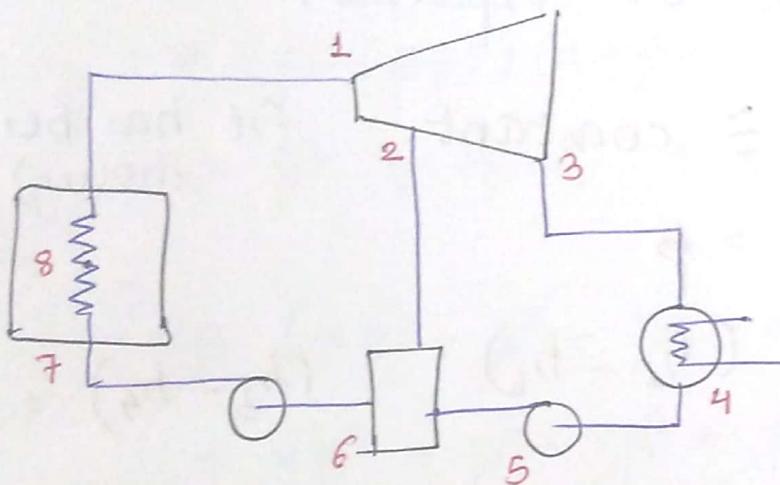
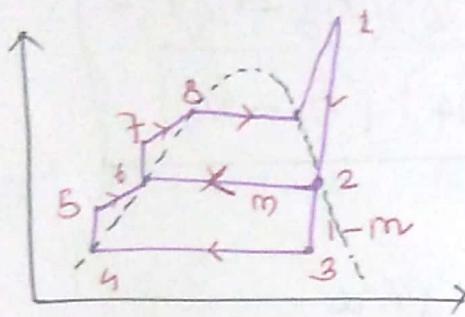


Optimum placement of feed heaters:-



Pump works are negligible

$$h_5 \approx h_4$$

$$h_7 \approx h_6$$

7-8 → Economiser pump
8-1 → Evaporator + superheater

5-6 → water is heated in the open FWH.
7-8 → water is heated in an economiser.
8-1 → Boiler (Evaporator, superheater)

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

$$m(h_2 - h_6) = (1-m)(h_6 - h_4)$$

$$m = \frac{h_6 - h_4}{h_2 - h_4}$$

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

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

1 - 2 - 3 → Expansion line

any point on expansion line

$$(h - h_f) \approx \text{constant} \quad (\text{it has been shown})$$

$$= \beta$$

$$(h_1 - h_8) = (h_2 - h_6) = (h_3 - h_4) = \beta$$

Heat transferred to the working fluid
in the feed water heater

$$= h_6 - h_4 = \beta + \gamma$$

$$h_2 - h_4 = (h_2 - h_6) + (h_6 - h_4) = \beta + \gamma$$

and total amount of heat transferred to the
working fluid to bring it to the
saturated condition at boiler pressure.

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

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

$$= \beta + \alpha - \gamma$$

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

for efficiency to be maximum

$$\frac{d\eta}{d\beta} = 0$$

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

$$\Rightarrow -2\beta(\alpha\beta + \beta^2 - r\beta + \alpha r + \beta r - r^2) + \alpha\beta^2 + \beta^3 - r\beta^2 + \beta^3 + \beta^3r = 0$$

$$\Rightarrow -2\alpha\beta^2 - 2\alpha\beta r + 2\beta r^2 + \alpha\beta^2 = 0$$

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

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

But β was constant 

$$r = h_6 - h_4 \rightarrow \text{heat given by the feedwater (variable)}$$

$\alpha = (h_8 - h_4) \rightarrow \text{heat needed to bring water to saturation point (variable)}$

$$\frac{dn}{dr} = 0 \text{ for max. efficiency}$$

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

$$\alpha + \beta - r - \beta - r = 0$$

$$\Rightarrow r = \alpha/2$$

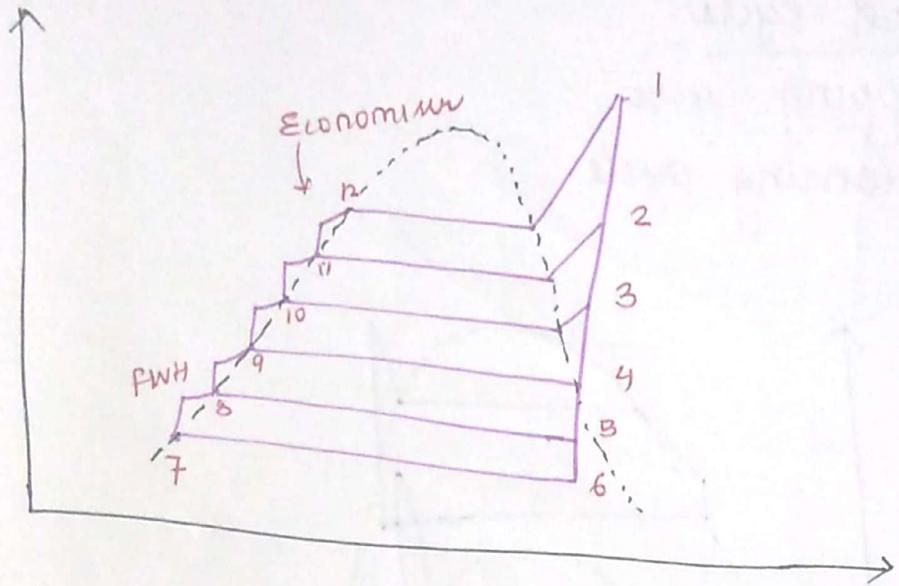
$$\boxed{r = \alpha/2}$$

without feedwater heater

$$\begin{aligned} n = n_0 &= 1 - \frac{h_3 - h_4}{h_1 - h_4} \\ &= 1 - \frac{\beta}{\alpha + \beta} = \frac{\alpha}{\alpha + \beta} \end{aligned}$$

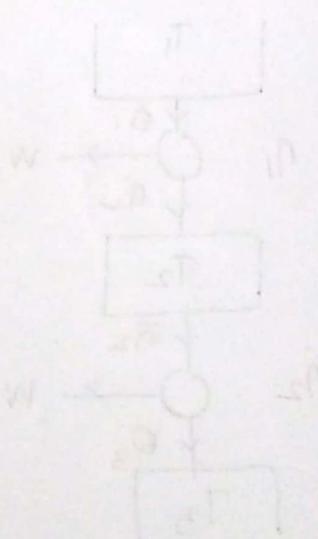
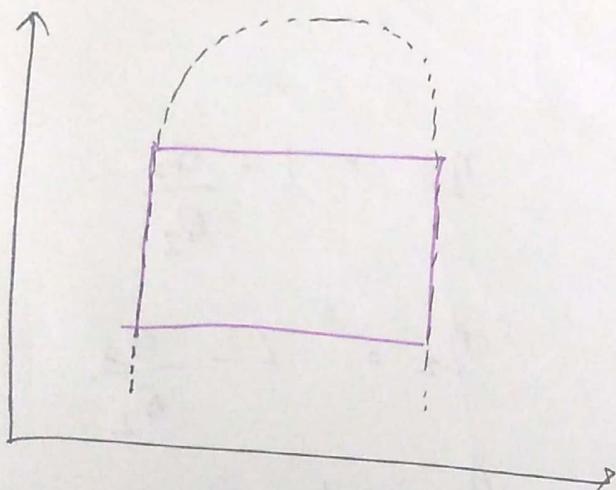
increase in efficiency

$$\Delta n = n - n_0 = \frac{\alpha^2 \beta}{(\alpha + \beta)(\alpha + 2\beta)^2}$$

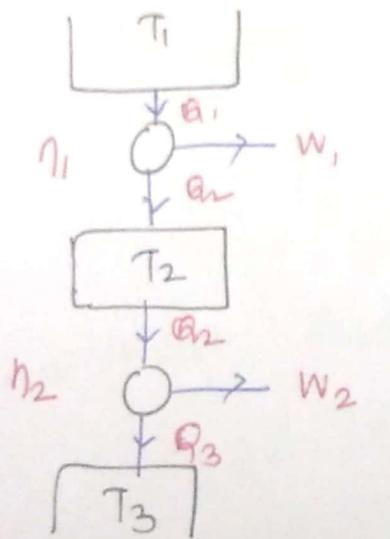
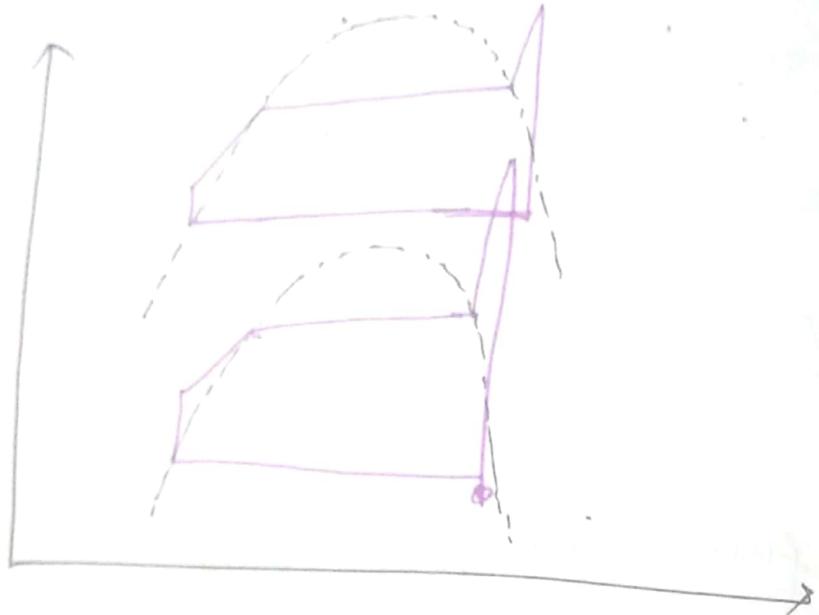


