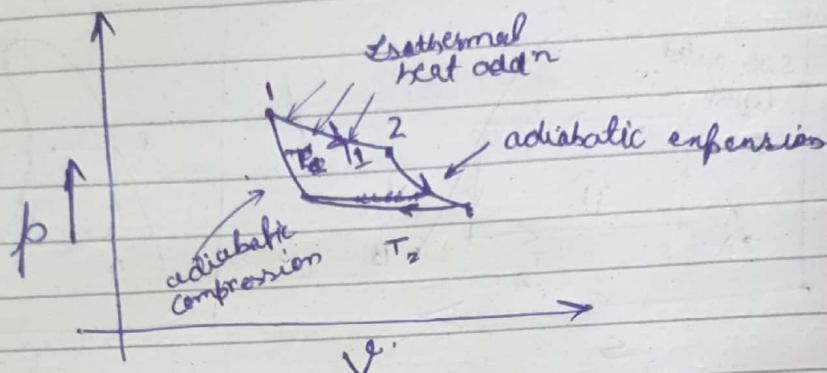
Factors of Irreversibility -

- Internal - Friction, viscosity, mixing, Joule heating, expansion in vacuum.
- External - Heat transfer, finite temp. difference.

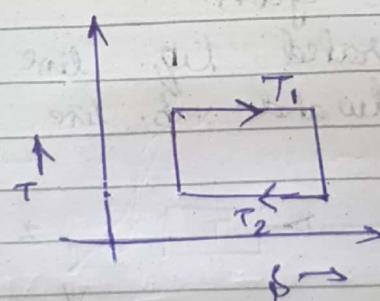
Kelvin - Planck statement for 2nd law -

- It's impossible to generate work ^{by an engine} while interacting ^{interacting} with a single body.

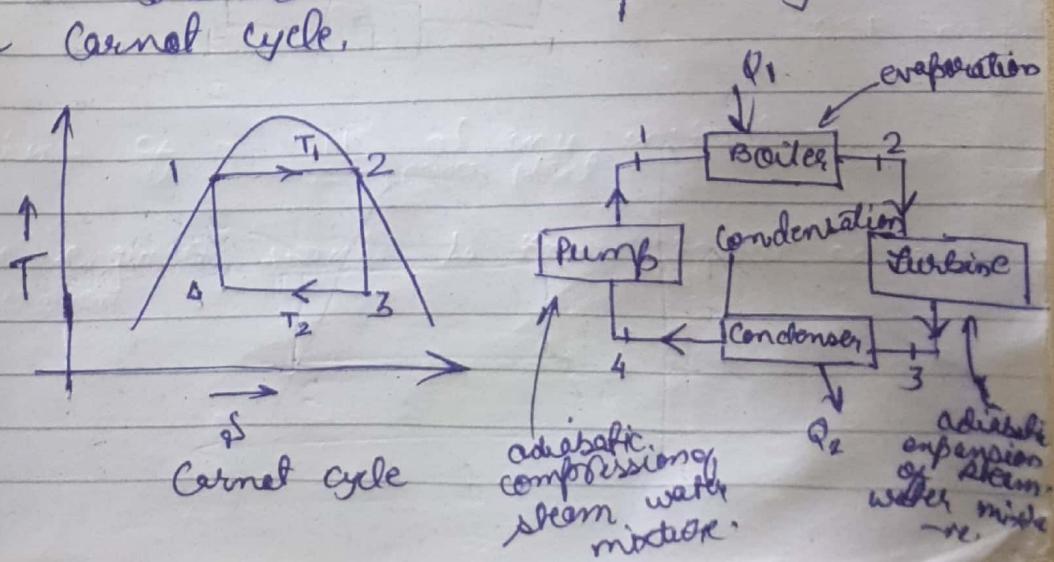
Construction of a heat engine cycle.



$$\eta_{Carnot} = 1 - \frac{T_2}{T_1} = 1 - \frac{T_{min}}{T_{max}}$$

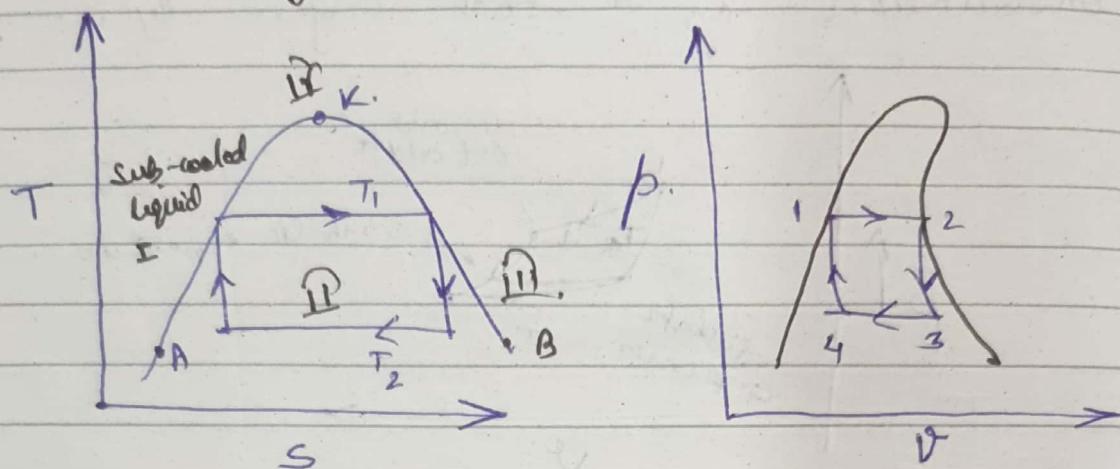


Try to construct a steam power cycle based on Carnot cycle.

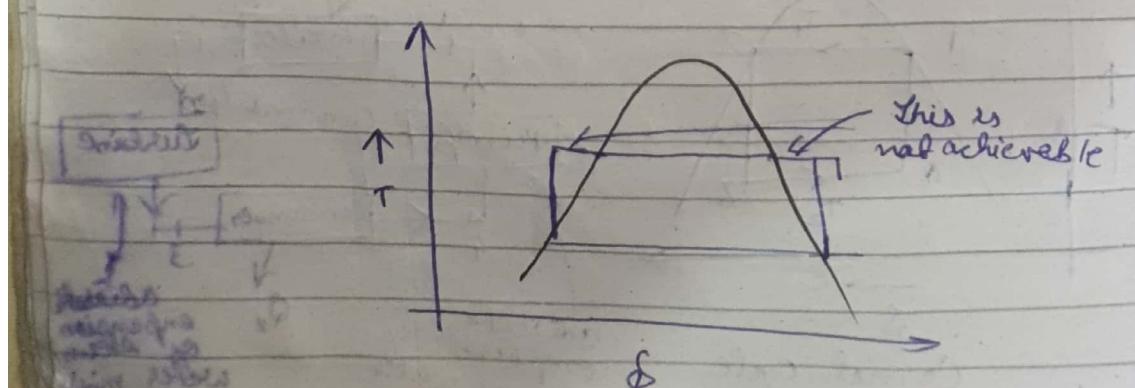
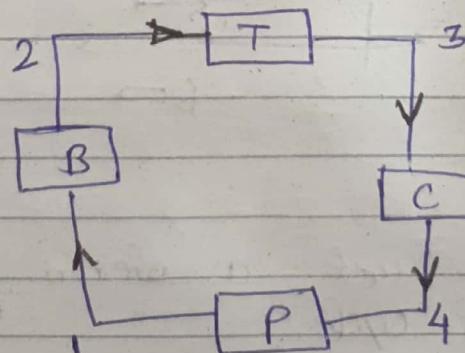


We do not use Carnot cycle as a vapour power cycle.

A Practical cycle with good efficiency with vapour as the working substance.



- I : Sub-cooled liquid
- II : Mixture of vapour + liquid
- III : Superheated vapour
- IV : Gas region
- AK : Saturated liquid line
- BK : Saturated vapour line

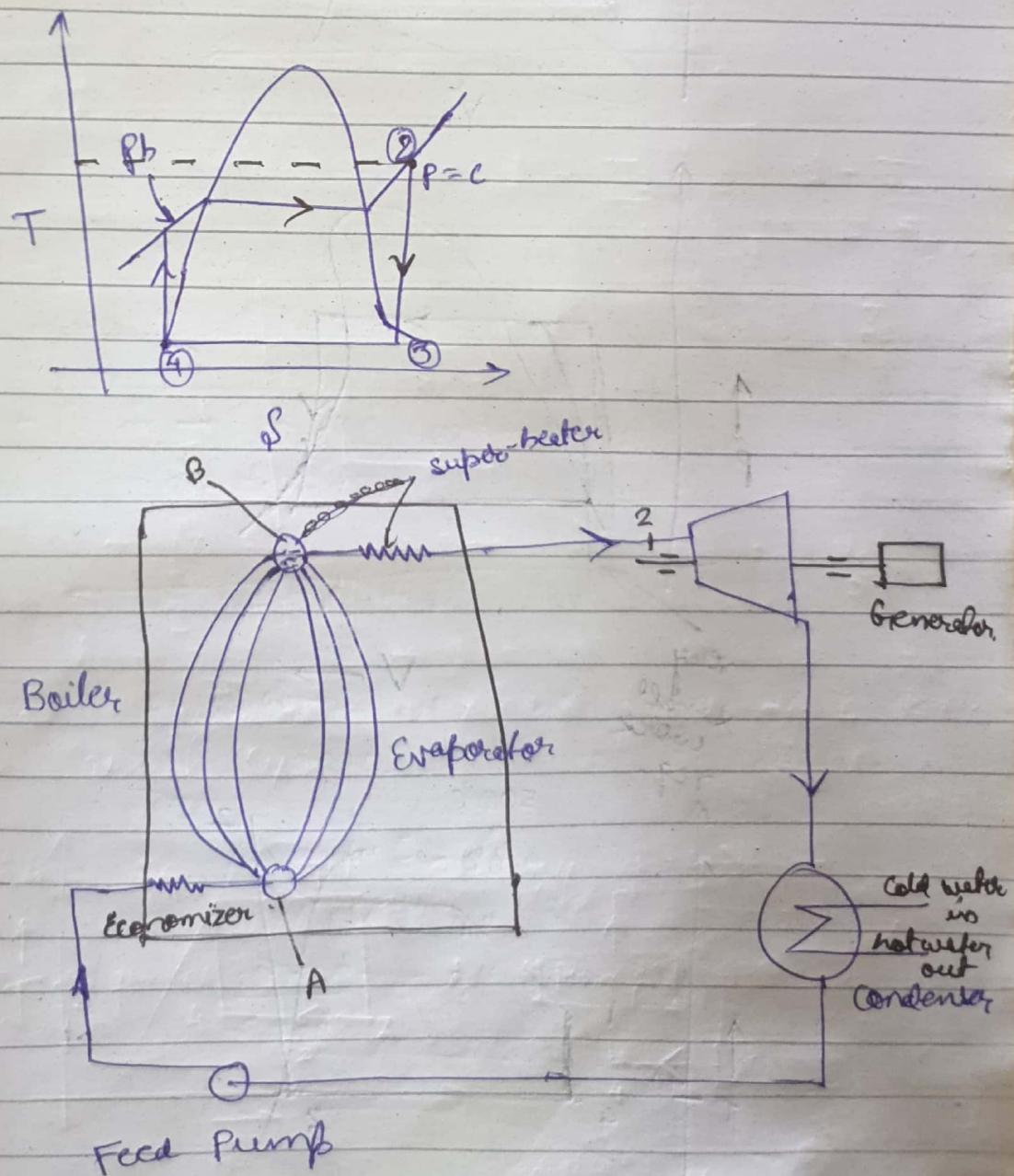


From practical point of view for vapour as the working substance Carnot cycle is not suitable. Rankine cycle is proposed.

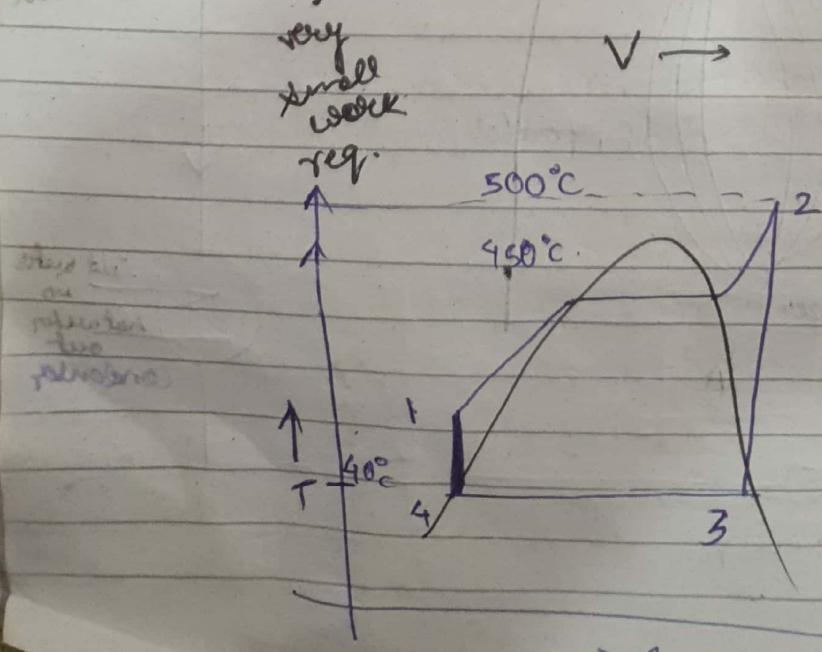
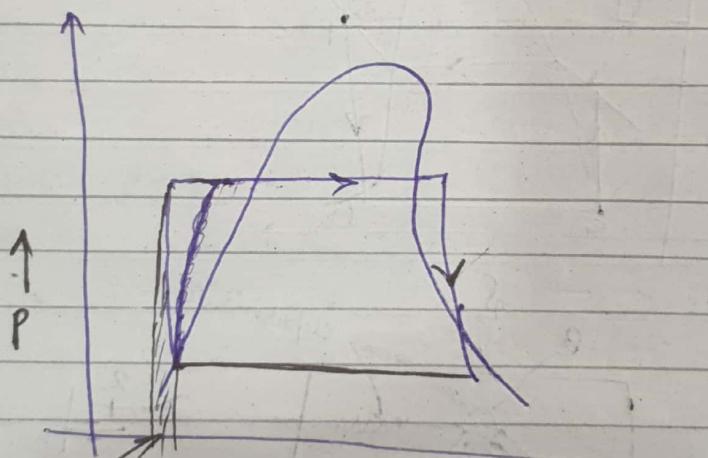
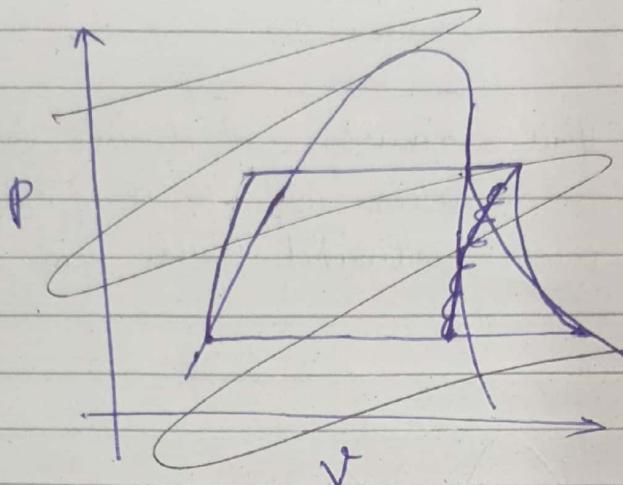
Carnot cycle :- Heat addition at const. Temp.

Rankine cycle :-

- Heat addition at const. pressure.
- Condensation will be complete till we reach saturated liquid line.



- 1-2 → Constant pressure heat addition (Boiler)
 2-3 → Isentropic expansion of steam (Turbine)
 3-4 → Constant pressure (constant temp.) Condensa
~~4-1~~ → ion (heat rejection) - Condensa.
 4-1 → Isentropic compression of water (pump).



- Rankine cycle is also reversible.
- In rankine cycle not all of heat is given at highest temp., but control to cycle have all. heat addⁿ at const^{high const} temp.
- So, whole of the rankine cycle, can be broken down to large no. of small Carnot cycles, that give efficiency combinedly.

$$\eta_{\text{Rankine}} = \frac{W_{\text{net}}}{Q_{\text{in}}} = \frac{W_{\text{Turbine}} - W_{\text{Pump}}}{Q_{\text{supplied}}}$$

Thermal Efficiency of Rankine Cycle -

$$\eta_R = \frac{W_{\text{net}}}{Q_{\text{supplied}}} = \frac{W_T - W_P}{Q_{\text{supplied}}}$$

Assumptions:-

- Plant is operating under steady state.