$$(h_2 - h_{11}) m_r = (1-m) (h_{11} - h_{10})$$

Ideal fluid for power plant



Combined cycle
 Mopping cycle
 Bottoming cycle



$$\eta_1 = 1 - \frac{Q_2}{Q_1}$$

$$\eta_2 = 1 - \frac{Q_3}{Q_2}$$

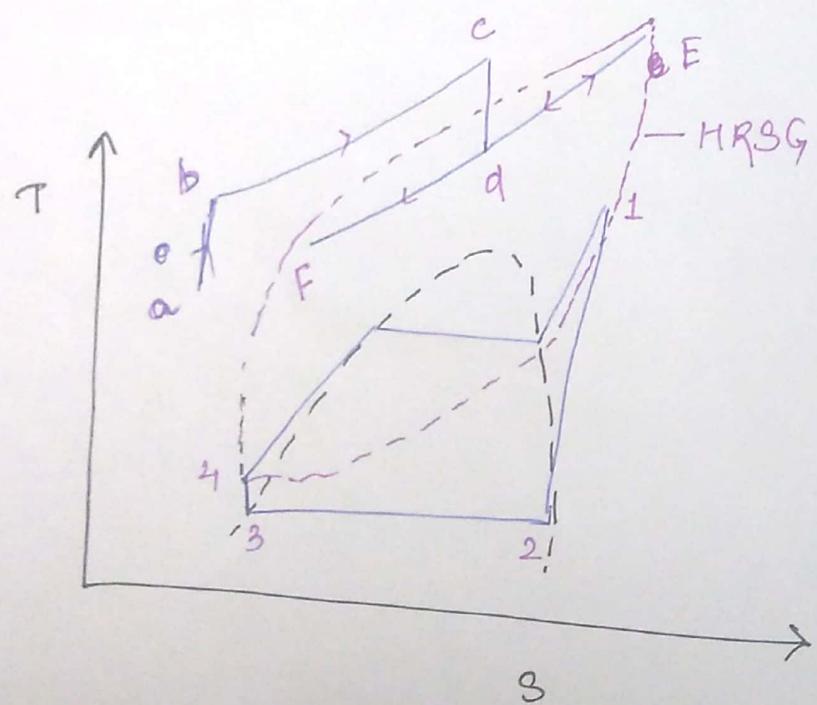
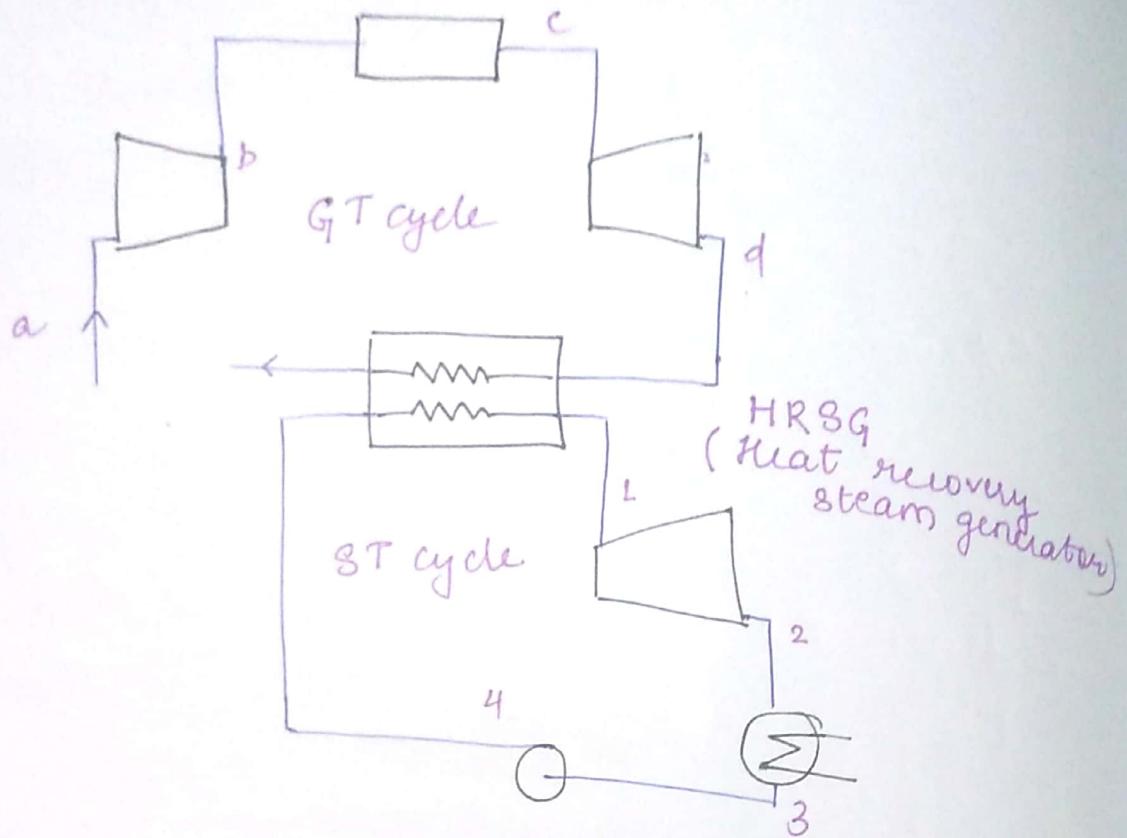
$$\eta = 1 - \frac{Q_3}{Q_1}$$

$$\eta = \eta_1 + \eta_2 - \eta_1 \eta_2$$

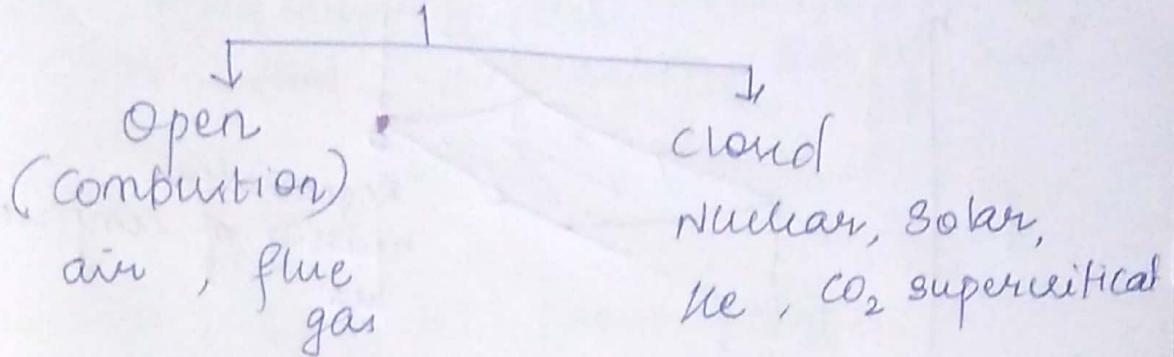
$$(1-\eta) = (1-\eta_1)(1-\eta_2)$$

$$(1-\eta) = \prod (1-\eta_i) \text{ for multiple cycles.}$$

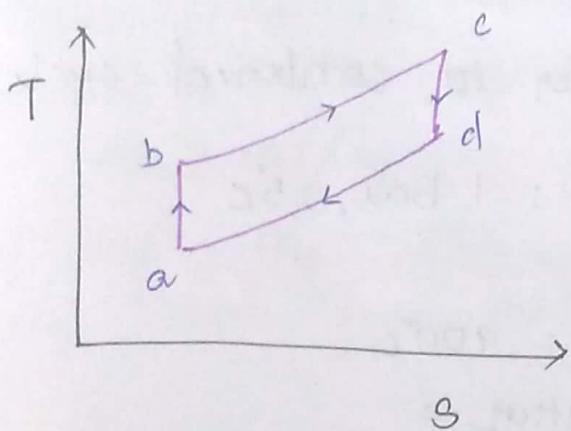
The efficiency of the combined cycle is more than individual cycles.



GT cycle



GT cycle



$$r_p = \frac{r_b}{r_a}$$

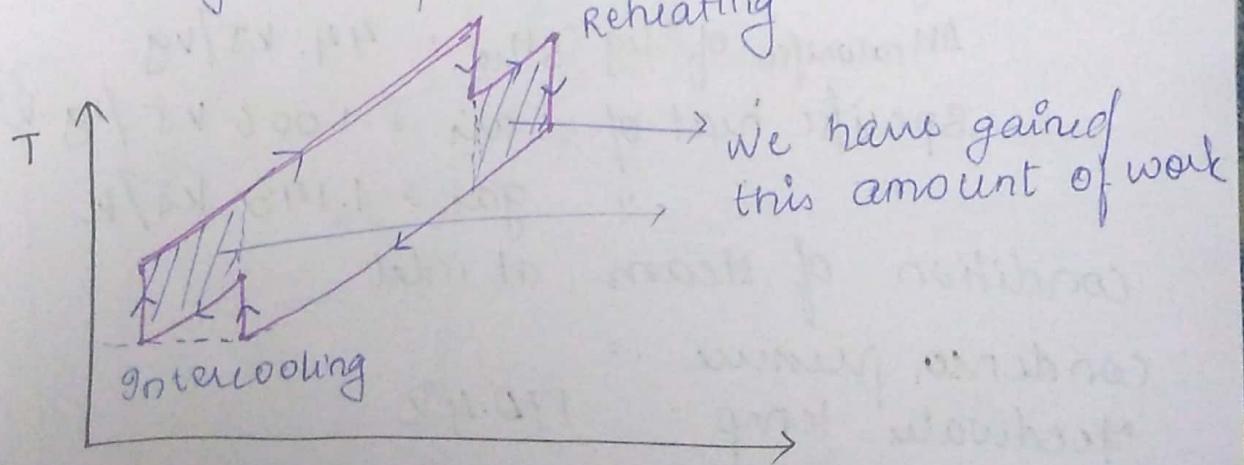
$$\gamma = 1 - \frac{1}{r_p^{r-1} r}$$

methods of increasing η of GT cycle:

(i) multistage compression

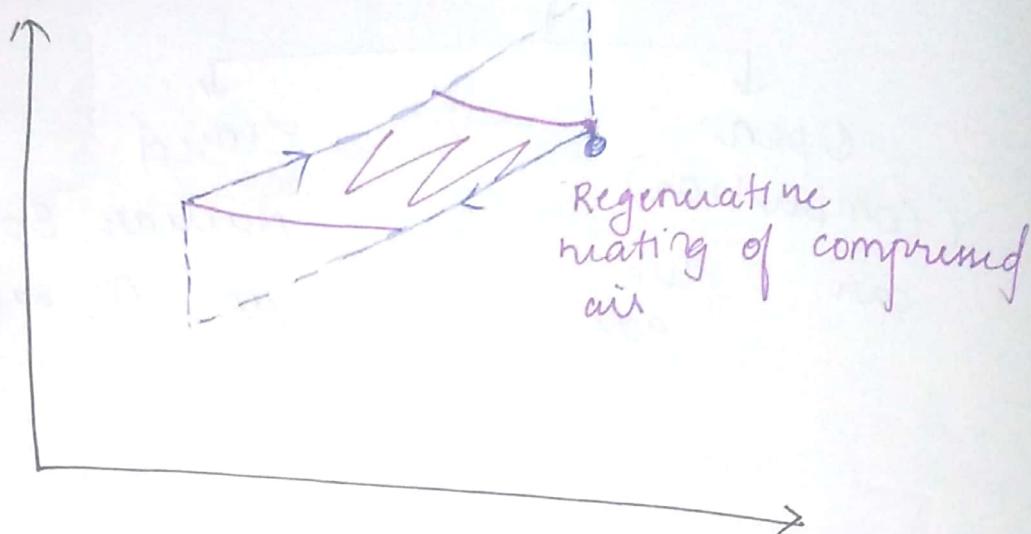
with intercooling

Reheating



(ii) multistage expansion with reheating

(iii) Regenerative heating of compressed air



Regenerative heating is not used in combined cycle

Q. Following data refer to combined cycle power plant

Air to compressor : 1 bar, 25°C

$$\lambda_p = 8$$

T_{max} at inlet = 900°C

ΔP at combustion =

$\eta_{compressor} = 0.88$

$\eta_{gas\ turbine} = 0.88$

$\Delta H_{calorific\ of\ big\ C_8H_{18}} = 44\text{ kJ/kg}$

Specific heat of air = 1.006 kJ/kg-k

" " " gas = 1.148 kJ/k

condition of steam at inlet

condenser pressure =

feedwater temp = 170.4°C

$\eta_{turbine} = 0.82$

ΔP in HRSG = 5 kPa

steam flow rate = 29.8 kg/s

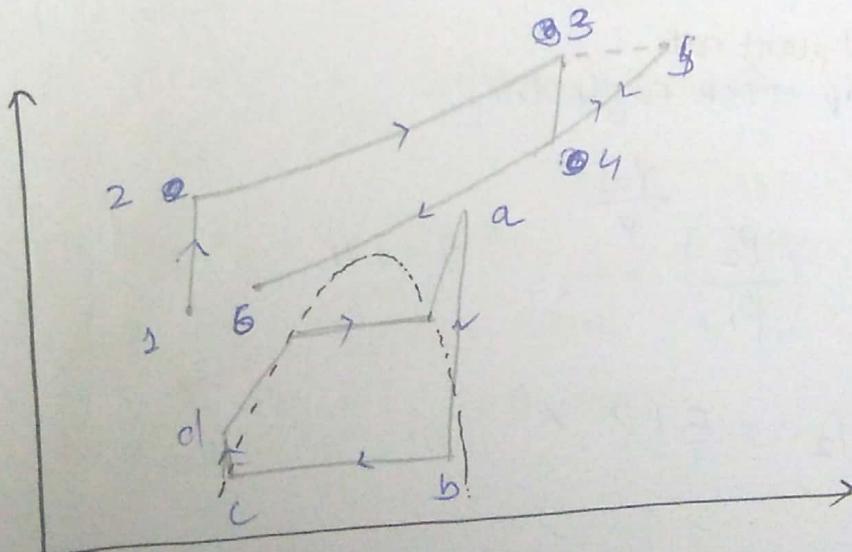
Determine total power output and overall efficiency of the combined cycle plant and give an estimation of heat loss.

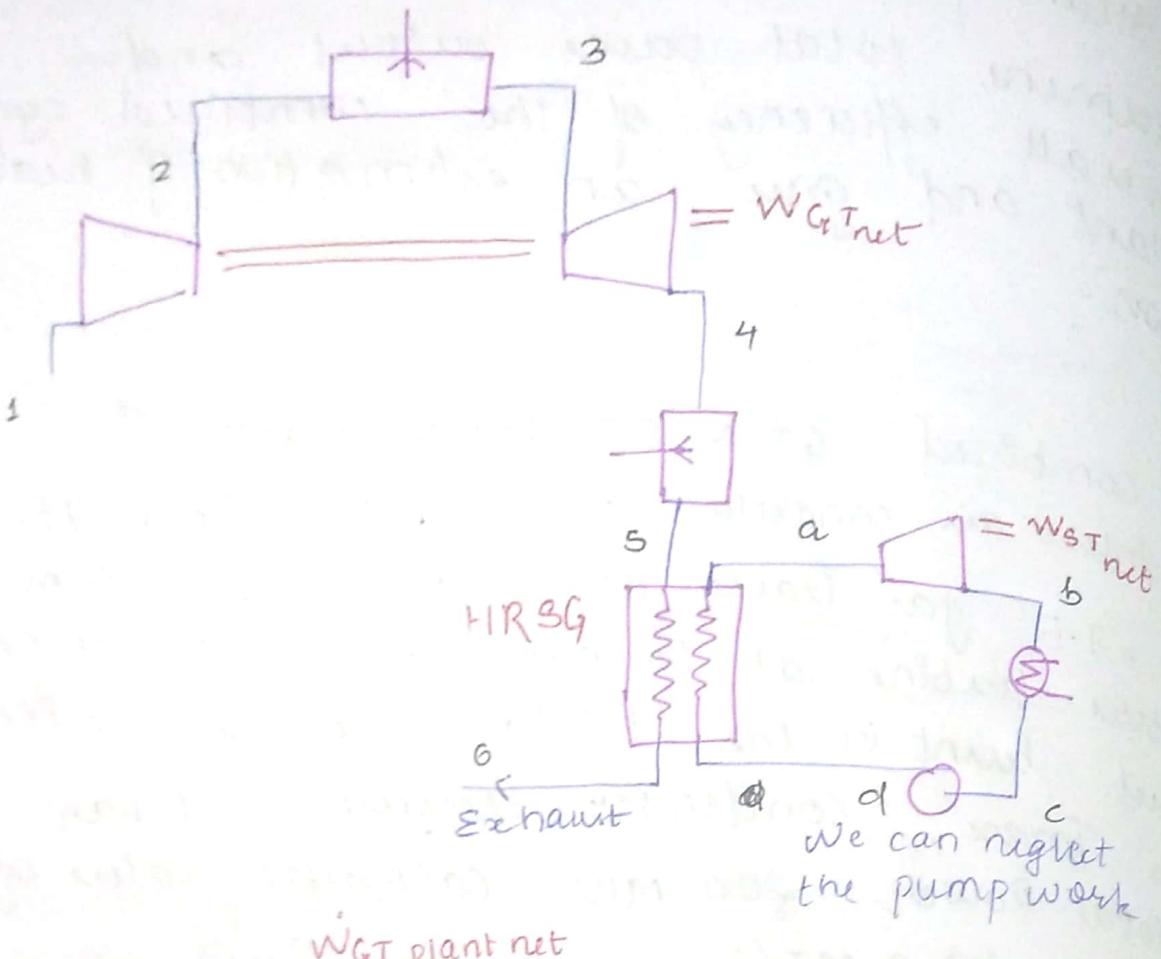
combined GT & ST Power plant.