Using first law for a control volume.

$$h_2 + \frac{V_2^2}{2} + gz_2 + q = W_T + h_3 + \frac{V_3^2}{2} + gz_3$$

$\downarrow \frac{q}{m}$

$$h_2 + q = W_T + h_3$$

generally small, neglecting neglected
q. Some better estimate is not available

- Process 3-4 is known because it's for extracting max. work. temp. 3-4 shall be at atm. p temp.

we can take $b_1 \approx b_2$

$$\dot{m}_p = \dot{m}(b_2 - b_3)$$

$$\dot{m}_p = \dot{m}(b_2 - b_3)$$

Generally we don't get b_3 from table.

$$\begin{aligned} b_2 - b_3 &= (u + (f_{\infty} v)) - (u_p + (f_{\infty} v_p)) \\ &= u(u_p - u_p) + (f_{\infty} v) - (f_{\infty} v_p) \\ &\quad \text{almost zero} \\ &= P_0 v_p - f_c v_p \quad (\text{with } v \text{ being same} \\ &\quad \text{-wise } v_p = v_2) \\ &\approx (P_0 - P_c) v_p \end{aligned}$$

also, $T \frac{d\theta}{dt} = db - v dp$

$$\begin{aligned} db &= v dp \\ &= v_p (f_c - f_p) \end{aligned}$$

$$\therefore \dot{m}_p = \dot{m}(b_2 - b_3) \approx \dot{m} v_p (P_0 - P_c)$$

$$\text{Required} = \dot{m}(b_2 - b_1)$$

$$n_R = \frac{\dot{m}(b_2 - b_3) - \dot{m}(A - R)v_p}{\dot{m}(b_2 - b_1)}$$

$$b_1 = b_2 + (A - R)v_p$$

Some approximation can be done if the exit pressure is not too high.

$$\dot{m}_p \ll \dot{m}$$

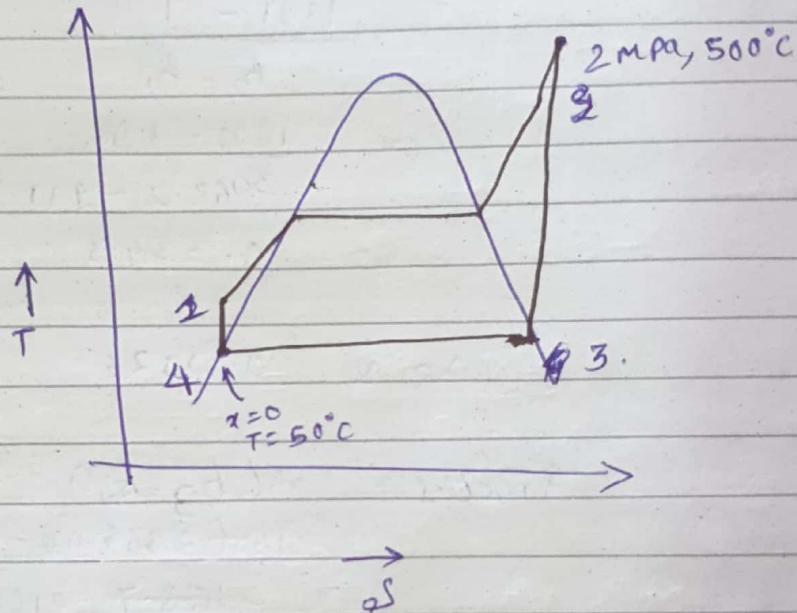
$$v_p \approx v_2$$

$$n_R = \frac{b_2 - b_3}{b_2 - b_1}$$

for n_R

A steam power plant operates on an ideal rankine cycle. Superheated steam goes into turbine at 2 MPa, 500°C with 100 kg/s flow rate. It exits the condenser at 50°C as saturated water. Determine the net power output, η_{rankine} , quality of steam at turbine exit. Heat rejected in condenser. What would be efficiency in winter if condenser temp. drops to 30°C.

Soln:



$$h_2 = 3468.2 \text{ kJ/kg}, s_2 = 7.4337 \text{ kJ/kgK}$$

$$s_2 = s_3, T_3 = 50^\circ\text{C}, h_3 =$$

$$s_f$$

$$7.4337 = x \cdot 8.0748 + (1-x) 0.70381$$

$$x = 0.873 \cdot 0.913$$

$$h_3 = \frac{0.913}{0.873} \times 2591.3 + (1 - \frac{0.913}{0.873}) \times 209.34$$

$$= 2288.8 \text{ kJ/kg} - 2384.06 \text{ kJ/kg}$$

$$\vartheta_4 = 0.00101215, h_4 = 209.34 \text{ kJ/kg}, s_4 = 0.70381$$

$$s_1 = s_4, P = 2 \text{ MPa}, h_1 = ?$$

$$w_t = (h_2 - h_3)$$

$$= (3468 - 2388) \cancel{\text{kJ/kg}}$$

$$= 1091 \text{ kJ/kg}$$

$$w_p = (P_B - P_C) \vartheta_4 = (2 - 0.01235) \times 10^6 \cancel{\text{N/m}^2}$$

$$= 1.987 \text{ kJ/kg}$$

$$\begin{aligned} h_1 &= h_f + W_p \\ &= 209 + 1.98 \\ &= 211 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} n_R &= \frac{W_T - W_p}{Q_{\text{supplied}}} \approx \frac{h_2 - h_3}{h_2 - h_1} \\ &= \frac{1091 - 1.98}{h_2 - h_1} \\ &= \frac{1091 - 1.98}{3468.2 - 211} \\ &= 0.3343 \\ n_R &\approx 0.3326 \end{aligned}$$

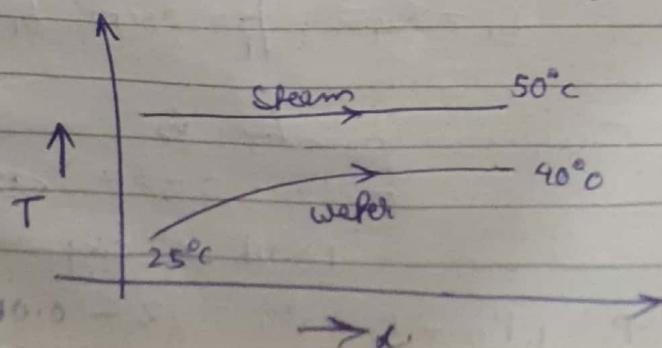
$$\begin{aligned} Q_{\text{rejected}} &= m(h_3 - h_4) \\ &= 100(2389.06 - 209.34) \\ &= 2168.7 \text{ kJ/kg. (Condenser)} \end{aligned}$$

*~~Q_{rej}~~ $Q_{\text{supplied}} = 3257.2 \text{ kJ/kg. (boiler)}$

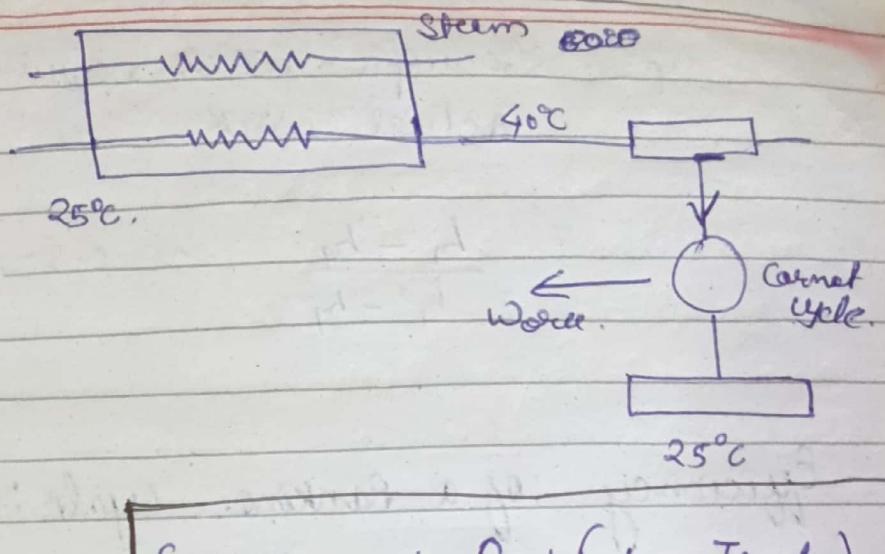
$$\begin{aligned} n_R &= \frac{Q_{\text{supp}} - Q_{\text{rej}}}{Q_{\text{supp}}} \\ &= 1 - \frac{Q_{\text{rej}}}{Q_{\text{supp}}} \\ &= 0.3344. \end{aligned}$$

NOTE :

* Energy of rejected heat is very small.



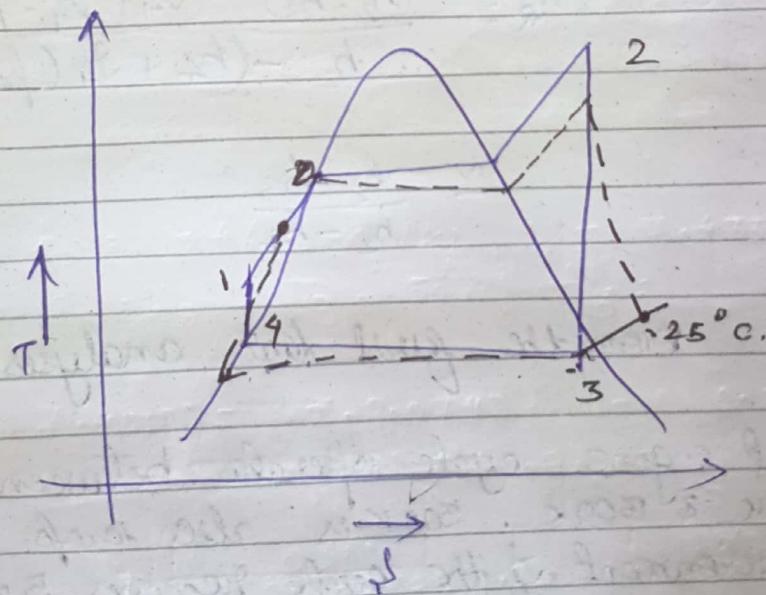
NOTE -



$$\text{Exergy} = Q_{\text{ref}} \left(1 - \frac{T_{\text{amb}}}{T_{\text{ref}}} \right)$$

$$\eta_{\text{for } 30^\circ\text{C condenser}} = 36.5\%$$

Losses in Rankine cycle -



- Lubricant & pump irreversibility are important in

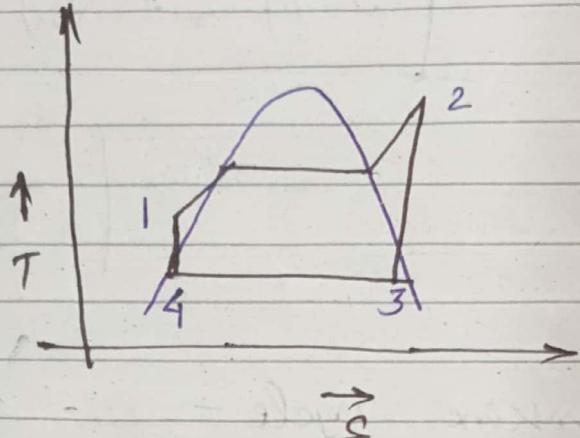
$$\eta_T = \frac{\text{Actual work done}}{\text{Isentropic work done}} = \frac{h_2 - h_3'}{h_2 - h_3}$$

This value is supplied by manufacturers

$n_p = \frac{\text{Isentropic work required}}{\text{Actual work}}$

$$= \frac{h_1 - h_4}{h_1' - h_4} \approx 0.8 - 0.85$$

Efficiency of a Rankine cycle :-



$$\eta_R = \frac{(h_2 - h_3) - s_4(p_1 - p_4)}{h_2 - (h_4 + s_4(p_4 - p_1))}$$

$$\approx \frac{h_2 - h_3}{h_2 - h_4}$$

From the first law analysis -

- Q. A heat engine cycle operates between two temps 900K & 300K. 300K is also temp. of the environment. If the cycle receives 500kW of thermal energy & produces 100kW of work.
find eff. η_{thermal} , η_D , η_{Carnot}

Sol'n

$$\eta_{\text{thermal}} = \frac{\text{work}}{\text{Q}_{\text{in}}}$$

$$= \frac{100}{500} = 0.2$$

$$\eta_{\text{Actual}} = 1 - \frac{T_{\text{min}}}{T_{\text{max}}}$$

$$= 1 - \frac{300}{900}$$

$$= \cancel{0.4} \frac{2}{3}$$

$$\eta_{II} = \frac{W_{\text{Actual}}}{W_{\text{ideal}}} = \frac{100}{\frac{200 \times 500}{3}} = \cancel{\frac{1}{2}} \cdot 0.5 = \frac{300}{1000} = 0.3$$

How 2nd law can be used to analyse the cycle?
 → Exergy analysis.

Irreversibilities in a Rankine cycle -

→ Internal - ~~pressure loss~~ ~~pump work~~

→ External - ~~pressure loss (less)~~
 • pump work not isentropic (less)
 ✓ • turbine work not isentropic.

Problem on Rankine cycle

Consider dead state as 100 kPa, 300 K

Consider a mass flow rate of 86.65 kg/s.

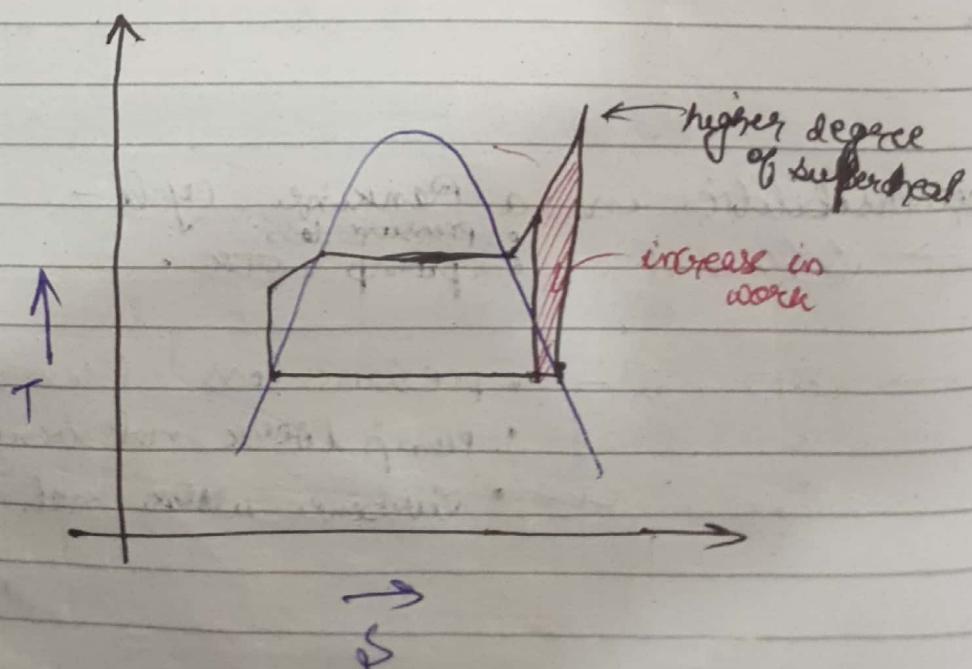
Prepare an energy balance sheet for entire process power plant.

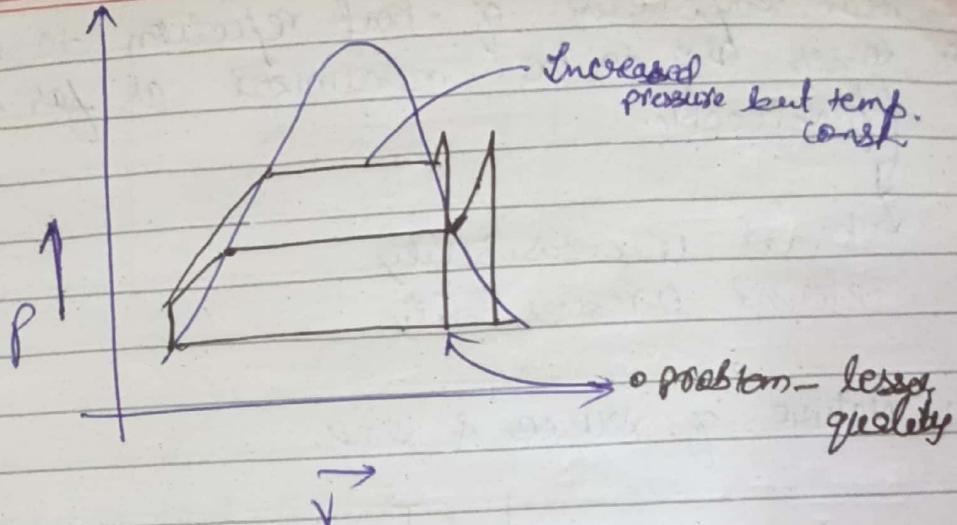
For increasing efficiency of Rankine cycle-

- Restrictions imposed
- 2nd Law
 - Carnot principle
 - Practical equipment
- 2 will be much less compared to 1

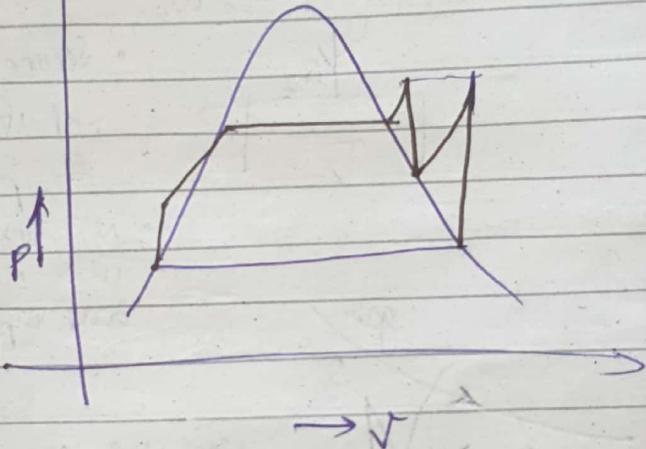
- Remedy (Partial)
- Selection of parameters -
(modification of design of the cycle)
 - Equipment design.

Turbine material is most vulnerable to degree of superheat because of its dynamic nature as it rotates.





Reheat Rankine cycle



Normal operating range of parameters-

Ideal Rankine cycle, $\eta \approx 33\%$
 In practical cycle no. of losses are then
 $\eta_{\text{practical}} < 33\%$

Need to improve the cycle performance.

1. Increase in temp. (Super heat) } material &
cost limitation
2. Increase in Boiler pressure }

Can we modify the basic Rankine cycle?

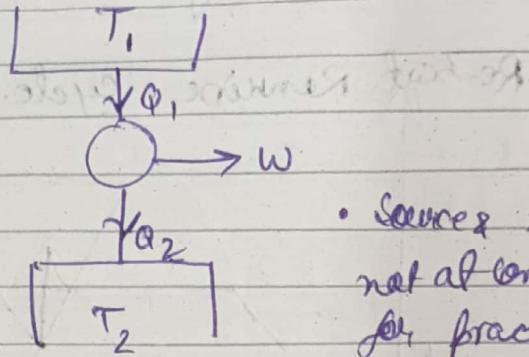
"Carnotization"

1. Mean temperature of heat addition to be high.

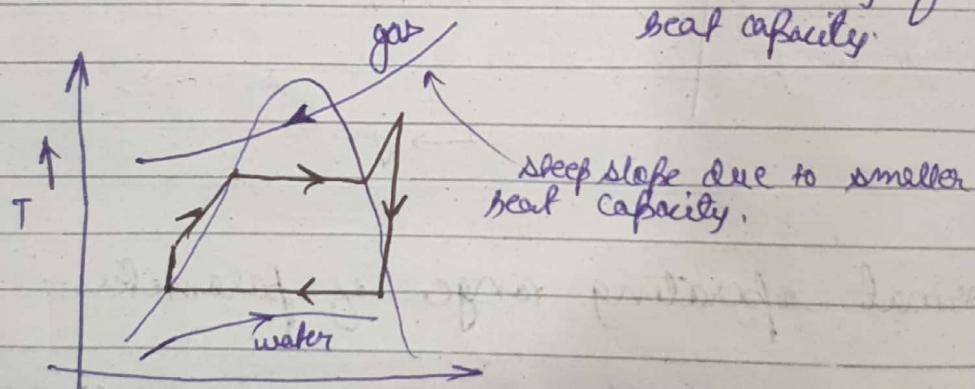
2. Mean temperature of heat rejection to be low.
3. Losses due to be minimized as far as practicable.