Q. Inlet air condition 15°C , 1 atm, $T_{max} 750^\circ\text{C}$
 $\dot{m}_a = 7.5$ kg leaves HRSG @ 100°C . steam enters turbine at 50 bar 600°C . 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_s , m_a , n_{th} , individual power, air-fuel ratio

$$\begin{array}{ll} \text{gas} & c_p = 1.11 \quad \gamma = 1.33 \\ \text{air} & c_p = 1.005 \quad \gamma = 1.4 \end{array}$$





$$\begin{aligned}
 & \underbrace{m_g C_{pg} (T_3 - T_4)}_{w_{GT}} - \underbrace{m_a C_{pa} (T_2 - T_1)}_{w_{comp}} \\
 & + \underbrace{m_g (h_a - h_b)}_{w_{ST \text{ plant net}}} = \text{Power} = 200 \times 10^3
 \end{aligned}$$

$w_{ST \text{ plant net}}$
(pump work neglected)

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} \quad \gamma = 1.4$$

$$\Rightarrow T_2 = 512 \text{ K}$$

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4} \right)^{\gamma_{\text{gas}}} \quad \gamma_g = 1.33$$

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

h_a at 50 bar & 600°C from Table

$$\rightarrow 3666.5 \text{ kJ/kg}$$

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

$$s_a = s_b$$

$$h_b = 2305 \text{ kJ/kg}$$

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

• Energy balance for HRSG

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

$$\dot{m}_g C_p g (T_5 - T_6) = \dot{m}_s (h_a - h_c)$$

$$\dot{m}_a = 39$$

$$\dot{m}_s = 81.9 \text{ kg/s}$$

$$W_{GT, \text{net}} = 88.22 \text{ MW}$$

$$W_{ST, \text{net}} = 111.78 \text{ MW}$$

$$\eta_{th} = \frac{200 \times 10^3}{m_a C_p g (T_3 - T_b) + m_a C_p g (T_5 - T_4)}$$

$$= 50\%$$

④ $43.3 \times \dot{m}_f = 400$

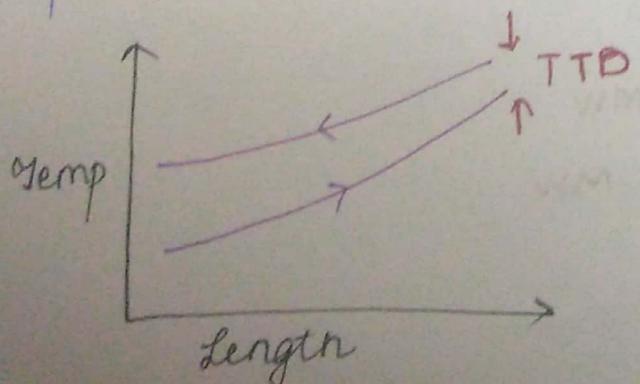
$$\dot{m}_f = 9.24 \text{ kg/s}$$

Advantages & specialities of combined ST & GT plant

- (i) Individual Plants are simple.
- (ii) High η & W_{net}
- (iii) GT plant & ST plant are complementary

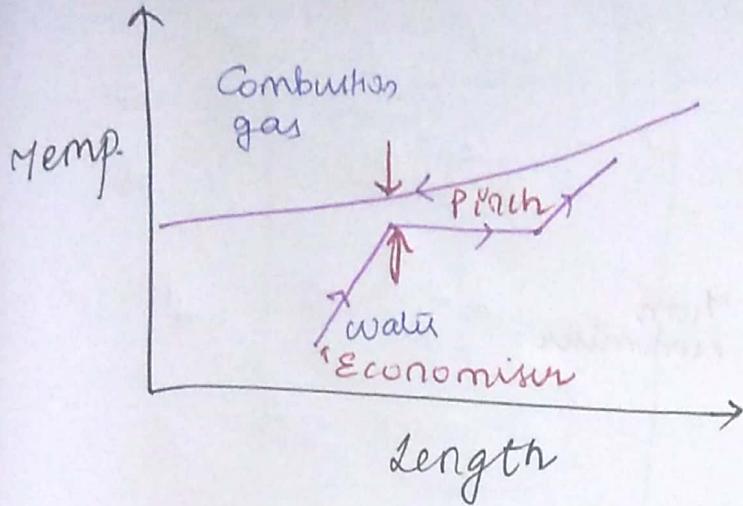
features ↓	↓
Installation takes less time	Installation takes more time,
More expensive	Less expensive.

HR SG
HEX where phase change of water takes place.

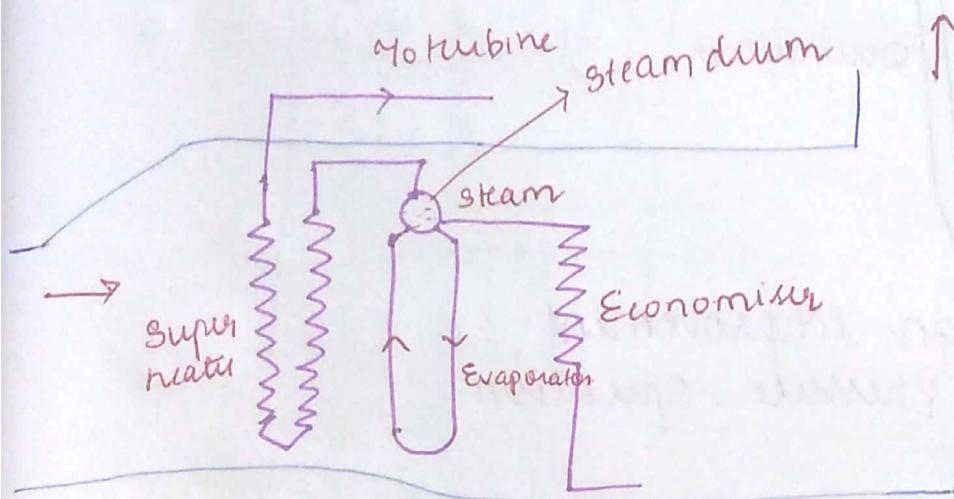


Terminal Temperature Difference (TTD)

We can go beyond it but it would ~~unnecessarily~~ unnecessarily increase ~~temp~~ length and cost

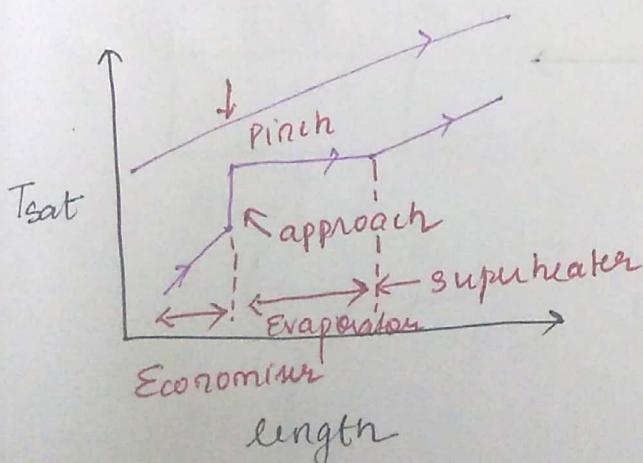


Pinch is the minimum temp. difference along ~~the~~ the heat exchange.

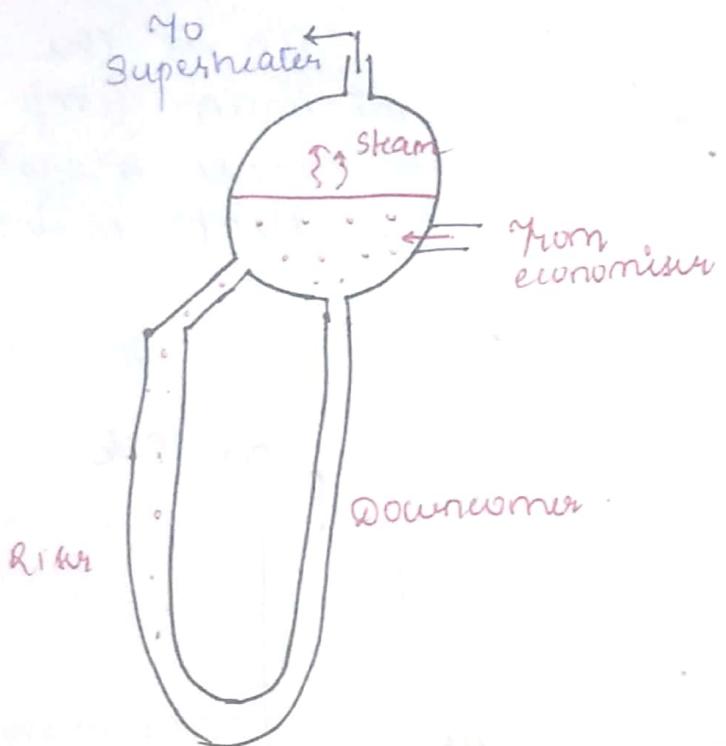


from gas turbine exhaust.