Internal irreversibility
External irreversibility

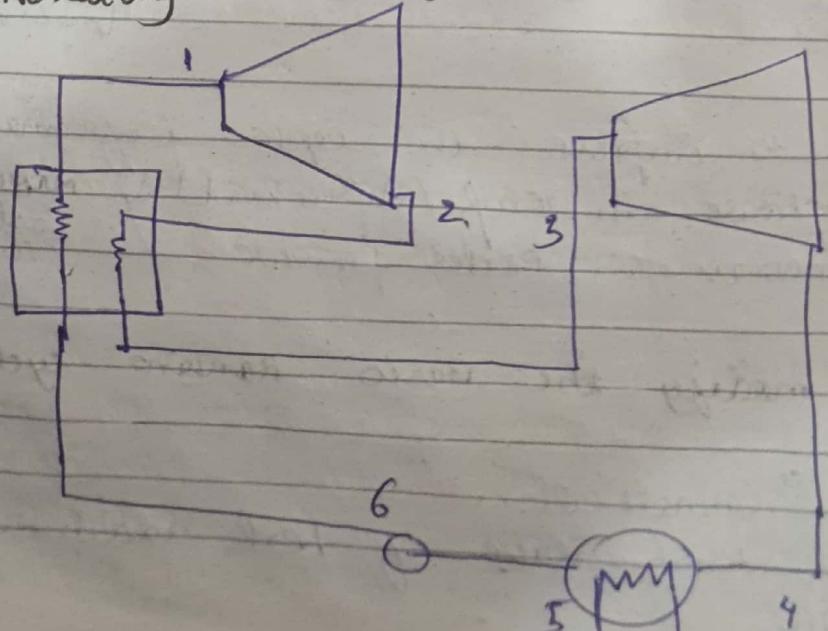
4. Nature of source & sink.

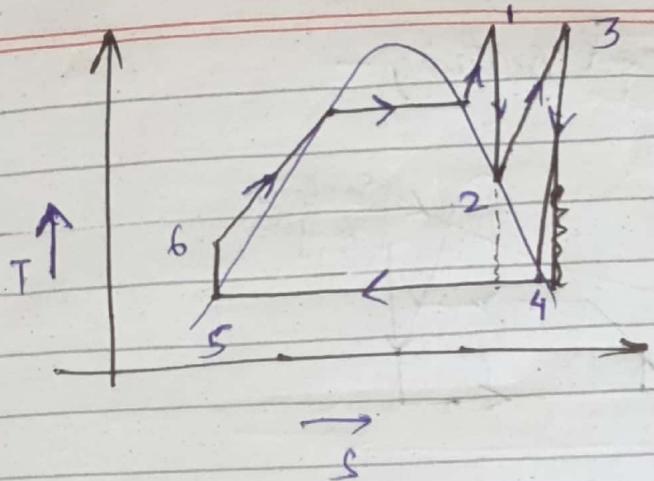


- Source & sink are not at const. temp for practical cycle.
- Normal reservoirs are having finite heat capacity.



Reheating rankine cycle





1. Temp. of heat addition increases \Rightarrow increased η
2. more work output for same amount of working fluid
3. dry ~~steam~~ at turbine exit.

more cost, piping, large boiler.

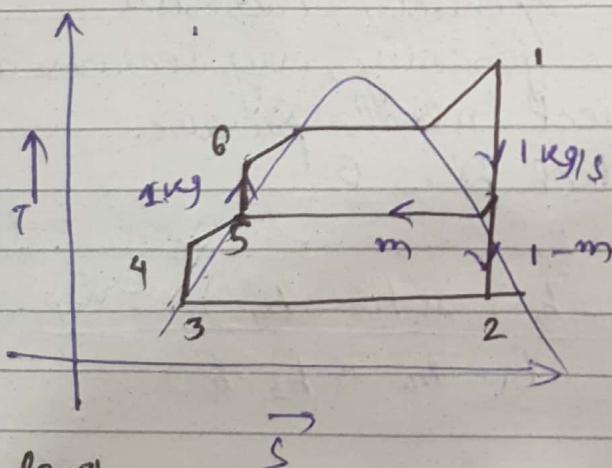
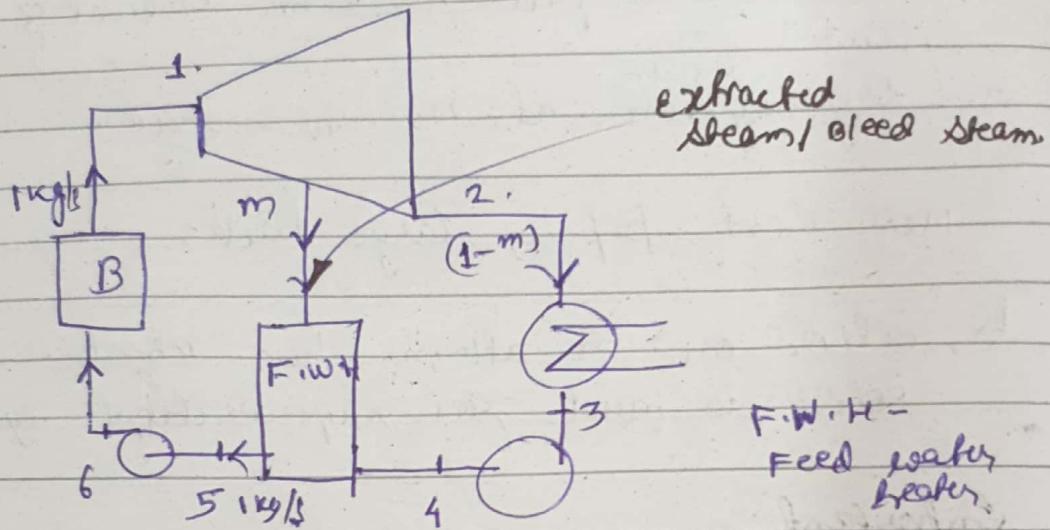
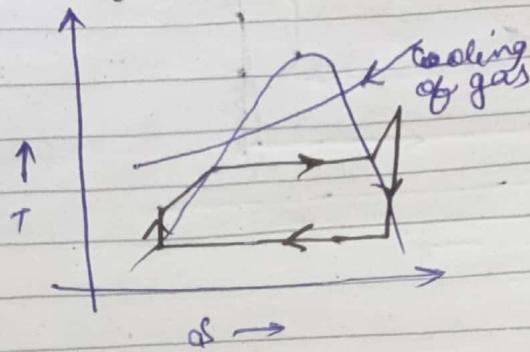
↳ either one or atleast two reheat.
reheat is must for supercritical cycle.

Important :-

1. work output definitely increases
2. η increases generally, may decrease also.
3. How to select reheat pressure.
How to select pt. ②

$$\eta = \frac{(h_1 - h_2) + (h_3 - h_4)}{h_1 - h_2 + (h_3 - h_2)} - w_p$$

Regenerative feed heating -



Advantages -

1. Amount of heat addition ① low temp. reduced $\rightarrow \eta$ increased.
2. Turbine size is less (because as we are taking steam out, so lesser steam goes forward & hence turbine size is small. Also, the tapped steam would give lesser work, at expense of this work, we get to same rating in boiler.)

disadvantages-

1. less amount of work.
2. extra equipment, piping etc.

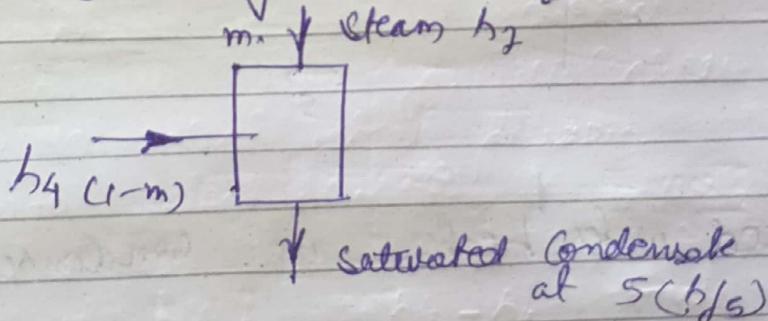
Big utility power plant \rightarrow Reheat + Regenerative cycle.

$$\eta = \frac{(h_1 - h_f) + (1-m)(h_f - h_2) w_f}{h_1 - }$$

$$\eta = \frac{(h_1 - h_f) + (1-m)(h_f - h_2) - w_A - w_B}{(h_1 - h_6)}$$

If pressure temp. values are known m is only unknown.

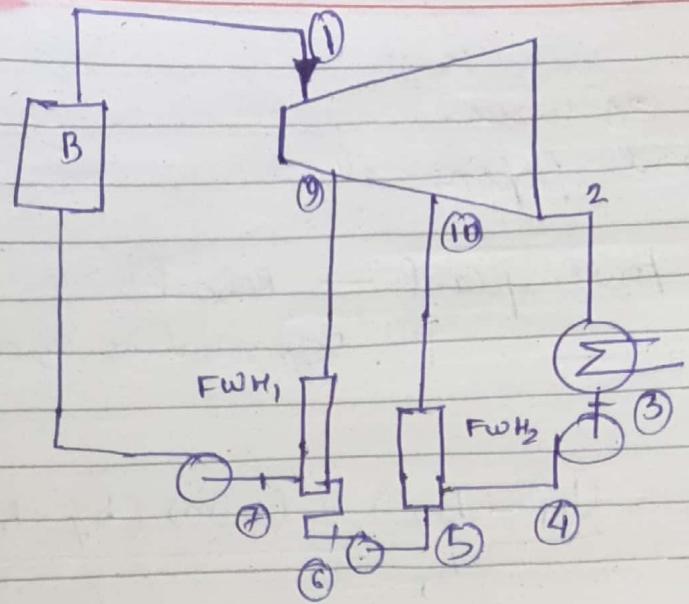
Considering energy balance for FWH,



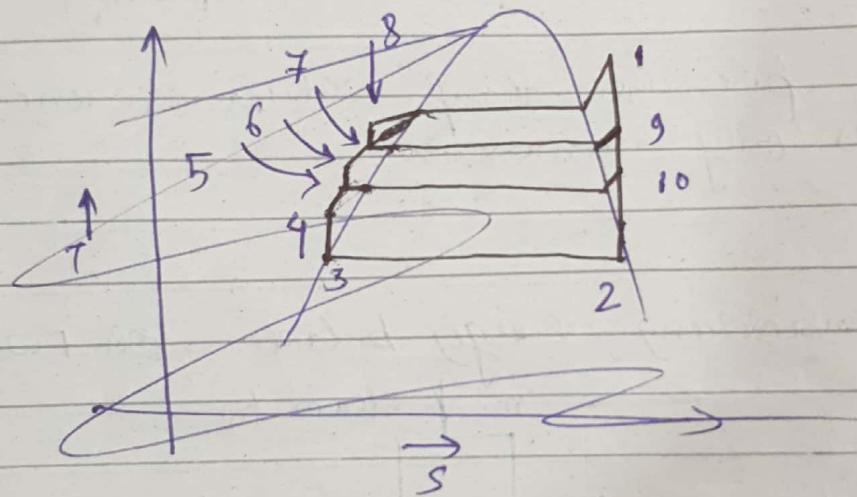
$$m h_2 + (1-m) h_4 = h_{f5}$$

Type of FWH -

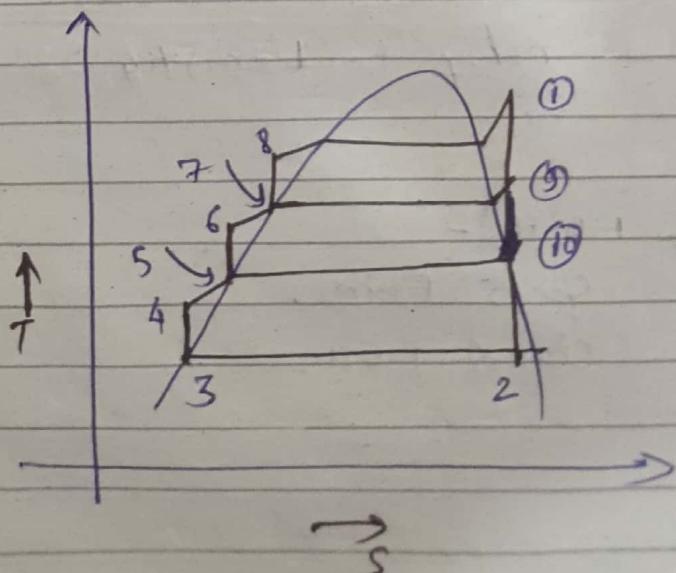
- (1) open FWH
- (2) closed FWH.



Open FWH



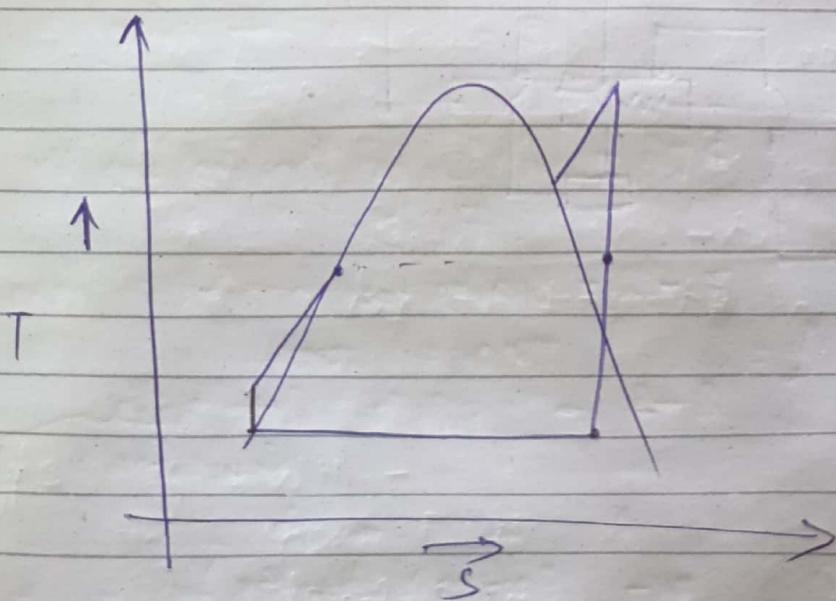
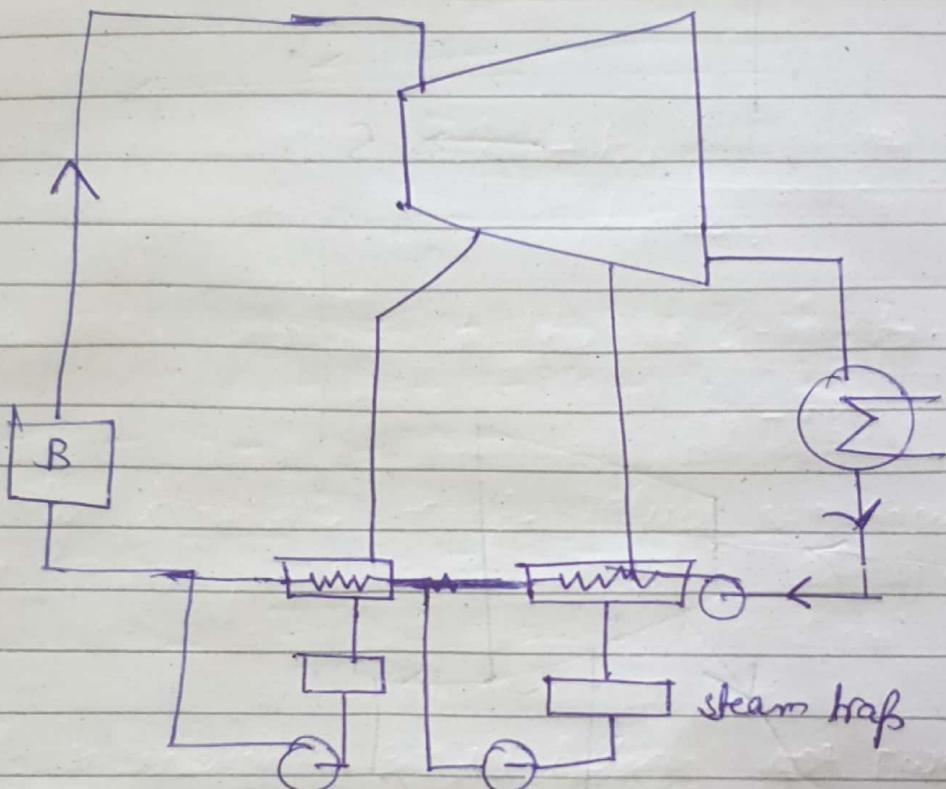
Feed water heaters are condensers.

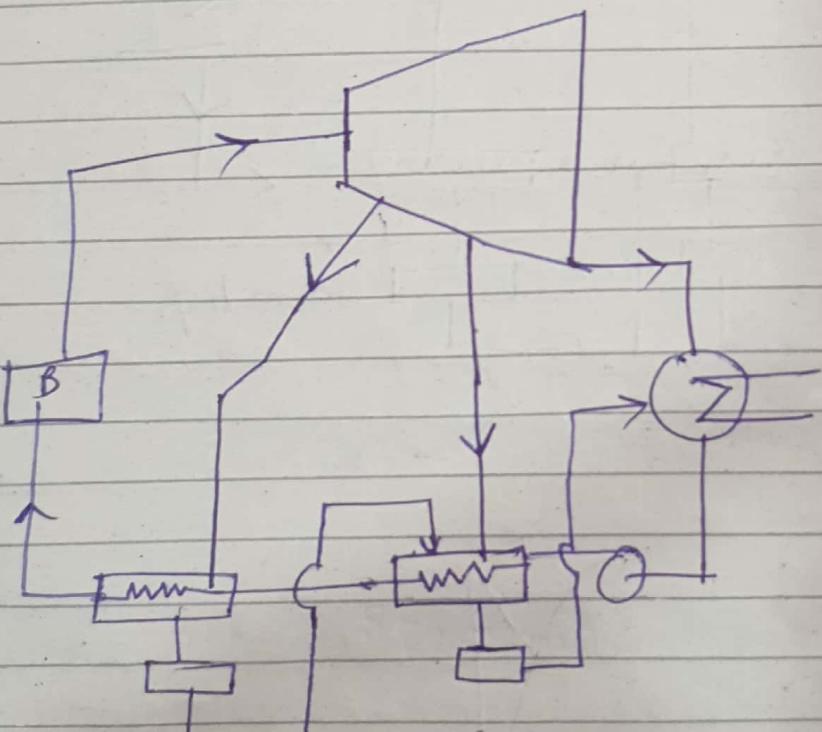
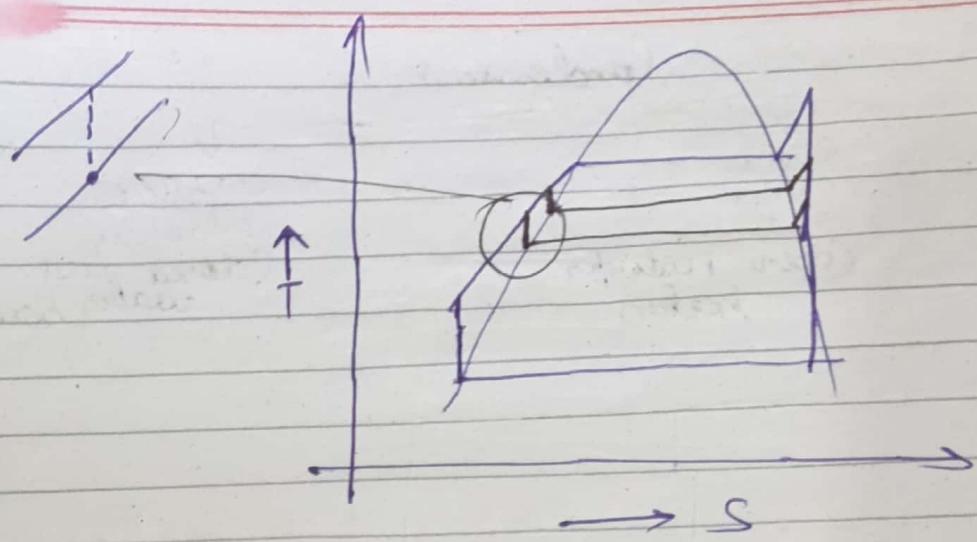


Condensers -

↓
Direct
Contact
Condenser
(Open Feedwater
heater)

↓
Surface
Condenser
(closed feed
water heater)





#1 Large no. of feedwater heaters (both open & closed)

2. At least one open FWH to be used

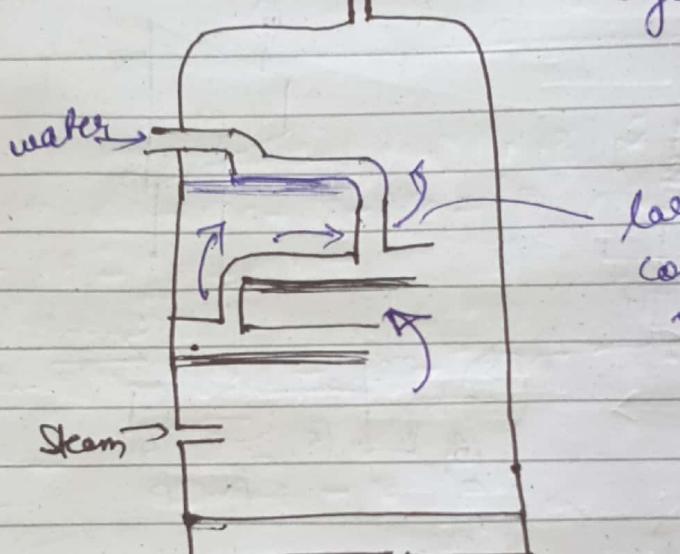
separately.

Dear separator -

open feed water heater.

→ non condensable

gas (produced
by certain
reaⁿ in
pipes)



large lengths
covered by
steam

by. out.

Q. How will the FWH_c be placed?

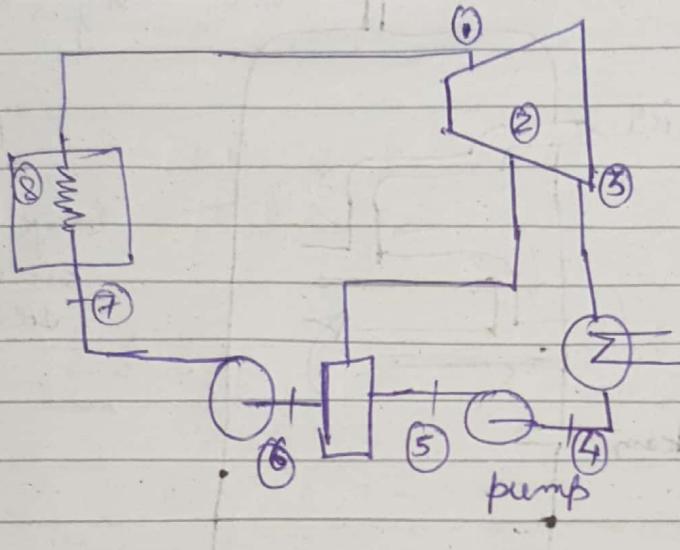
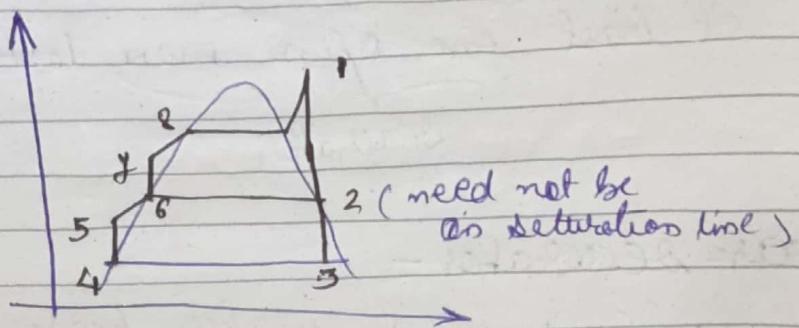
Q. A cycle .

turbine inlet ~~pressur~~ ^{10 MPa},
 660°C , Condenser $\rightarrow 10\text{ kPa}$, leaving pressure
 2 MPa , Then fraction of steam which
needs to be extracted & thermal efficiency?

$$\eta_t = 45.19\%$$

$$\text{Steam extracted} = 23.9\%$$

Optimum placement of feed heaters:-



7-8 - Economizer (fuel is needed)

8-1 - evaporator + Superheater

5-6 - water is heated in the open FWH.

7-8 - water is heated in an economizer.

8-1 - Boiler (evaporator + superheater)

$$\eta = 1 - \frac{(1-m)(h_3 - h_4)}{(h_1 - h_6)}$$

$$m(h_2 - h_6) = (1-m)(h_6 - h_4) \left(\frac{\text{Pump work}}{\text{Heat}} \right)$$

$$m = \frac{h_6 - h_4}{h_2 - h_4} \quad \text{neglected}$$

$$\eta = 1 - \frac{1 - \frac{h_6 - h_4}{h_2 - h_4} (h_3 - h_4)}{(h_1 - h_6)}$$

$$= 1 - \frac{(h_2 - h_6)(h_3 - h_4)}{(h_2 - h_4)(h_1 - h_6)}.$$

1-2-3 → expansion line.

Any point on expansion line,
 $(h - h_f) \cong \text{const.}$, it has been shown.
 $= \beta,$

i.e $(h_1 - h_8) = (h_2 - h_6) = (h_3 - h_4) = \beta$
 Heat transferred to the working fluid in
 the feed water heater $= (h_6 - h_4) = r$

$$h_2 - h_4 = (h_2 - h_6) + (h_6 - h_4)$$

$$= \beta + r$$

And Total amount heat transferred to the working fluid to bring it to the saturated condition at boiler pressure.

$$h_8 - h_4 = \alpha \text{ (assume)}$$

$$h_1 - h_6 = (h_1 - h_8) + (h_8 - h_4) + (h_4 - h_6)$$

$$= \beta + \alpha - r$$

$$\eta = 1 - \frac{(h_2 - h_6)(h_3 - h_4)}{(h_2 - h_4)(h_1 - h_6)}$$

$$= 1 - \frac{\beta^2}{(\beta + r)(\alpha + \beta - r)}$$

For efficiency to be maximum,
 $\frac{dn}{d\beta} = 0$

$$\frac{dn}{d\beta} = \frac{2(\beta+r)(\alpha+\beta-r)\beta - \beta(\alpha+\beta-r) - (\beta+r)\alpha}{(\beta+r)^2(\alpha+\beta-r)^2}$$

$$\Rightarrow \cancel{2\beta + \beta^2}$$

$$0 = 2(\beta+r)(\alpha+\beta-r) - \beta(\alpha+\beta-r) - (\beta+r)\alpha$$

$$= 2\cancel{\beta} + \alpha\beta - \beta r + \alpha r + \cancel{\beta\alpha - r^2} - \cancel{\alpha\beta - \beta^2 + \beta r - \beta^2 - r\beta}$$

$$\Rightarrow \cancel{\alpha\beta} - \beta r + \cancel{\alpha r + \beta\alpha - r^2} = \cancel{\beta(\alpha - r)}$$

$$\cancel{\alpha\beta} + \cancel{2\alpha r - r\beta - 2r^2} =$$

$$\beta = \frac{2r^2 - 2\alpha r}{\alpha - r}$$

$$= \frac{2r(r-\alpha)}{\alpha - r}$$

$$\eta = 1 - \frac{\beta^2}{(\beta+r)(\alpha+\beta-r)}$$

$$= 1 - \frac{-\beta^2}{(\beta^2 + \alpha\beta - \beta r + r\alpha + r\beta - r^2)}$$

$$= 1 - \frac{\beta^2}{(\beta^2 - r^2 + \alpha\beta + r\alpha)}$$

$$= \frac{\beta^2 - r^2 + \alpha\beta + r\alpha - \beta^2}{\beta^2 - r^2 + \alpha\beta + r\alpha}$$

$$\eta = \frac{\alpha\beta + r\alpha - r^2}{\beta^2 - r^2 + \alpha\beta + \alpha r}$$

$$\frac{d\eta}{d\beta} = \frac{(\beta^2 - r^2 + \alpha\beta + \alpha r)(\alpha)}{(\beta^2 - r^2 + \alpha\beta + \alpha r)^2}$$

$$- (\alpha\beta + r\alpha - r^2)(2\beta + \alpha)$$

$$0 = \cancel{\alpha\beta^2 - \alpha r^2 + \alpha^2\beta + \alpha^2r} - \cancel{\alpha^2\beta - \alpha^2r + \alpha r^2} - 2\alpha\beta^2 - 2r\beta\alpha + 2\beta r^2$$

$$\cancel{\alpha\beta^2} \cdot 2\beta r^2 - 2r\beta\alpha - \cancel{\alpha\beta^2} = 0$$

$$\beta(2r^2 - 2r\alpha - \alpha\beta) = 0$$

$$\beta = 0 \quad | \quad \beta = \frac{2r^2 - 2r\alpha}{\alpha}$$

$$\beta = \frac{2r(r-\alpha)}{\alpha}$$

$\beta =$ const. from assumption already been shown from SPP.

$r = b_f - b_g \rightarrow$ heat given in the FWHM (variable)

$$\alpha = (b_f - b_g)$$

$$\frac{d\eta}{dr} = 0 \quad \text{for max. efficiency.}$$

$$\frac{d\eta}{dr} = \frac{d}{dr} \left(\frac{\alpha\beta + r\alpha - r^2}{\beta^2 - r^2 + \alpha\beta + \alpha r} \right)$$

$$= \frac{(\beta^2 - r^2 + \alpha\beta + \alpha r)(\alpha - 2r) - (\alpha\beta + \alpha r - r^2)(\alpha - 2r)}{(\beta^2 - r^2 + \alpha\beta + \alpha r)^2}$$

$$\Rightarrow (\alpha - 2\gamma) \left(\beta^2 - \gamma^2 + \alpha\beta + \gamma\alpha - \alpha\beta - \gamma(\alpha + \gamma^2) \right) = 0$$

$$\beta^2 + (\alpha - 2\gamma) = 0$$

$$\beta = 0 \quad \text{or} \quad \alpha = 2\gamma$$

$$\Rightarrow \boxed{\gamma = \frac{\alpha}{2}}$$

$$\begin{aligned} n_{max} &= 1 - \frac{\beta^2}{(\beta + \frac{\alpha}{2})(\alpha + \beta - \frac{\alpha}{2})} \\ &= 1 - \frac{-\beta^2}{(\frac{\alpha}{2} + \beta)(\beta + \frac{\alpha}{2})} \\ &= 1 - \frac{4\beta^2}{(\alpha + 2\beta)^2} \\ &= \frac{\alpha^2 + 4\alpha\beta - 4\beta^2}{(\alpha + 2\beta)^2} \end{aligned}$$

$$n_{max.} = \frac{\alpha^2 + 4\alpha\beta}{(\alpha + 2\beta)^2}$$

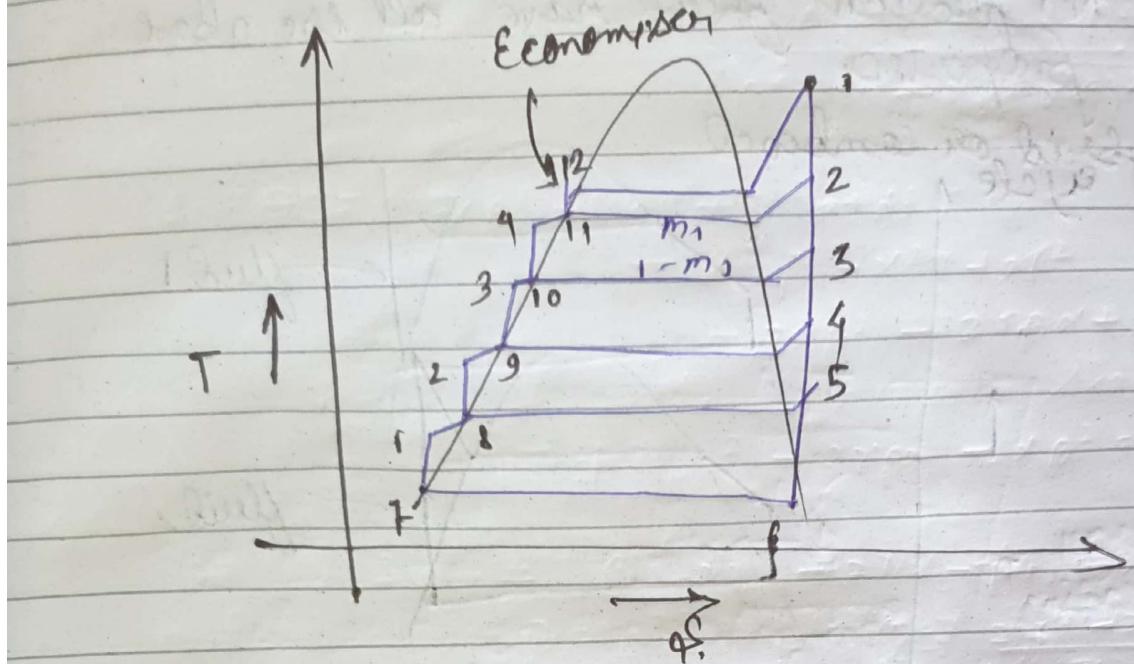
~~with~~
without feedwater breaker,

$$\begin{aligned} \eta &= \eta_0 = 1 - \frac{h_3 - h_4}{h_1 - h_4} \\ &= 1 - \frac{\beta}{\alpha + \beta} = \frac{\alpha}{\alpha + \beta} \end{aligned}$$