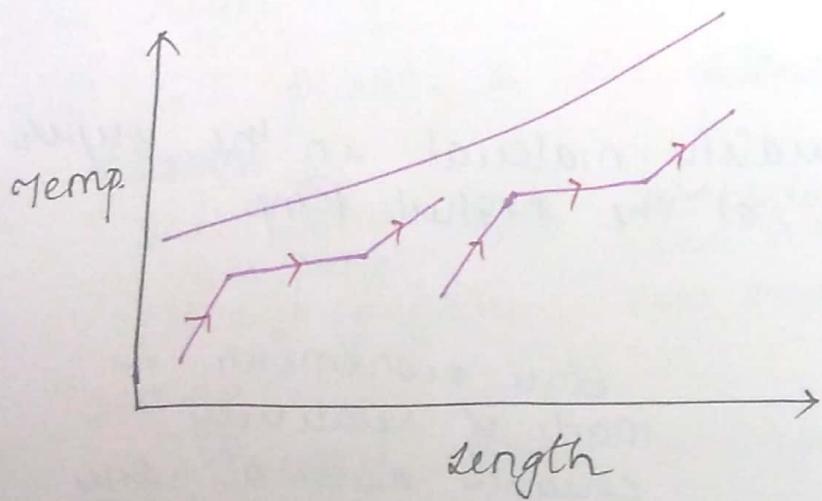
we need the best quality material in the super heater since it is at the highest temp.

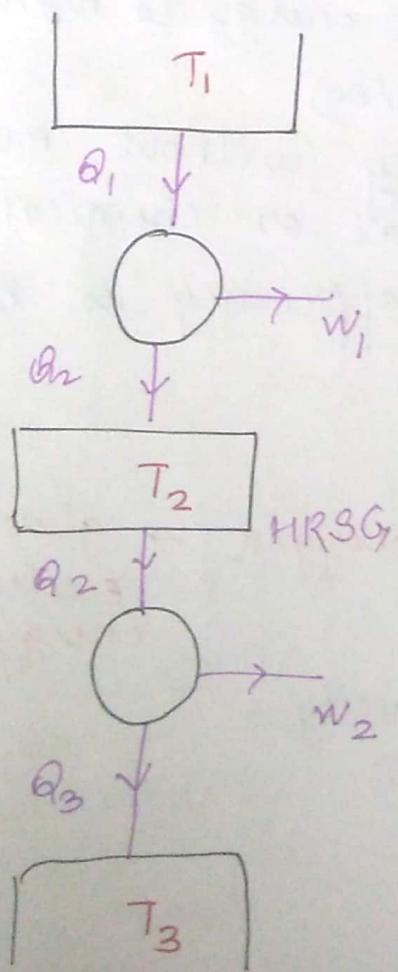
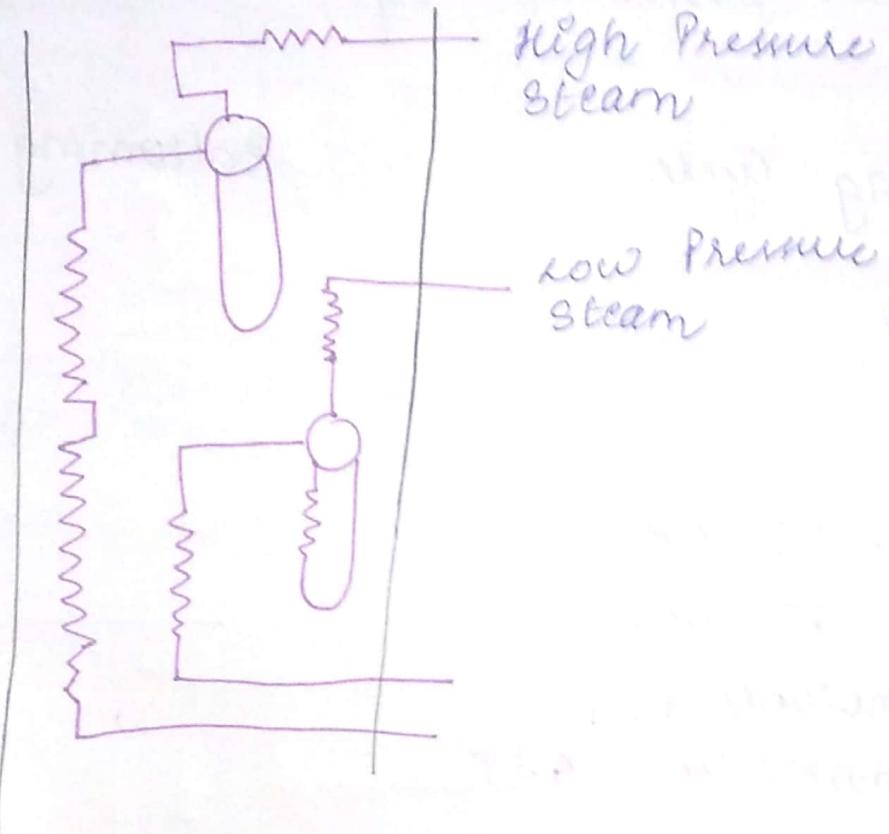


give economy. Is made of relatively cheaper material any vapours contact must be avoided



HRSG design improvement
- Dual Pressure operation





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

consider in HRSG some additional fuel is burnt (Q_a) and there is some heat loss (Q_c)

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

$$\beta = \frac{Q_a}{Q_2}$$

$$\text{find out } \eta = f(\eta_1, \eta_2, \alpha, \beta)$$

other possibilities of combined cycle:-

Mopping cycle

MHD

Bottoming cycle.