Increase in efficiency, $\Delta\eta = \eta_{max} - \eta_0$

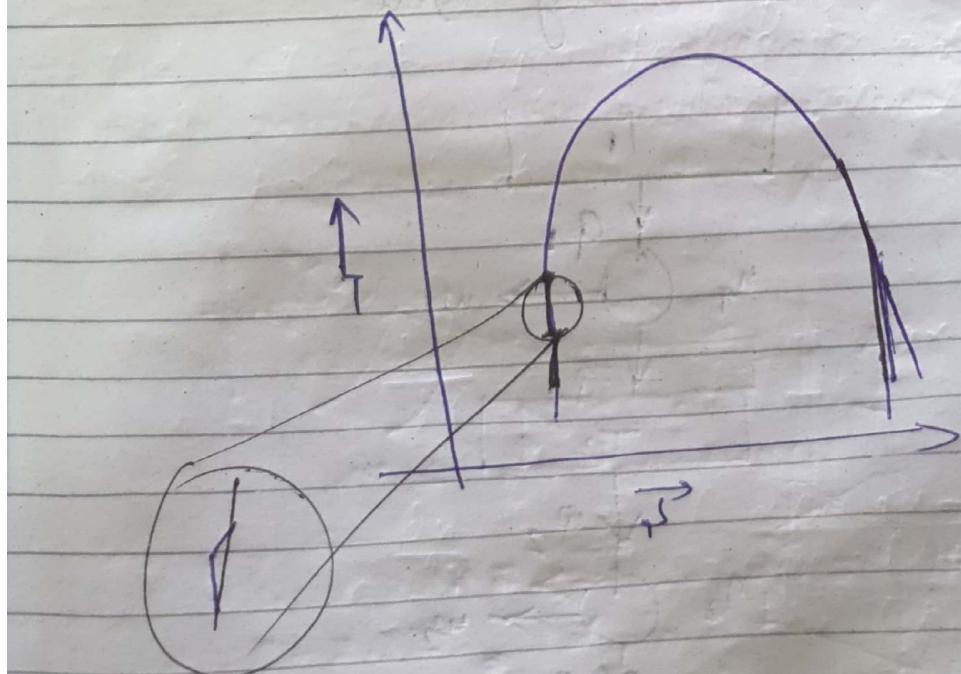
$$= \frac{\alpha^2 + 4\alpha\beta}{(\alpha + 2\beta)^2} - \frac{\alpha}{\alpha + \beta}$$

$$= \frac{\alpha^2 \beta}{(\alpha + \beta)(\alpha + 2\beta)^2}$$



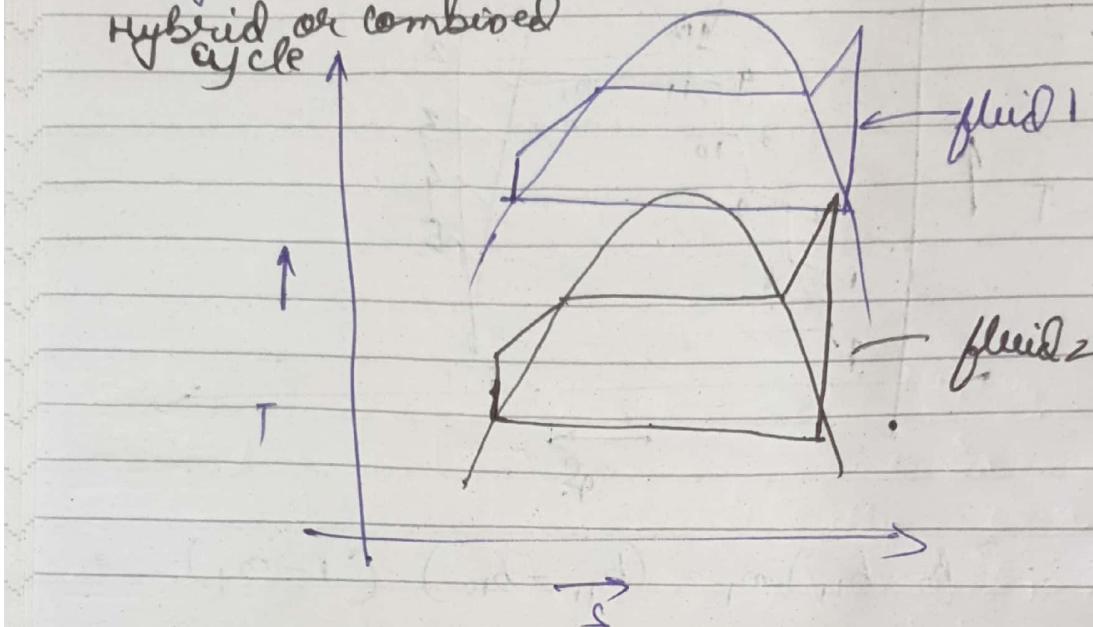
$$(h_2 - h_{11})m_1 = (h_{11} - h_{10})(1 - m_1)$$

Ideal fluid for vapour power cycle -

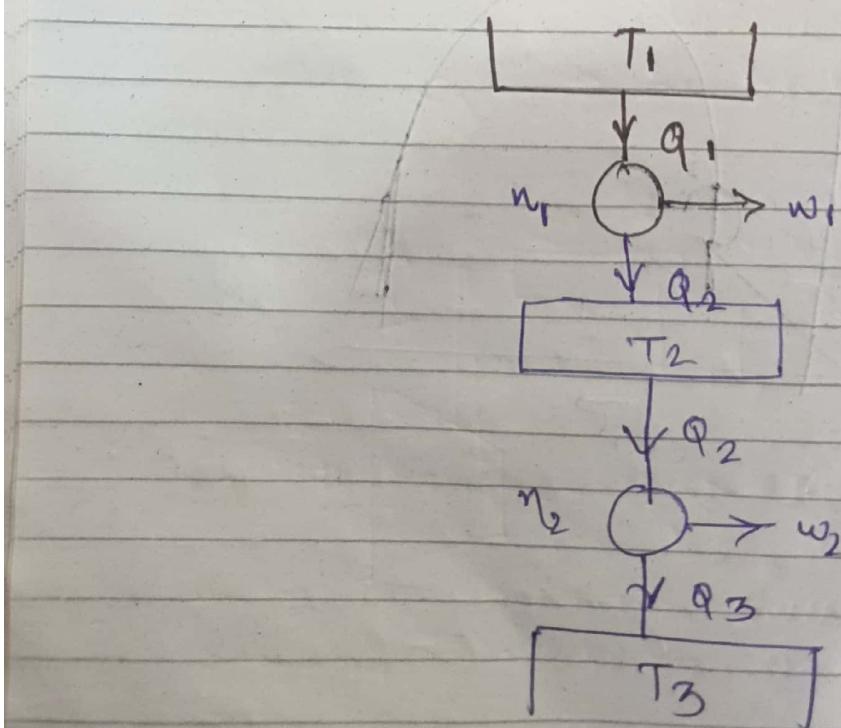


- fluid should have high critical temp.
- sat. liquid & sat. vapour line must be almost vertical.
- high latent heat
- No practical fluid have all the above properties.

hybrid or combined cycle



- ~~Good~~
- one topping cycle
 - Bottoming cycle.



$$\eta_1 = 1 - \frac{q_2}{q_1}$$

$$\eta_2 = 1 - \frac{q_3}{q_2}$$

$$\eta = 1 - \frac{q_3}{q_1}$$

Find η as function of η_1 & η_2 .

Sol "Y"

$$\frac{q_2}{q_1} = 1 - \eta_1$$

$$\frac{q_3}{q_2} = 1 - \eta_2$$

$$\frac{q_3}{q_1} = 1 - \eta$$

$$\Rightarrow \frac{q_2}{q_1} \times \frac{q_3}{q_2} = \frac{q_3}{q_1}$$

$$\Rightarrow (1 - \eta_1)(1 - \eta_2) = (1 - \eta)$$
$$1 - \eta_1 - \eta_2 + \eta_1 \eta_2 = 1 - \eta$$

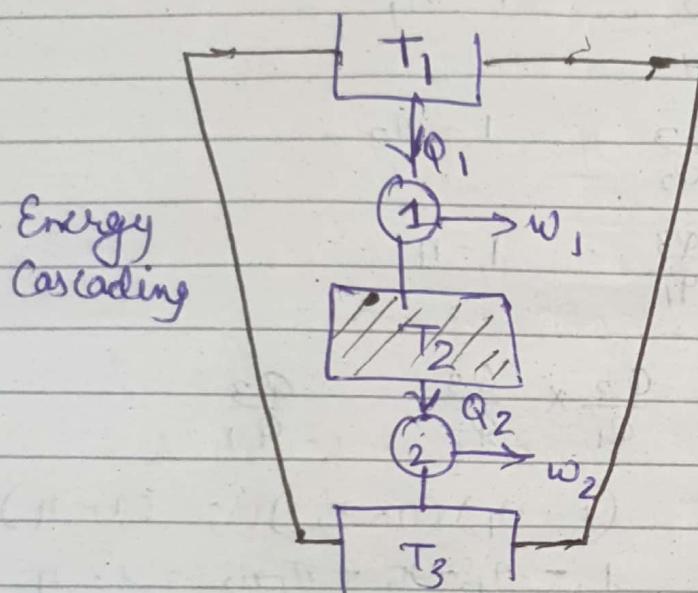
$$\boxed{\eta = \eta_1 + \eta_2 - \eta_1 \eta_2}$$

Similarly for large no. of cycles

$$1 - \eta = \prod_{i=1}^n (1 - \eta_i)$$

Combined power cycles -

↓
 Parallel
 ↓
 more w
 but no
 gain in
 efficiency



$$\eta = \frac{w_1 + w_2}{q_1}$$

ideally

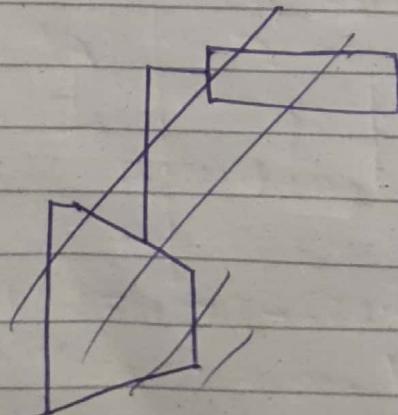
$$1-\eta = \prod_{i=1}^{i=n} (1-\eta_i)$$

$$i = n$$

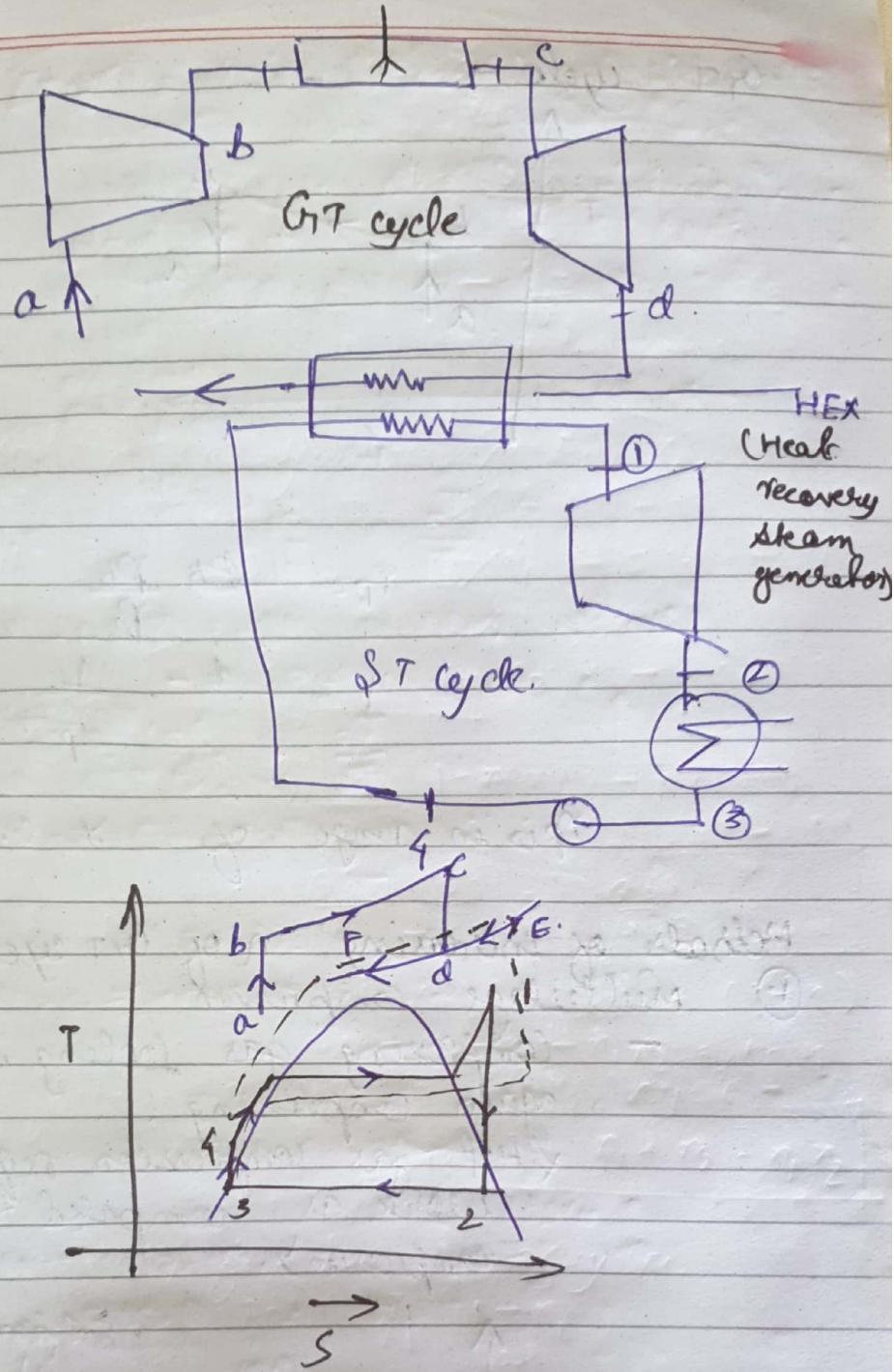
for n no. of cycles
combined series

Practical points -

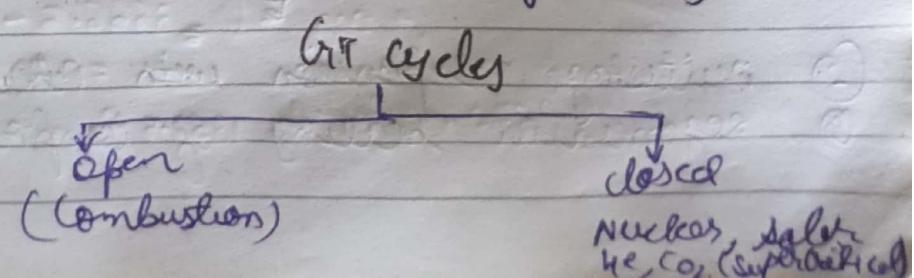
- ① is the ideal picture "true".
- ② what cycle(s) to be combined.



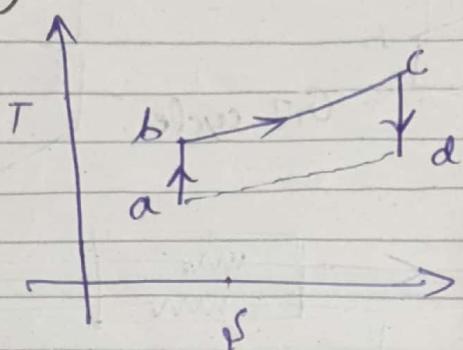
- In boiler major heating of water takes place due to radiation.



- Brayton cycle is Gas power cycle.
 - Both open & closed.
- If air is used for combustion \rightarrow open
If air or other gas used for heat exchange only \rightarrow closed



$T-s$ cycle -



$$r_p = \frac{P_b}{P_a}$$

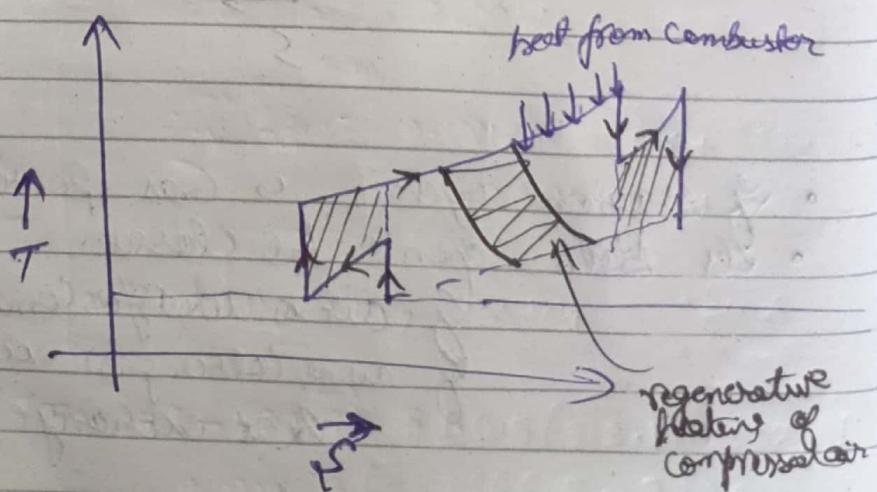
$$\eta = 1 - \frac{1}{r_p^{\gamma-1}}$$

r_p is in range of $7-8$.

Methods of increasing η of $T-s$ cycle.

(1) multistage compression.

- Compressing gas cooling it \downarrow & again compressing (called intercooling).
- \times Hot gas compression requires more work as compared to cold gas compression).



(2) multistage expansion with reheating
(3) regenerative heating of compressed air.

Following data refer to Combined cycle power plant.

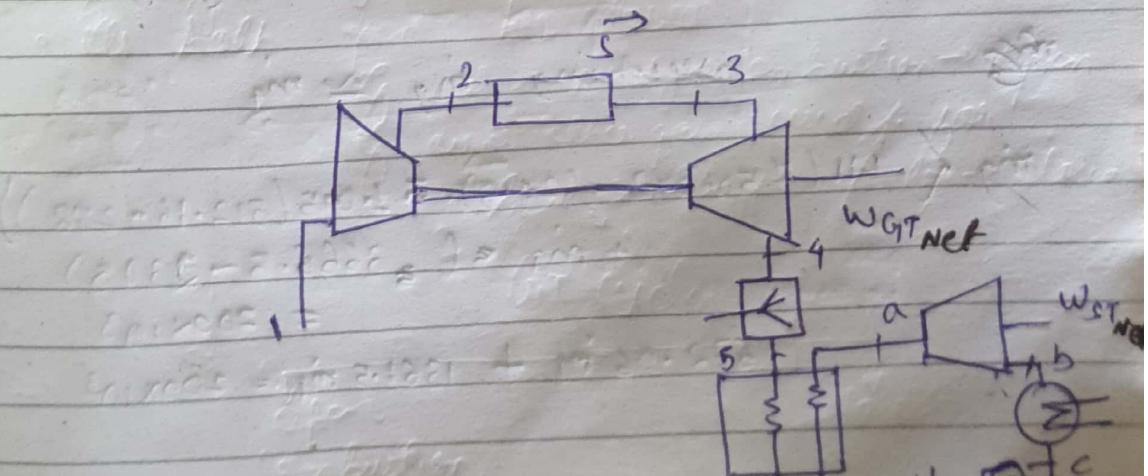
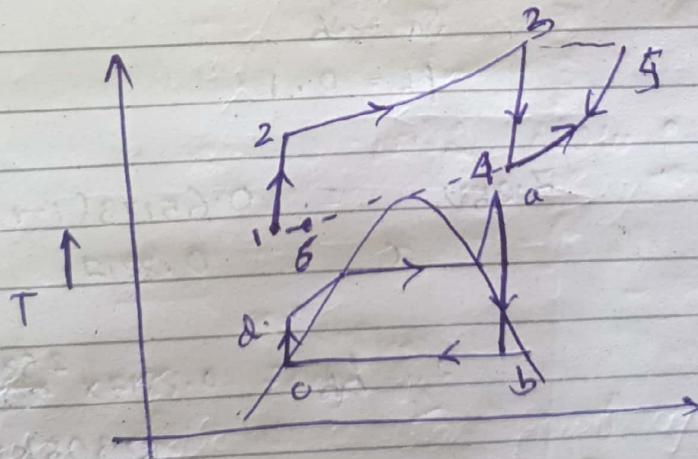
Air to compressor 1 bar 25° , $T_p = 8$.

Q. Combined GT & ST powerplant. Inlet air condition 15° , 1 Atm, $T_{max} 750^\circ$, $P_r = 7.5$ goes leaves HRSG @ 100° . Steam enters turbine at 50 bar 600° . Additional fuel burnt in the HRSG to bring the temp. to T_{max} , condenser pressure = 0.1 bar. Total power 200 MW, calorific value of fuel = 43.3 MJ/kg.

Find out m_g , m_a , n_{GT} , individual power, air-fuel ratio.

gas:	$C_p = 1.11$	$r = 1.33$
Air:	$C_p = 1.005$	$r = 1.4$

Soln



$$\dot{m}_g (P_{d_1} (T_3 - T_4) - \dot{m}_a C_{p,a} (T_2 - T_1))$$

$\dot{w}_{a,T}$

+ $\dot{m}_s (h_a - h_b)$ = Power
 $= 200 \times 10^3$

(Pump work neglected)

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = 7.5$$

$$T_2 = 512.16 \text{ K}$$

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{n-1}{n}} \quad n_{\text{gas}} = 1.33$$

$$T_4 = 620.5 \text{ K}$$

h.e.

$$h_a = 3666.5$$

$$s_a = 2.81 \text{ kJ/kg} \cdot \text{K} - 7.2589$$

$$s_b = 58$$

$$P_b = 0.1$$

$$7.2589 = 0.65173(1-\gamma) + 0.1633$$

$$\gamma = 0.8817$$

$$\therefore h_b = 0.8817 \times 2586 + 196.8 \text{ (12)} \\ = 2305 \text{ kJ/kg}$$

assuming $\dot{m}_g \approx \dot{m}_a$

$$\dot{m}_g \left\{ 1.11(750.273 - 620.5) + 0.005(512.16 - 288) \right\} \\ + \dot{m}_a \times (3666.5 - 2305) \\ = 200 \times 10^3$$

$$672.06 \dot{m}_g + 1361.5 \dot{m}_a = 200 \times 10^3$$

$$\begin{aligned} \dot{m}_a &= 3 \\ \dot{m}_g &= 81.9 \text{ kg/s} \end{aligned}$$

$$\begin{aligned} h_a &\approx h_f (@ P = 50 \text{ bar}) \\ &= -1154.9 \quad h_c = 192.62 \end{aligned}$$

⑩

$$\dot{m}_g C_{p,g} (T_5 - T_6) = \dot{m}_g (h_a - h_d)$$

$$\dot{m}_g \cdot 1.01 (750 - 100) = \dot{m}_g (3666.5 - 192.62)$$

$$721.5 \text{ mg} = 3474.5 \text{ ms}$$

gas turbine wt
88.22 MW
steam turbine
wt
111.78 MW

$$\eta_t = \frac{200 \times 10^3}{\dot{m}_a C_{p,g} (T_3 - T_2) + \dot{m}_g C_{p,g} (T_5 - T_4)}$$

$$A \cdot F = 92.7 \%$$

Advantages & Specialities of Combined ST & GT plant

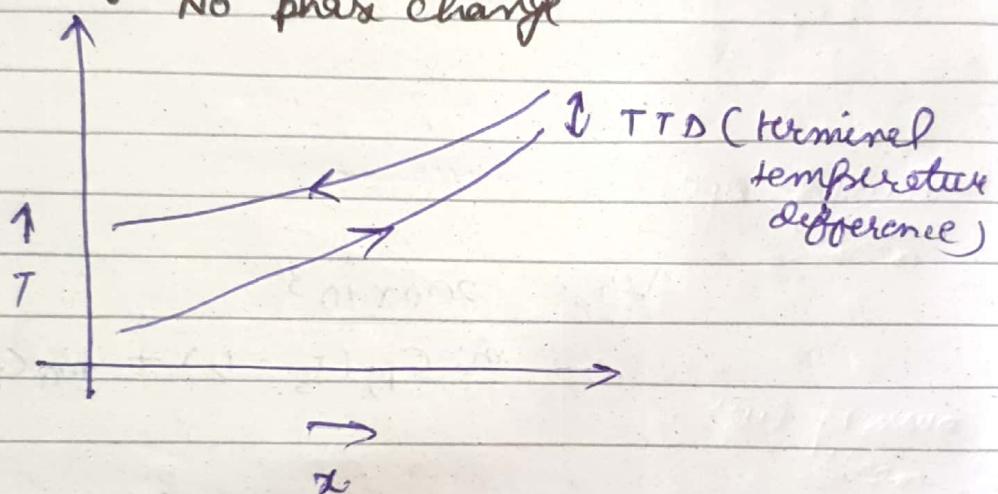
- Individual plants are simple.
- High η & when
- GT plant & ST plants are complementary

\hookrightarrow HRSG₁

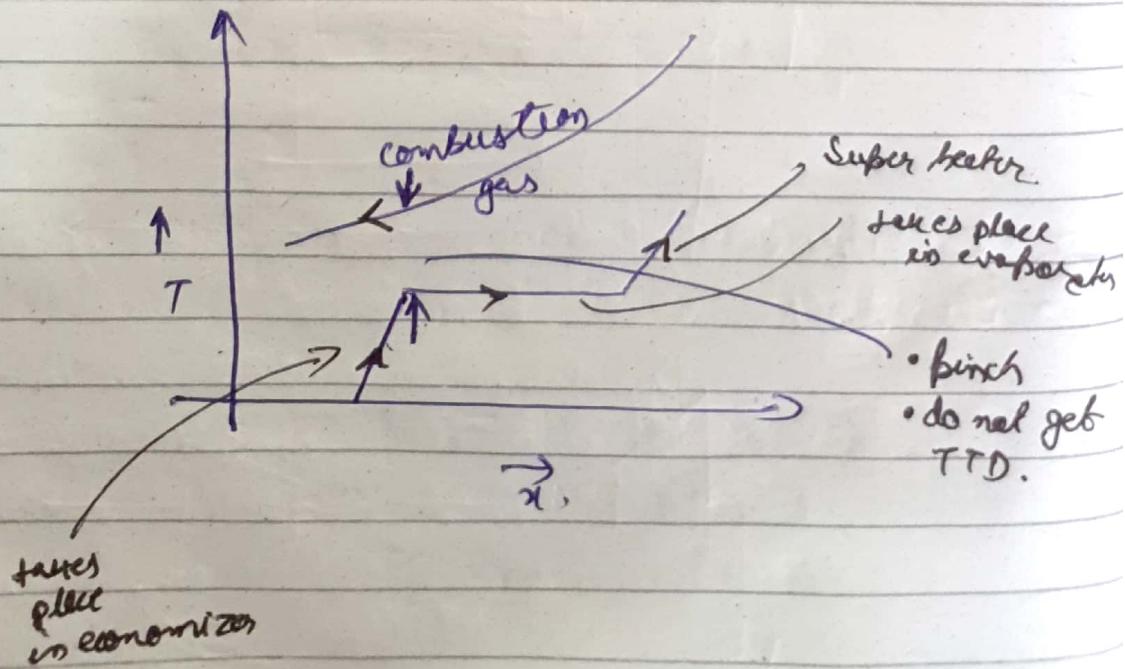
HEX where phase change of water takes place.

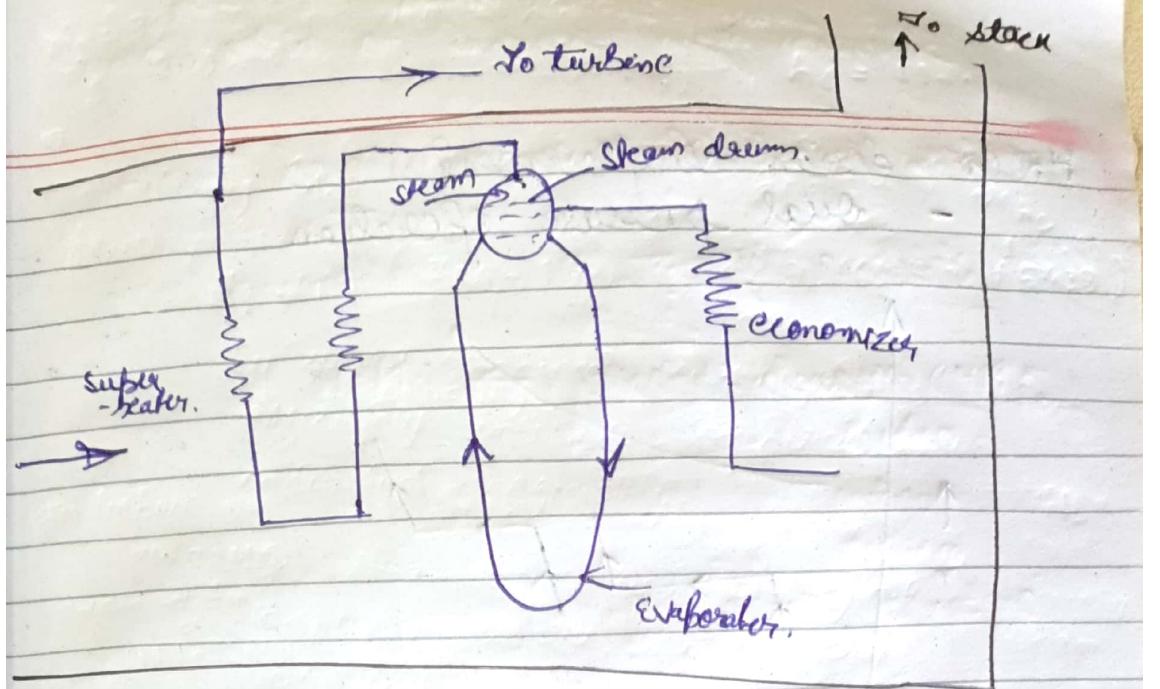
Counter current HEX.

- NO phase change

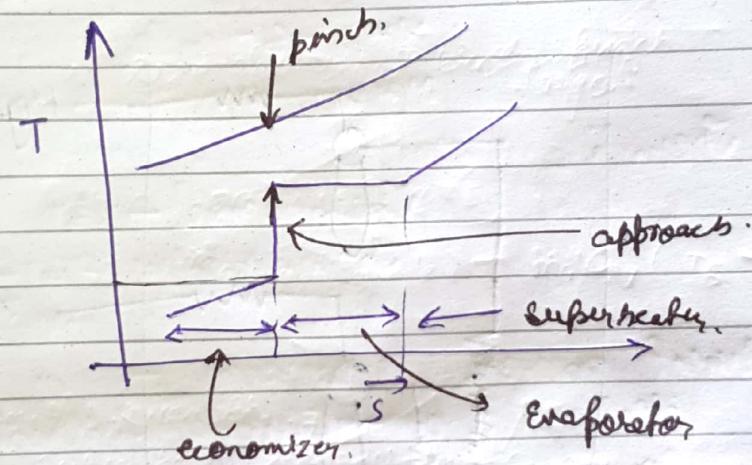


- with phase change



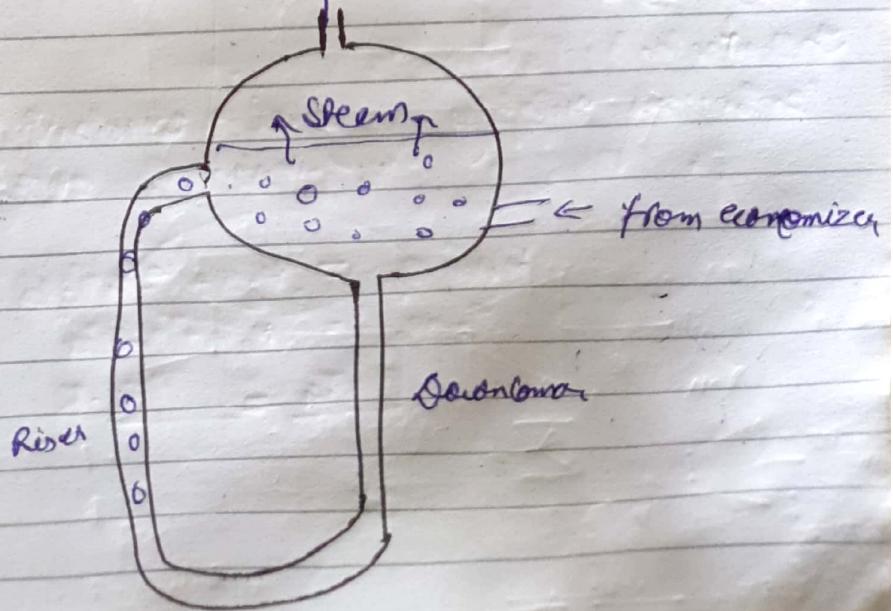


For gas
turbine
exhaust

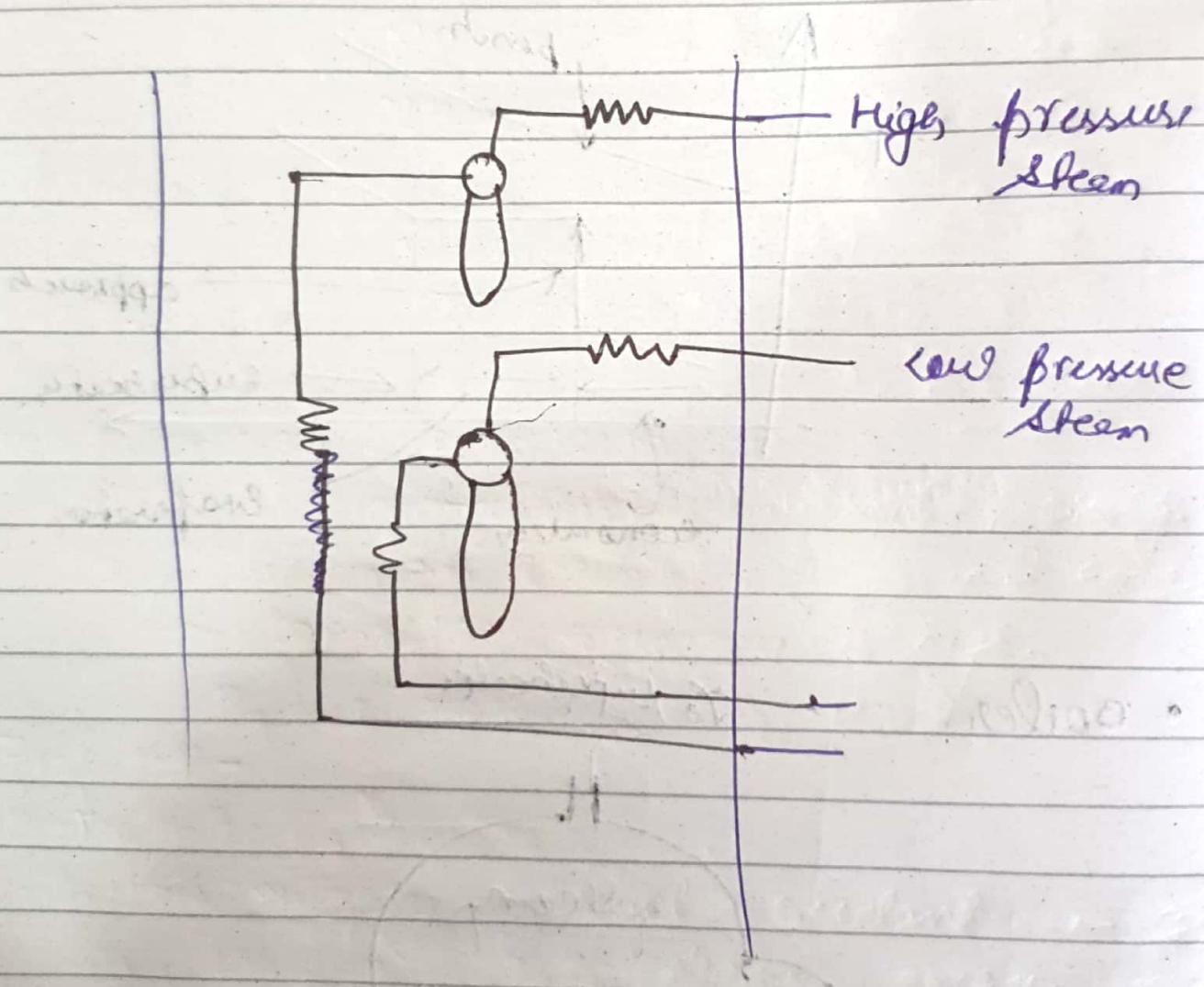
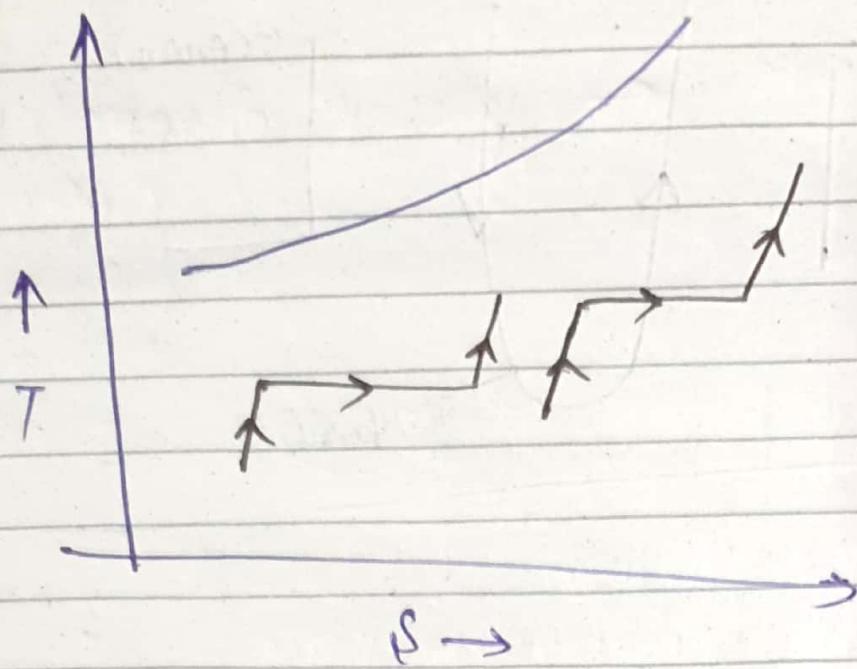


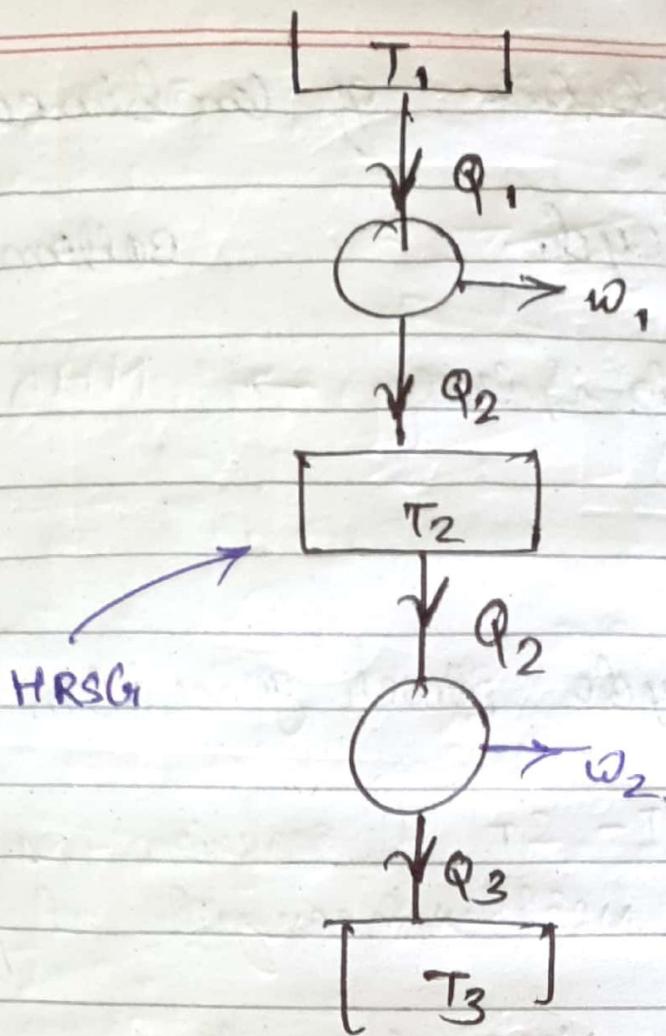
• Boiler.