MHD - ST cycle

MHD - GT cycle

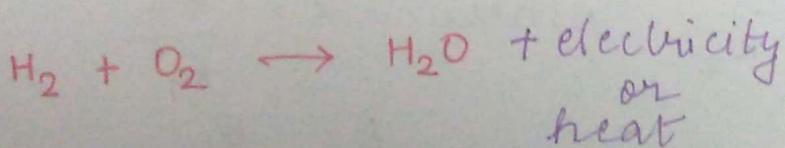
Thermionic + ST

Thermo electric + ST

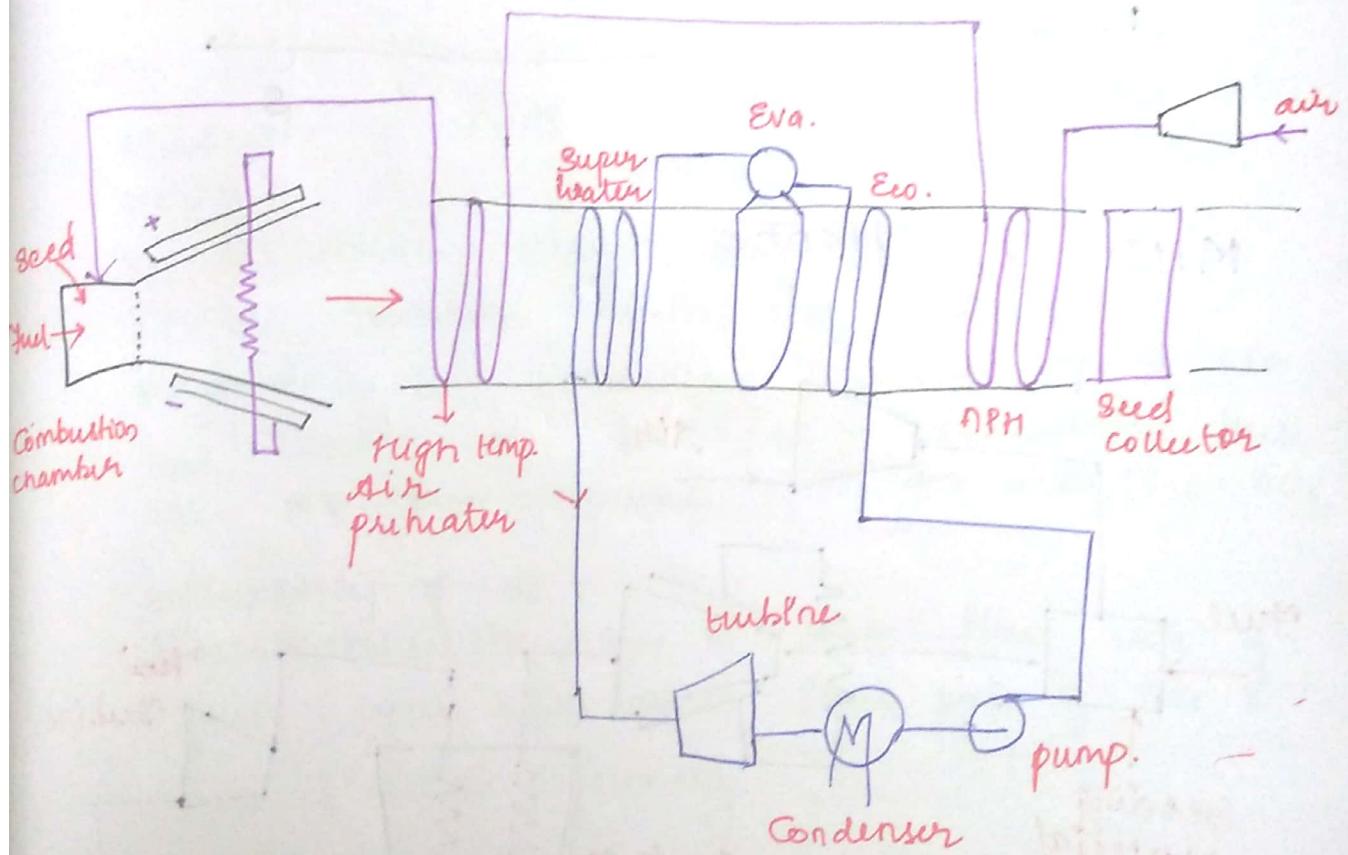
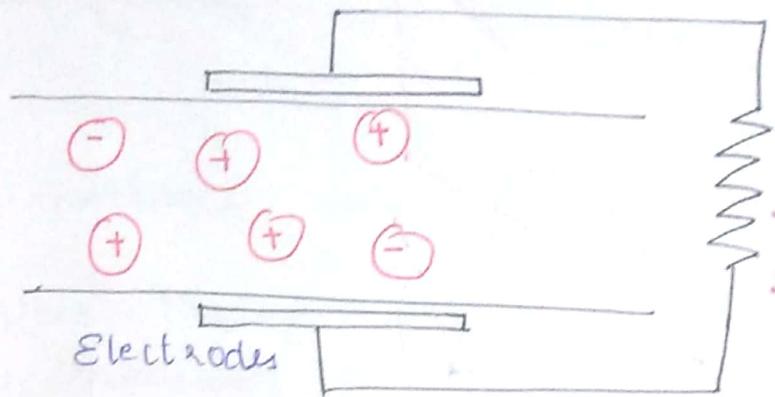
- Direct Energy conversion
cannot principle is not applicable here.
(Directly higher form of energy to higher
form of energy conversion)
- electrical energy directly (without moving
component) from thermal or chemical
energy \rightarrow conversion efficiency is high.

Fuel cell

continuous supply of fuel + oxygen \rightarrow gives
electrical energy (DC)



MHD → Magneto hydrodynamics



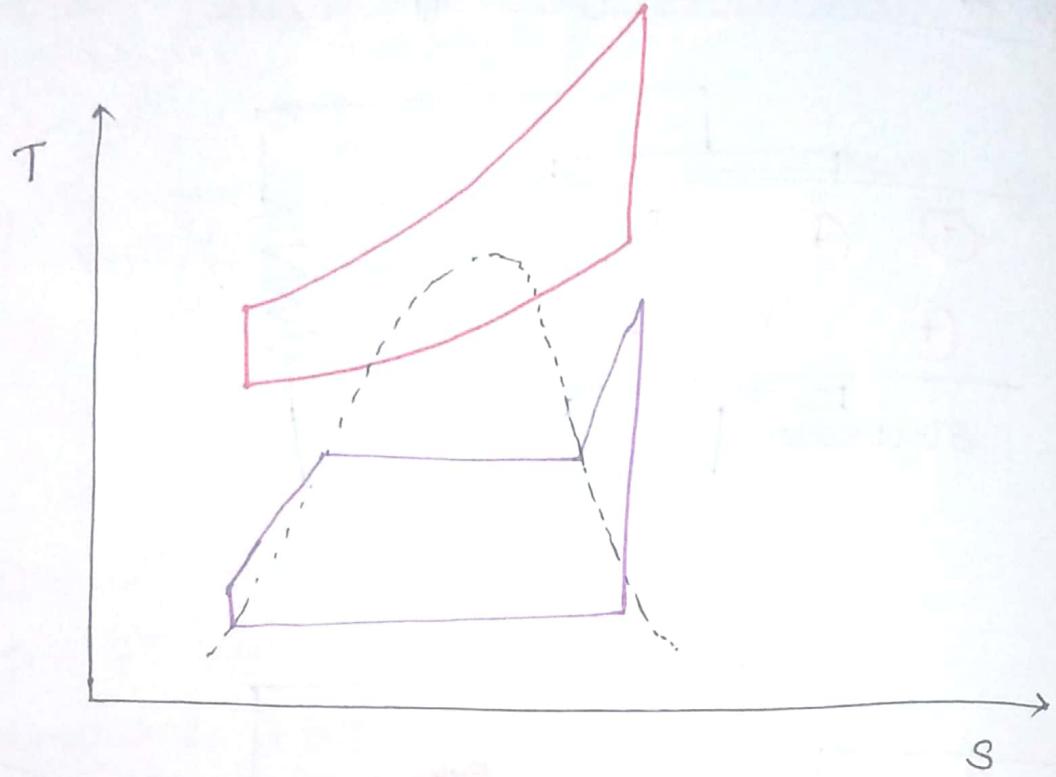
Air temperature after combustion

2200°C - 2700°C

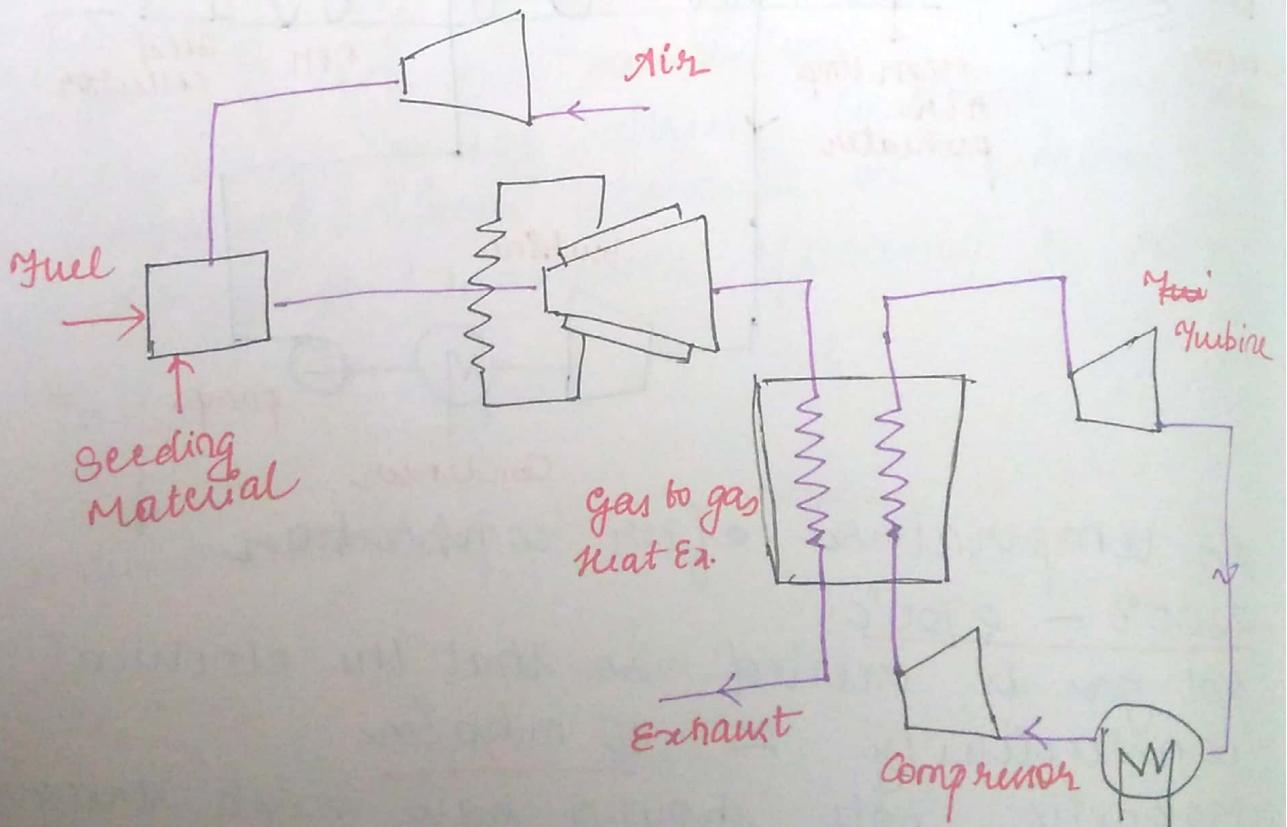
hot gas is needed so that the electrical conductivity $\approx \frac{10}{mho/m}$

Magnetic pole should have high strength

4 - 5 Tesla



MHD - GT plant



Q 8

Thermionic Device

A combined cycle

(a) air enters through compressor at 100 kPa, 300K.
The compression $\gamma = 1.2$ and $(\eta_{i,10})_{\text{comp}} = 85\%$.

$\eta_{\text{turb}} = \cancel{85\%} 90\%$, inlet condn = 1200 kPa, 1400K

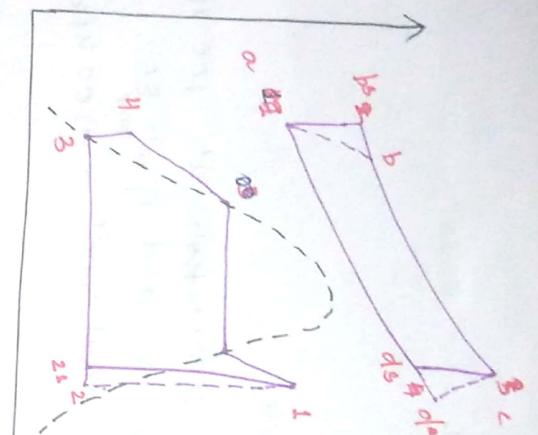
$P_{\text{exit}} = 100 \text{ kPa}$

air from the turbine exhaust passes
through a heat exchanger and exits at
400K.

In ST cycle, steam at 8 MPa, 400°C
enters turbine with $\eta_{i,80} = 0.85$ &
expands to condenser pressure of 8 kPa.
sat. water at 8 kPa is circulated back
to HX by a pump with an ~~is~~ $\eta_{i,10} = 80\%$.

Efficiency of 80%.

Determine (i) the ratio of mass flow rate of
two cycle (ii) mass flow rate of air &
(iii) thermal efficiency



Ans 9

a. $p_a = 100 \text{ kPa}$, $T_a = 300 \text{ K}$

b. $p_b = 1200 \text{ kPa}$

$$T_{bs} = \left(\frac{p_b}{p_a}\right)^{\frac{y-1}{y}} \cdot T_a$$

$$= 12^{\frac{0.43}{1.43}} \times 300$$

$$= 670.2 \text{ K} \approx 673 \text{ K} = 610.2 \text{ K}$$

~~Eq 2.9~~

$$\frac{T_{bs} - T_a}{T_b - T_a} = 0.85$$

$$T_{bs} = \frac{(310.2)}{0.85} + 300$$

$$= 664.94 \text{ K}$$

$$c. \quad P_b = 1200 \text{ kPa}, \quad T_{b,c} = 1400 \text{ K}$$

$$d. \quad P_d = 100 \text{ kPa}$$

$$\begin{aligned} T_{d,ls} &= \left(\frac{P_{bd}}{P_{cd,b}} \right)^{\frac{r-1}{r}} \cdot 1400 \text{ K} \\ &= \frac{112}{12}^{0.4/0.4} \times 1400 \\ &\rightarrow 688.32 \text{ K} \end{aligned}$$

$$T_a \quad T_d$$

$$\frac{T_c - T_d}{T_c - T_{d,ls}} = 0.9$$

$$(T_c - T_d) = (0.9) \times 711.68$$

$$T_d = 759.488 \text{ K}$$

heat supplied to the GT cycle (Mo the combined cycle)

$$= C_p (T_{b,c} - T_b) = 735.06 \text{ kJ/kg}$$

$$\begin{aligned} \text{Compressor work} &= C_p (T_b - T_a) \\ &= 364.94 \text{ kJ/kg} \end{aligned}$$

$$\text{Turbine work} = C_p (T_d - T_c)$$

$$= 640.5 \text{ kJ/kg}$$

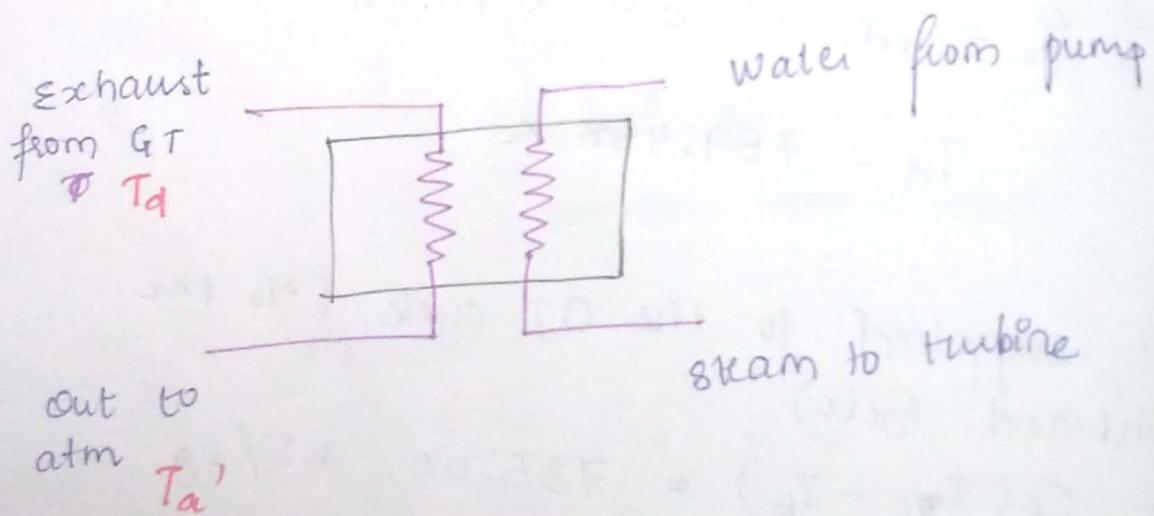
- Compressor of GT cycle is very crucial as it takes ~~more~~ significant amount of work as compared to the compressors of ST cycle.

$$\eta_{\text{turbine}} = \frac{640 - 364}{735} \\ = 37.55 \%$$

HRSG calculation:

$$\dot{m}_a (T_4 - T_1)$$

$$\dot{m}_a (T_d - T_c) \text{ GPa}$$



\bullet $P_{q3} = 8 \text{ kPa}$

$n_{q3} = 173.5 \text{ kJ/kg}$

$$P_{4s} = 8 \text{ MPa}$$

~~8000~~

$$\dot{w}_{p\text{ isoentropic}} = \dot{v}_{f1} \frac{f_{P_0} - P}{P} \quad \dot{v}_{f1} (P_1 - P_4)$$
$$= 0.001 \times (8 \times 10^3 - 8) \text{ kJ/kg}$$

$$\dot{w}_{p\text{ iso}} = 8.05977 \text{ kJ/kg}$$

$$\dot{w}_p = \dot{w}_{p\text{ iso}} / 0.8$$

$$= 10 \text{ kJ/kg}$$

~~h₂₀₀₀~~
$$h_{20} = h_{23} + \dot{w}_p = 183.5 \text{ kJ/kg}$$

$$h_{21} = 3139.4 \text{ kJ/kg}$$
$$s_1 = 6.36 \text{ kJ/kg-K}$$

~~h_{d3}~~
$$h_{63} = 1989 \text{ kJ/kg}$$

~~h_d~~
$$h_6 = 2219 \text{ kJ/kg}$$

$$\eta_{SPP} = \frac{\dot{w}_T - \dot{w}_p}{Q_{in}}$$

$$= 30.7 \%$$

$$\eta = \eta_1 + \eta_2 - \eta_1 \eta_2 = 56.2 \%$$

(not entirely correct) should around 53%.

Combined Cycle Power Generation

Mopping ~~at~~ Cycle

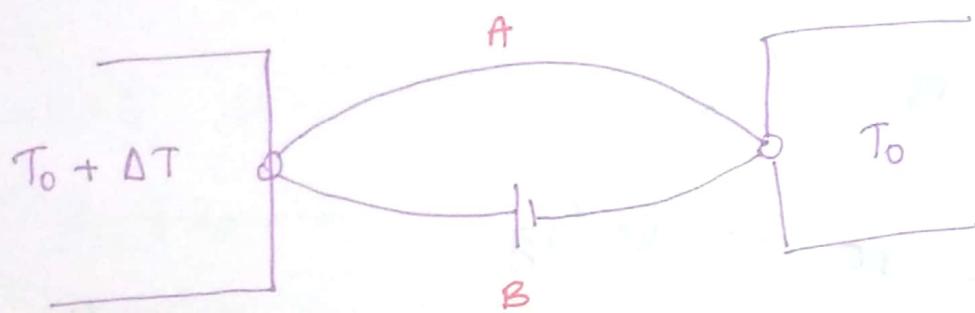
GT cycle

(Temp limitation)

Bottoming Cycle

ST cycle

Thermo electric Power Generation



For specific combination of A & B
emf will be generated in the loop
Seebeck effect.

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

↓
Seebeck coefficient

current I

$I^2 R_g$ - amount of heat will be
generated.