To superheater



HRSG design improvement
- dual pressure operation





$$(1-\eta) = (1-\eta_1)(1-\eta_2)$$

Q. Consider in HRSG some additional fuel is burnt (Q_a) & there is some heat loss (Q_L)

$$\text{where } \alpha = \frac{Q_a}{Q_1}$$

$$\beta = \frac{Q_L}{Q_1}$$

Find out $\eta = f(\eta_1, \eta_2, \alpha, \beta)$

- Carnot principles are valid only for conversion from thermal to work (form)

Other possibilities of combined cycles -

Lopping cycle

Bottoming cycle.

- MHD (Magnetohydrodynamics) → MHD
-namic)

Combined cycle power generation :-

GT-ST (Boyleton - Rankine)
most successful at present

MHD - ST cycle

MHD - GT cycle.

Thermionic - ST

Thermo electric - ST

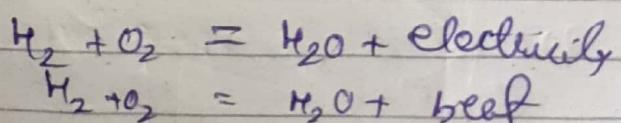
Direct energy conversion -

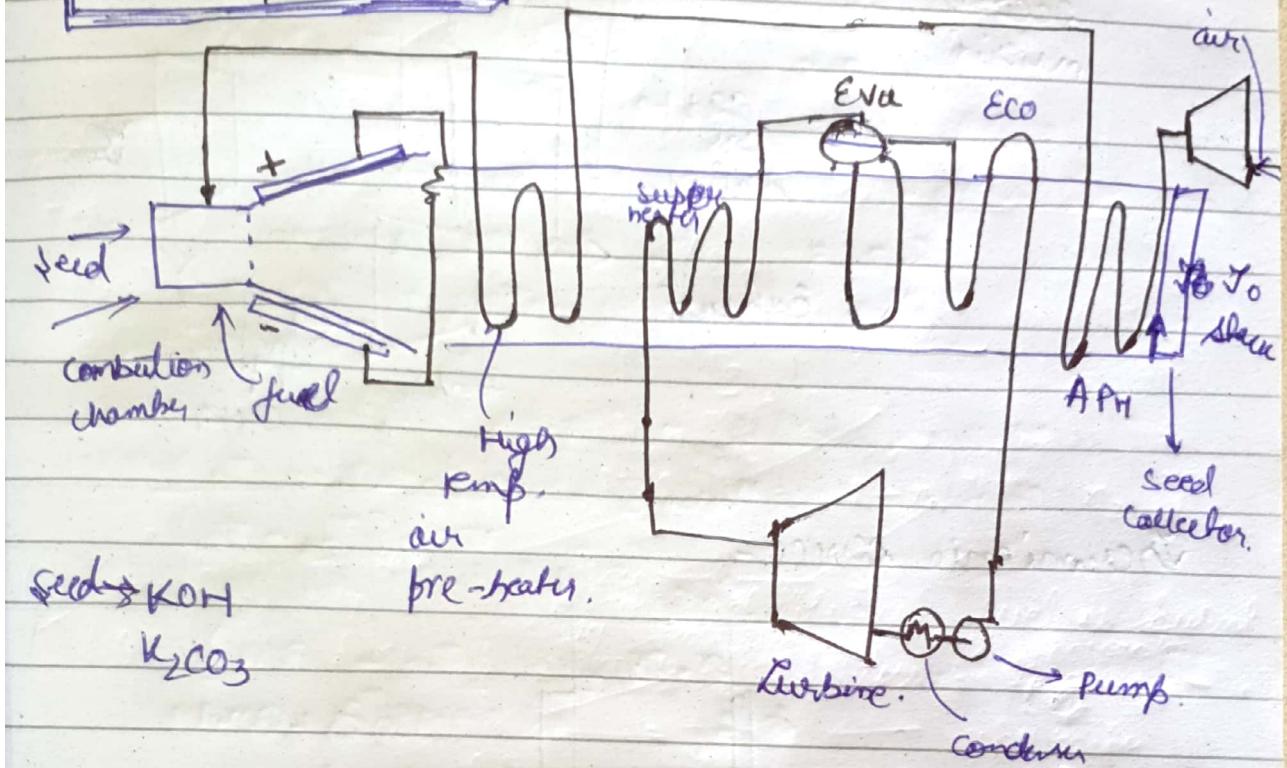
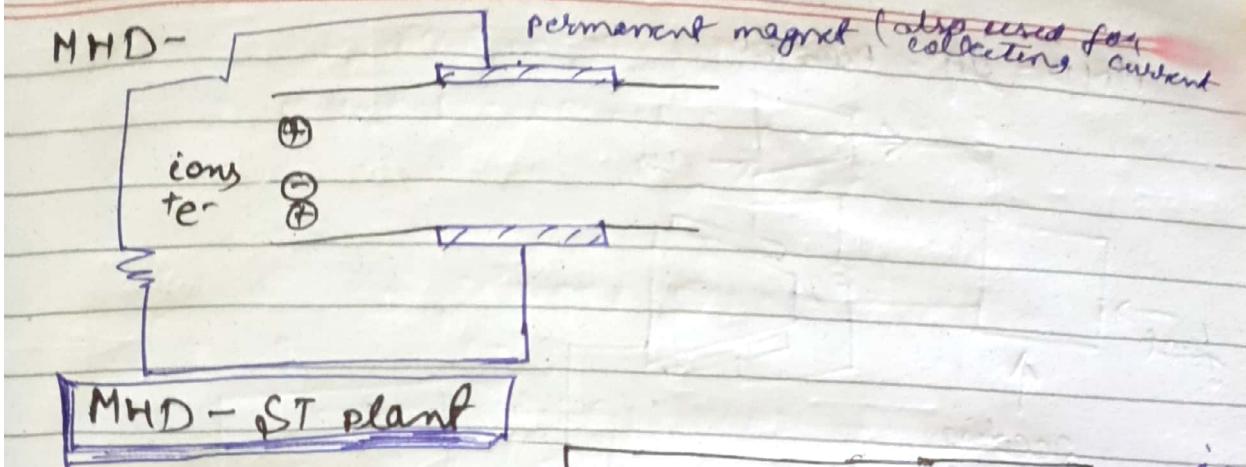
Electrical energy directly (without moving component) from thermal or chemical energy
→ conversion efficiency is high.

Fuel cell -



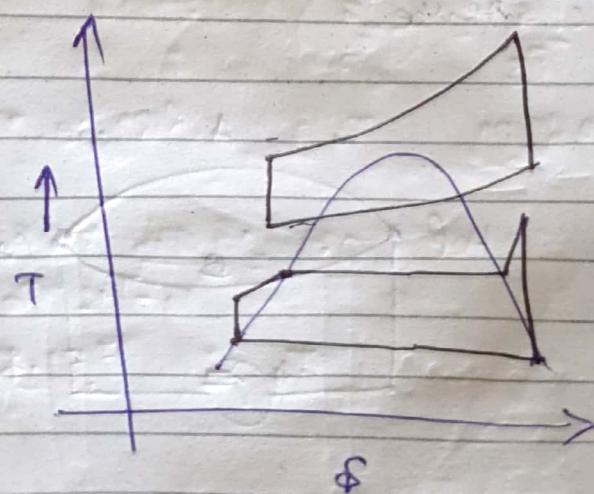
continuous supply of fuel + oxidant → gives electrical energy (DC)



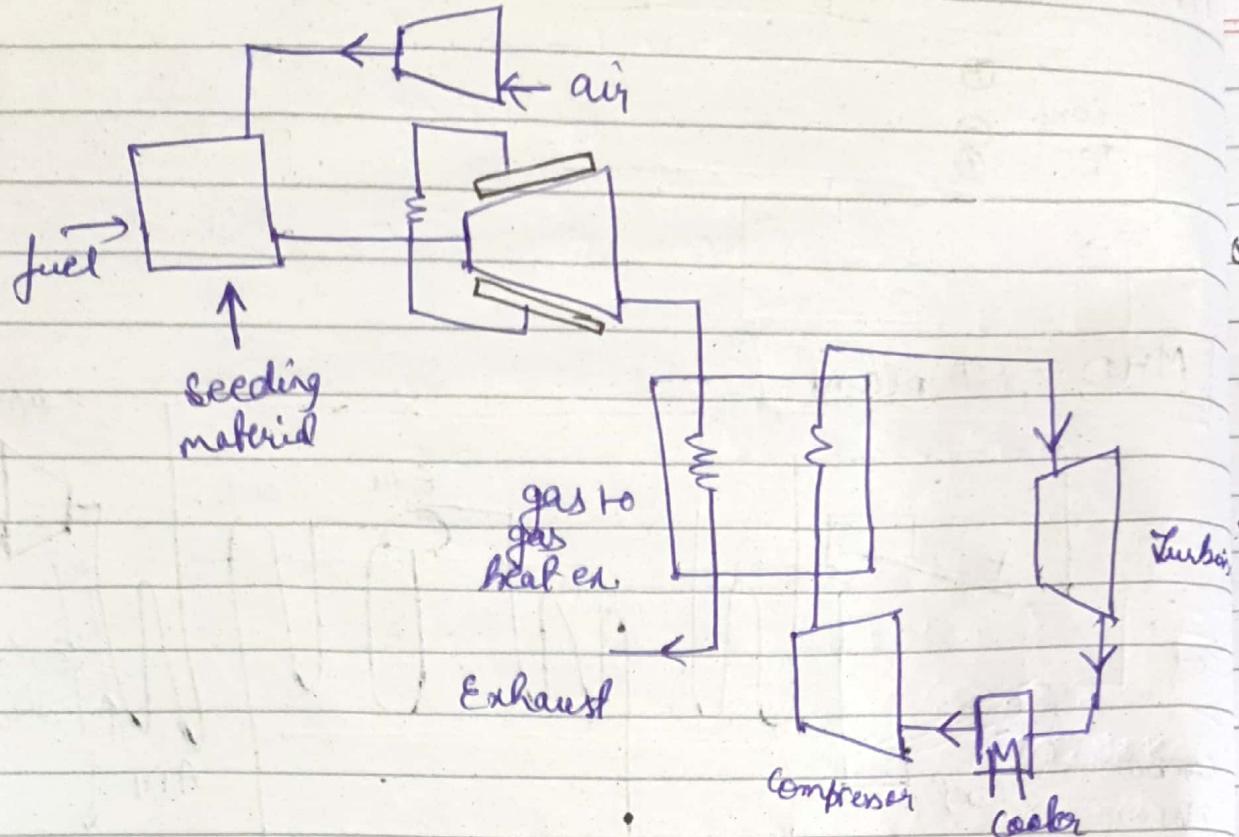


Air temperature after Combustion
 $2200^\circ C - 2700^\circ C$.

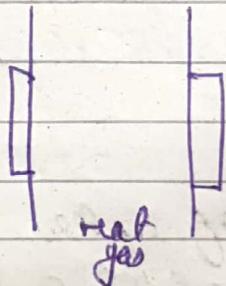
Hot gas is needed so that the electrical conductivity $\approx 10 \text{ mho/m}$.



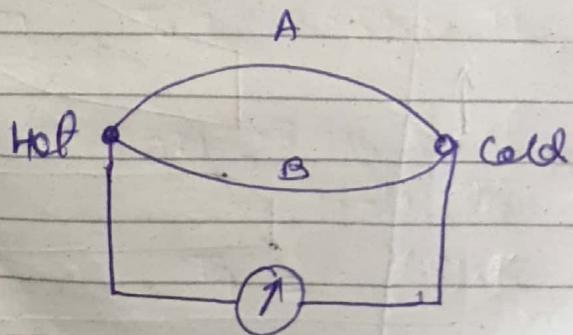
MHD - GT plant



Thermionic device -



Thermoelectric device

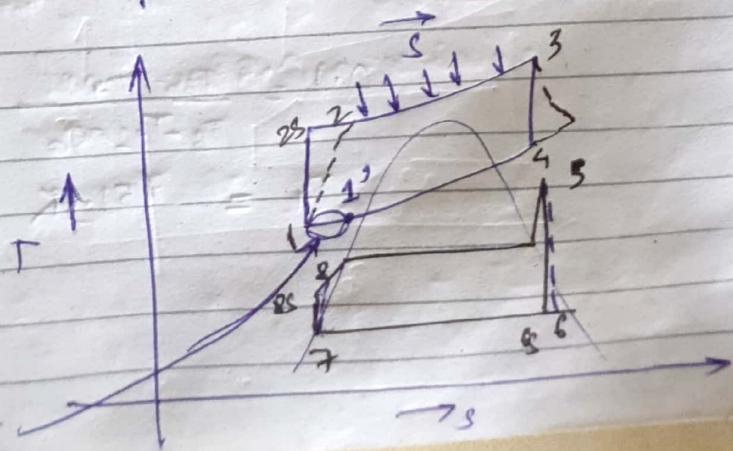
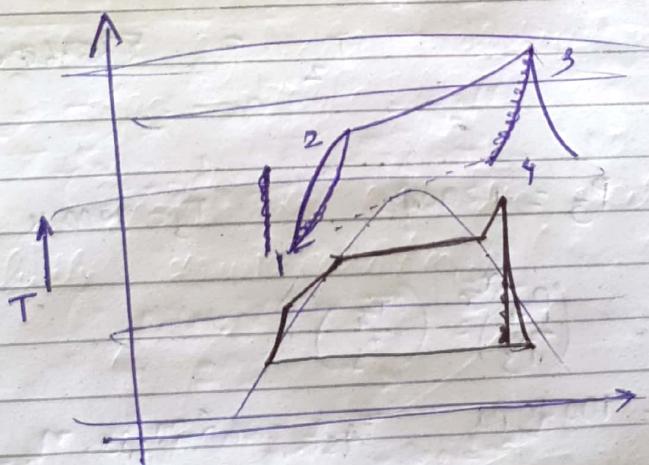


Thermo-electric cooler see
freeze.

- Caloric material uses of magnetic property varying with temp.
- magneto-caloric material
 - electro-caloric material

Q. A combined cycle produces net output of 500 MW. Air enters compressor of gas turbine at 100 kPa, 300 K. The compressor has compressor ratio = 12 & isentropic η of 85%. Turbine heat reject = 90 %. Inlet condⁿ 1000 kPa, 1400 kJ/kg, exit press of 100 kPa. Air from turbine exhaust passes through h.x' & exits at 400 K. On steam turbine side, steam at 8 MPa, 400°C enters turbines which have $\eta_{ts} = 0.85$. It expands adiabatically to condenser press. of 8 kPa sat. water at 8 kPa is calculated back to 1000 kPa by a pump with an isentropic efficiency of 80%. Determine the (i) ratio of mass flow rate of two cycle (ii) mass flow rate of air & (iii) Helmholtz effi.

Ans



$$p_1 = 100 \text{ kPa}, T_1 = 300 \text{ K}$$

$$p_2 = \gamma_p \cdot p_1 = 12 \times 100 = 1200 \text{ kPa}, \tau_2 = ?$$

$$\text{At } P V^{\gamma} = C$$

$$\frac{P^{\gamma} V^{\gamma}}{P^{\gamma} V^{\gamma}} = \frac{C}{P^{\gamma} V^{\gamma}}$$

$$P = C T^{\frac{1}{\gamma-1}}$$

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}}$$

$$(12)^{\frac{1}{\gamma-1}} = \frac{T_2}{T_1}$$

$$T_{2S} = 680.52 \text{ K}$$

$$T_{2S} = 610.98 \text{ K}$$

$$n_{iden} = \frac{m_C p (T_{2S} - T_1)}{m_C p (T_{2S} - T_1)}$$

$$0.85 = \frac{(T_{2S} - 300)}{(610.98 - 300)}$$

$$T_2 = 563.62 \text{ K} \quad 664.94 \text{ K}$$

$$P_3 = 1200 \text{ kPa}$$

$$T_3 = 1400 \text{ K}$$

$$\left(\frac{P_4}{P_3}\right)^{\frac{1}{\gamma-1}} = \left(\frac{T_4}{T_3}\right)$$

$$P_4 = 100 \text{ kPa} \quad T_{4S} = 688.32 \text{ K}$$

$$0.9 = \frac{T_3 - T_4}{T_3 - T_{4S}}$$

$$T_4 = 759.5 \text{ K}$$

$$\begin{aligned}
 \text{Heat supplied to G.T cycle} &= c_p(T_3 - T_2) \\
 &= 1 \times (1400 - 664.9) \\
 &= 735.1 \text{ kJ/kg}
 \end{aligned}$$

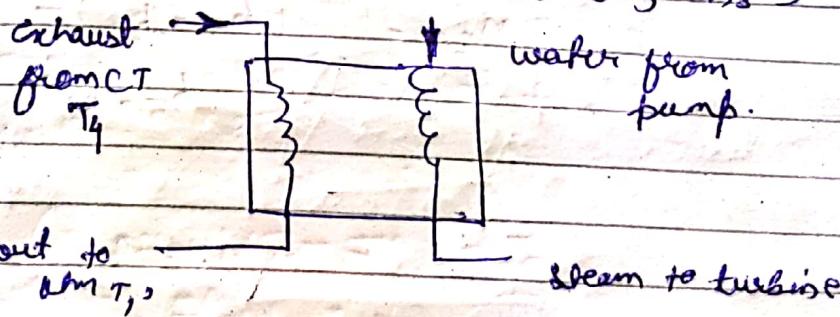
$$\begin{aligned}
 \text{Compressor work} &= c_p(T_2 - T_1) \\
 &= 1 \times (664.94 - 300) \\
 &= 364.94 \text{ kJ/kg.}
 \end{aligned}$$

$$\begin{aligned}
 \text{Turbine work} &= c_p(T_3 - T_4) \\
 &= 1 \times (1400 - 759.5) \\
 &= 640.5 \text{ kJ/kg.}
 \end{aligned}$$

$$\eta_{G.T} = \frac{640.5 - 364.94}{735.1} = 0.375$$

HRSG (Heat exchanger calculation)

$$\dot{m}_a(T_4 - T_{10}) c_{pa} = \dot{m}_w (h_5 - h_8)$$



$$h_7 = 173.8 \text{ kJ/kg.}$$

$$w_p \text{ isen} = y_7 (p_5 - p_7)$$

$$y_7 = 1.00848 \times 10^{-3}$$

$$p_5 = 8 \times 10^3 \text{ Pa.}$$

$$p_7 = 8 \text{ kPa.}$$

$$w_p \text{ isen} = 8.05977 \text{ kJ/kg.}$$

$$w_{pump} = \frac{10,89 \text{ Wissen}}{\text{Nissen}} g, gg$$

$$h_D = h_7 + w_p \\ = 173,8 + 9,99 \\ = 183,79$$

$$h_5 = 3139,4 \text{ kJ/kg}$$

$$h_5 = 63658$$

$$\underline{h_{6S}}$$

$$6,3658 = 0,5924g(1-x) + 8,2273x \\ x = 0,756$$

$$h_{6S} = 0,756 \times 2576,2 + (1-0,756) \\ \times 173,84$$

$$h_{6S} = 1989,99 \text{ kJ/kg}$$

$$h_{6S} = 2162,14$$

$$n_{SPP} = \frac{(h_5 - h_6) - (h_p)}{(h_5 - h_8)}$$

$$= 0,308$$

$$n_{Combined} = n_{GTT} + n_{SPP} - n_{GTT} n_{SPP}$$

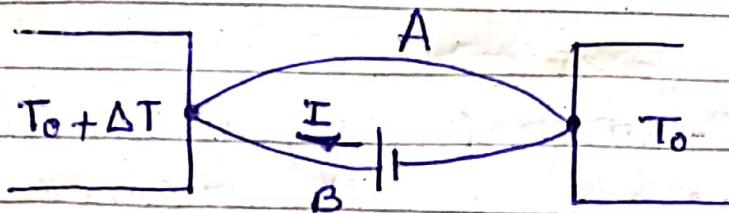
$$= 0,5675 \quad (\text{not exact as} \\ \text{some is heat loss})$$

~~n_{Combined}~~

Combined cycle power generation -

- ↳ Topping cycle $\xrightarrow{\text{GT Cycle, Temp. limitation}} \text{Thermal, MHD, Thermoelectric, Fuel cell}$
- ↳ Bottoming cycle

Thermoelectric power generation -



For specific combination of A & B, emf will be generated \rightarrow feedback effect.

$$\alpha_{A,B} = \lim_{\Delta T \rightarrow 0} \frac{\Delta V}{\Delta T}$$

see-back co-efficient

$$\text{Current} = I$$

$$\text{Resistance} = R_J$$

$$\text{amount of heat generated} = I^2 R_J$$

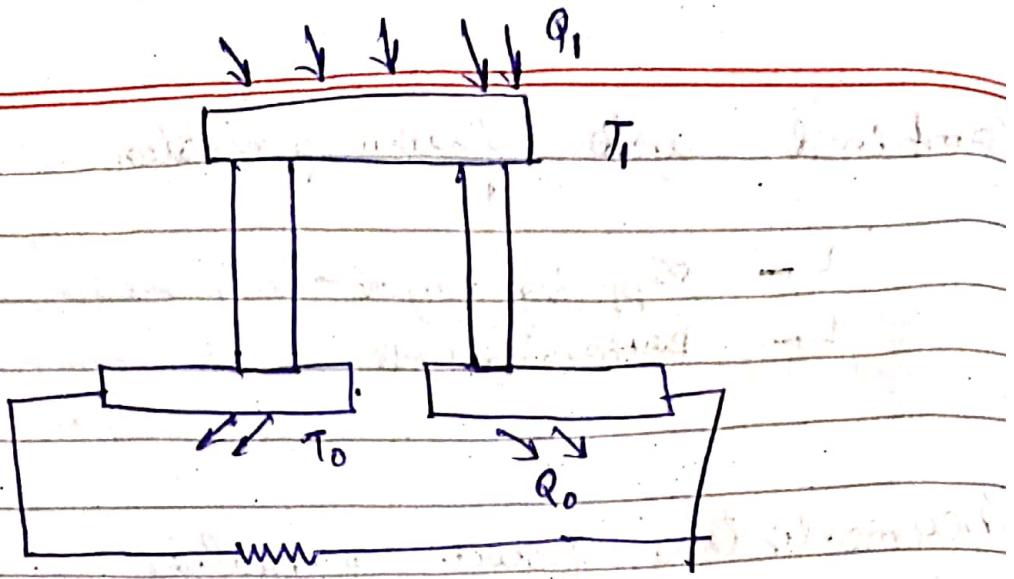
which is to be either absorbed or removed.

(This is called peltier effect)

$$Q_{AB} = \pi_{AB} I$$

$\pi_{AB} \rightarrow$ peltier co-efficient

$$\alpha_{A,B,T} = \pi_{A,B}$$



① Chemical energy - Thermal energy - Mechanical energy
- Electrical energy.

② Thermal energy - mechanical energy
- Electrical energy

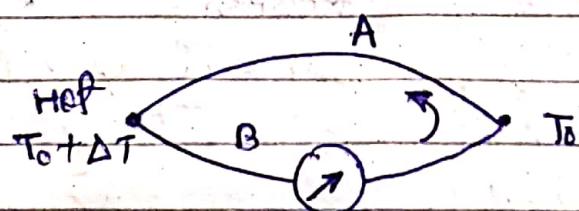
③ Thermal energy - Electrical energy

④ Chemical energy - electrical energy

⑤ Mechanical energy - electrical energy.

THERMOELECTRIC power generation -

- Seebeck effect -



$$\mathcal{E} = \sigma (-\nabla V + E_{emf})$$

↓
electrical conductivity

- Seebeck generator.

• Peltier effect - opposite of Seebeck effect.

• Peltier cooler

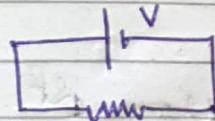
Thomson effect -

$$q = K T A J$$

(per unit volume)

$K \rightarrow$ Thomson Co-efficient
 $J \rightarrow$ current density.

Ohmic or Joule heating



$I^2 R$ loss

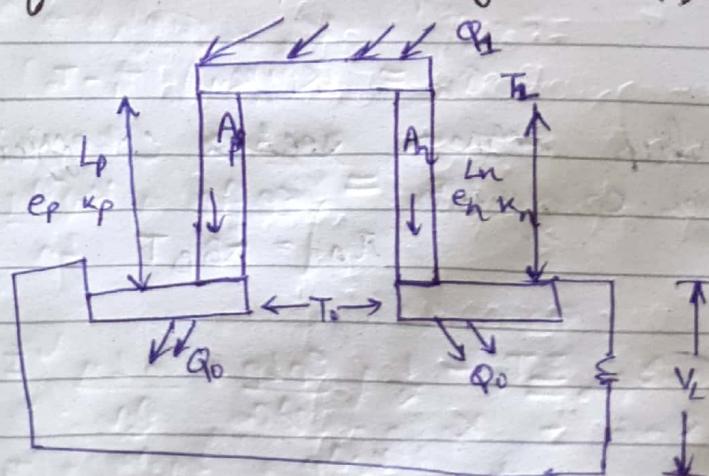
Thermo-electric effect

$$q = K J \cdot \Delta T$$

• Reversible process

• Reversible process

Analysis of a thermo-electric generator / Seebeck genera-



- Low thermal κ & high electrical conductivity.

↓
in order
to maintain
junction temp.
(otherwise conduction
may decrease temp.)

for better lower
resistance &
current

$$\text{Seebeck effect} \rightarrow \text{exp}(T_f - T_i) \propto \alpha_{se} (T_f - T_i)$$

*see - back
coefficient*

$$\alpha_{AB} = \lim_{\Delta T \rightarrow 0} \frac{\Delta V}{\Delta T}$$

$$\text{Peltier coefficient, } \dot{Q} = (\pi_A - \pi_B) I.$$

Analysis of the hot junction from 1st law
thermodynamics :-

$$\dot{Q}_1 + \frac{1}{2} \dot{Q}_j = \dot{Q}_p + \dot{Q}_k$$

\downarrow
 Peltier
effect

\downarrow
 Thompson
effect

$$\dot{Q}_p = \pi_{pn} I = \alpha_{pn} I T_1$$

Relationship between Seebeck co-efficient &
Peltier co-efficient

$$\pi_{AB} = \alpha_{AB} T$$

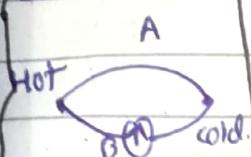
$$q = (R_p + R_n) I^2$$

$$= \left[\frac{\beta_p L_p}{A_p} + \frac{\beta_n L_n}{A_n} \right] I^2$$

revision

Thermo-electric effect

Seebeck effect



A, B are dissimilar metals.
junctions @ diff. temp.
emf generated

Peltier effect

reverse of
Seebeck effect

A
Hot
B
Cold
current is passed and we get temp. diff. on the hot & cold junction

Thomson effect

Hot Cold
I → then this metal would either heat or cool as heat or cold.

e.g. Cu
Hot Cold
Fe
Hot Cold
Its cold

- Heat would be exchanged only at junctions

Touche effect

$$q = I^2 R$$

Fourier effect

$$q = -k A \frac{dT}{dx}$$

$$\bullet q \propto I \quad q \propto I \quad \bullet q \propto I^2$$

Seebeck effect -

$$E_{\text{emf}} = \cancel{\alpha} - \alpha \Delta T$$

$$\alpha_{AB} = \lim_{\Delta T \rightarrow 0} \frac{-\Delta V}{\Delta T} \approx \frac{\Delta V}{\Delta T}$$

Seebeck
co-efficient

$$\text{Peltier effect, } \dot{Q} = \pi_{AB} I$$

π peltier co-efficient

$$\text{Thomson effect, } \dot{q} = -K J \cdot \Delta T$$

steep
Heat
gen/vol.

Thomson
Co-efficient
current
density

$$17 \quad K = \frac{d\pi}{dT} = -\alpha$$

$$\pi = T \alpha$$

Recalling,

$$\dot{Q}_i + \frac{1}{2} \dot{Q}_j = \dot{Q}_p + \dot{Q}_n$$

$$\dot{Q}_p = \pi_{pn} I = \alpha_{pn} I T_1$$

$$\dot{Q}_j = (R_p + R_n) I^2$$

$$= \left(\frac{e_p L_p}{A_p} + \frac{e_n L_n}{A_n} \right) I^2$$

$$\dot{Q}_n = (K_p + K_n) (T_1 - T_0)$$

$$\dot{Q}_n = \left(\frac{k_p A_p}{L_p} + \frac{k_n A_n}{L_n} \right) (T_1 - T_0)$$

$$\Rightarrow \dot{Q}_i = \alpha_{pn} I T_1 - \frac{1}{2} \left(\frac{e_p L_p}{A_p} + \frac{e_n L_n}{A_n} \right) I^2$$

$$+ \left(\frac{k_p A_p}{L_p} + \frac{k_n A_n}{L_n} \right) (T_1 - T_0)$$

$$W_L = I^2 R_L$$

$$V_L = \alpha_{pn} (T_1 - T_0) - I (R_p + R_n)$$

$$\text{also } V_L = IR_L$$

From Kirchhoff's law,

$$I = \frac{\alpha_{pn} (T_1 - T_0)}{R_L + (R_p + R_n)}$$

Let us define,

$$m = \frac{R_L}{R_n + R_p}$$

$$\Rightarrow I = \frac{\alpha_{pn} (T_1 - T_0)}{(R_p + R_n)(1+m)}$$

∴ Useful power = $I^2 R_L$

$$= \frac{\alpha_{pn}^2 (T_1 - T_0)^2}{(R_p + R_n)^2 (1+m)^2} \times (R_p + R_n)m$$

$$= \frac{m}{(1+m)^2} \frac{\alpha_{pn}^2}{(R_p + R_n)} \frac{(T_1 - T_0)^2}{(1+m)^2}$$

$$\dot{Q}_1 = \alpha_{pn} \frac{T_1 (T_1 - T_0)}{(R_p + R_n)(1+m)} - \frac{1}{2} \frac{\alpha_{pn}^2 (T_1 - T_0)^2}{(1+m)^2 (R_p + R_n)} + (K_p + K_n) (T_1 - T_0)$$

$$\eta = \frac{W_L}{Q_1} = \frac{T_1 - T_0}{T_1} \times$$

$$\eta = \frac{W_L}{Q_1} = \frac{(T_1 - T_0)}{T_1} \times \frac{m}{(1-m) \cdot \frac{T_1 - T_0}{T_1} - \frac{1}{2} \frac{(T_1 - T_0)}{T_1} + (K_p + K_n) (R_n + R_p) (1+m)^2} \alpha_{pn}^2 \cdot T_1$$

W Please check & reconfirm expression

Let's define,

$$Z = \frac{\alpha_m^2}{(K_p + K_n)(R_p + R_n)} \rightarrow \text{figure of merit}$$

$$K_p + K_n = K$$

$$R_p + R_n = R$$

$$Z = \frac{\alpha_m^2}{R \cdot K}$$

'Z' figure of merit most important parameter based on material properties.

Z increases $\rightarrow \eta$ increases.

$$RK = \left[\frac{e_p r_p}{A_p} + \frac{e_n r_n}{A_n} \right] \left[\frac{k_p A_p}{L_p} + \frac{k_n A_n}{L_n} \right]$$

$$\frac{A_p}{L_p} = r_p \quad \frac{A_n}{L_n} = r_n$$

$$RK = \left[\frac{e_p}{r_p} + \frac{e_n}{r_n} \right] [k_p r_p + k_n r_n]$$

$$\frac{d(RK)}{d(r_n/r_p)} = 0$$

$$k_n e_p - k_p e_n \left(\frac{r_n}{r_p} \right)^2 = 0$$

$$\frac{r_n}{r_p} = \sqrt{\frac{k_p e_n}{k_n e_p}}$$

on substitution;

~~RK_{min}~~

$$RK_{\min} = k_p e_p + k_n e_n \left(\frac{k_p e_p}{k_n e_n} \right)^{1/2} + k_n e_p \left(\frac{k_p e_p}{k_n e_n} \right) + k_n e_n$$

$$= (\sqrt{e_{pkp}} + \sqrt{k_{en}})^2$$

$$Z_{max.} = \frac{\alpha_{pn}}{(Rk)_{min}} \frac{X_{p,n}}{(\sqrt{e_{pkp}} + \sqrt{k_{en}})^2}$$

$$Z_{max.} = \left(\frac{\alpha_{pn}}{\sqrt{e_{pkp}} + \sqrt{k_{en}}} \right)^2$$

So, with $Z_{max.}$,

$$\eta = \frac{T_1 - T_0}{T_1} \cdot \frac{m}{\left(1-m\right) - \frac{1}{2} \frac{(T_1 - T_0)}{T_1} + \frac{(1+m)^2}{Z \cdot T_1}}$$

$$\frac{dn}{dm} = 0$$

$$m_{op} = \left\{ 1 + Z \frac{T_1 + T_0}{2} \right\}^{1/2} = m_0$$

$$m_0 + 1 = \frac{Z}{m_0 - 1} \times \frac{T_1 + T_0}{2}$$

$$\boxed{\eta = \frac{(T_1 - T_0)}{T_1} \times \frac{m_0 - 1}{m_0 + \frac{T_0}{T_1}}}$$

$$W_L = \frac{m}{(1-m^2)} = \frac{\alpha_{pn}^2 (T_1 - T_0)^2}{R_p + R_n}$$

$$\frac{dW_L}{dm} = 0 \quad \text{for max } m \text{ power.}$$

$$m \rightarrow 1$$

$$\overset{\circ}{W}_L = \frac{1}{4} \times \frac{\alpha_{pn}^2 (T_1 - T_0)^2}{(R_p + R_n)}$$

$$y_{de} \text{ max power} = \frac{T_1 - T_0}{T_1} + \underbrace{2 - \frac{1}{2} \left(\frac{T_1 - T_0}{T_1} \right)}_{\uparrow} + \frac{4}{ZT_1}$$