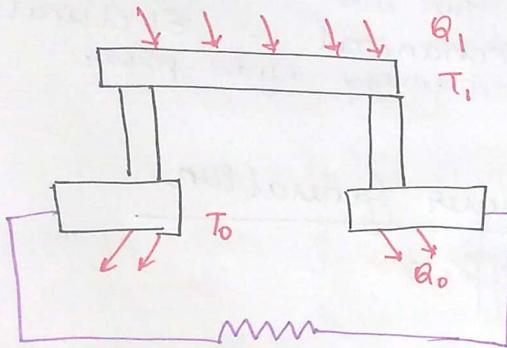
which is to be either absorbed or removed

This is ~~Peltier~~ Peltier effect

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

π_{AB} \rightarrow Peltier coefficient

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



Chemical - Thermal - Mechanical - Electrical
Conventional steam power plant

Thermal - Mechanical - Electrical
Nuclear plant, solar cell

Thermal - Electrical
Solar, Geothermal

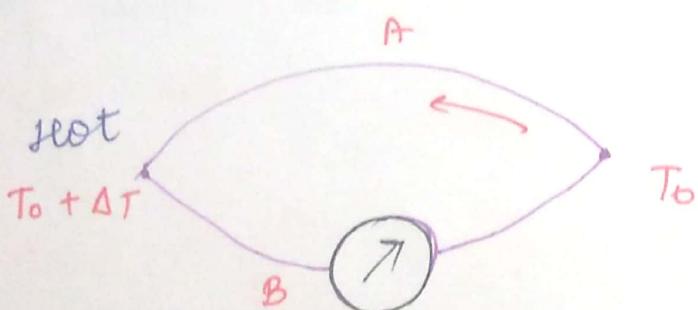
Chemical - Electrical
Fuel cells

Mechanical - Electrical
Wind energy, hydel power

Thermoelectric Power Generation

Thermoelectric effects

Seebeck effect



A and B are two dissimilar metals.

$$J = \sigma (-\nabla V + E_{emf}) \quad \text{Seebeck Generator}$$

Peltier effect

In this case, ~~emf~~ emf is produced
and from one side we get heat.
(junction)

Peltier cooler

Thomson effect

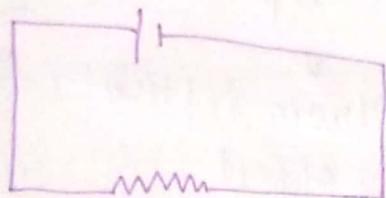
(Heat generation)

$$\text{per unit volume} = k J \cdot \Delta T$$

J → current density

k → Thomson coefficient

All the above are reversible cycles.

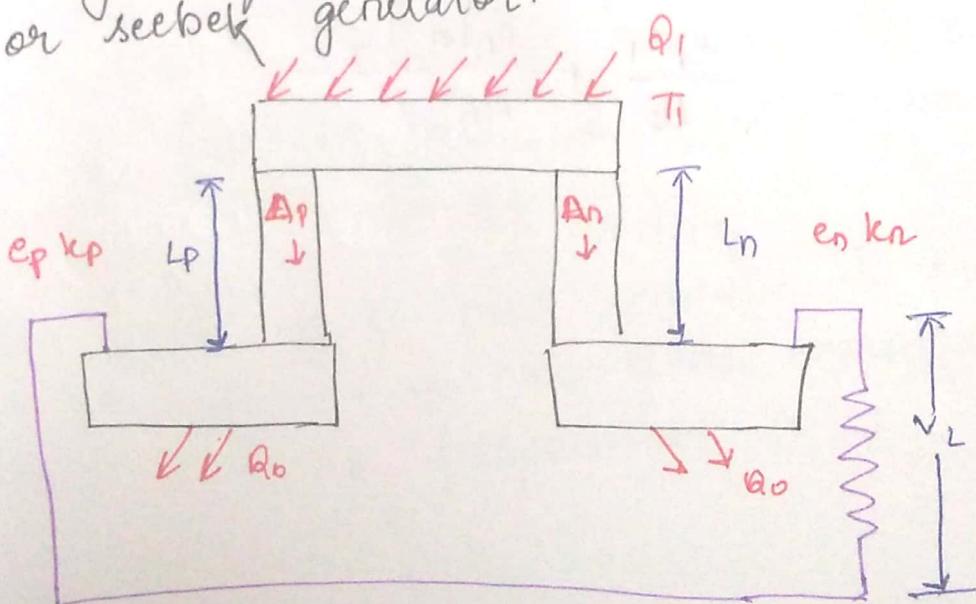


Ohmic heating or Joule heating

$$I^2 R$$

But this is an irreversible process
and the energy is dissipative.

- Analysis of a thermoelectric generator or Seebeck generator.



Seebeck effect $\rightarrow \alpha_{pn}(T_1 - T_0)$
 ↓
 Seebeck coefficient

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

Peltier Co-efficient $\dot{Q} = (\pi_A - \pi_B)$

Analysis of the hot junction from
1st law of thermodynamics

$$\dot{Q}_1 + \left(\frac{1}{2}\right) \dot{Q}_j = \dot{Q}_P + \dot{Q}_N$$

From Peltier

From thermo.
effect.

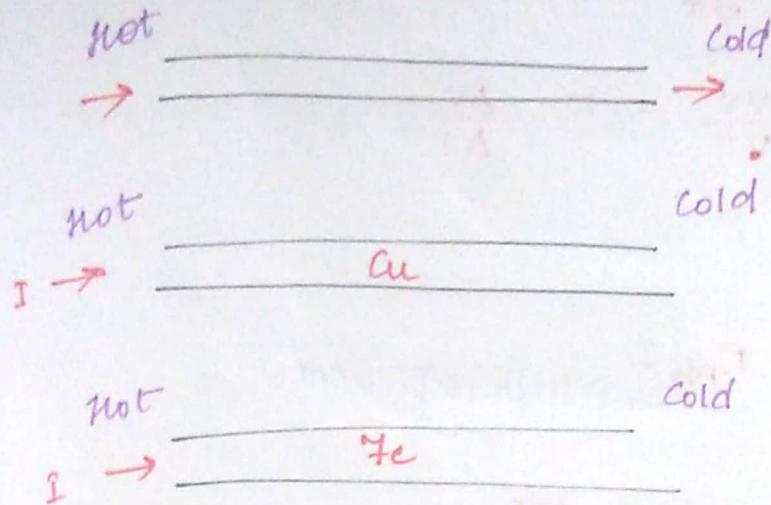
All heat generated effect
in Joule effect is equally
distributed in both the junctions.

$$\dot{Q}_P = \text{Per unit } \pi_P n I = \alpha_P n I T_1$$

$$\dot{Q}_j = (R_P + R_N) I^2$$

$$= \left(\frac{\epsilon_P I_P}{A_P} + \frac{\epsilon_N I_N}{A_N} \right) I^2$$

Thomson effect



In a conductor current flows and there is temperature gradient. Heat will either evolve or will be absorbed.

Joule effect

$$q = I^2 R$$

Fourier effect

$$q = -kA \cdot \frac{dT}{dx}$$

In the Peltier effect heat absorption or production is only at the junction but in case of Thomson effect, it is throughout the metal.

In Joule effect heat generated is proportional to I^2 whereas in case of all thermoelectric process, it is proportional to I .

Seebeck effect

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

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

↳ Seebeck coefficient

Peltier effect

$$\dot{Q} = \pi_{AB} I \quad \text{Peltier coefficient}$$

Gnmonson effect

$$\dot{q} = -K \cdot S \cdot \Delta T \quad \downarrow \text{Gnmonson coefficient}$$

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

$$\pi = T \alpha$$

Analysis of thermo-electric generator / Seebeck generator.

$$\dot{Q}_i = \dot{Q}_k + \dot{Q}_p \quad (\text{conduction + Peltier})$$

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

↳ heat generated half on each side.

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

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

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

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

$$= \left[\frac{K_p A_p}{L_p} + \frac{K_n A_n}{L_n} \right] (T_1 - T_0)$$

$$\dot{Q}_1 = \alpha_{pn} I T_1 - \frac{1}{2} \left[\frac{\epsilon_p L_p}{A_p} + \frac{\epsilon_n L_n}{A_n} \right] I^2$$

$$+ \left[\frac{K_p A_p}{L_p} + \frac{K_n A_n}{L_n} \right] (T_1 - T_0)$$

$$\dot{W}_L = I^2 R_L$$

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

From Kirchoff'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

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

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

$$\dot{Q}_1 = d_{pn} \cdot \frac{T_1 (T_1 - T_0)}{(R_p + R_n) (1+m)} - \frac{1}{2} \cdot \frac{\alpha_{pn}^2 (T_1 - T_0)^2}{(1+m)^2 (R_p + R_n)} + (k_p + k_n)(T_1 - T_0)$$

$$\eta = \frac{w_L}{\dot{Q}_1} =$$

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

Let us define

$$z = \frac{\alpha_{pn}^2}{(k_p + k_n) \cdot (R_n + R_p)}$$

'z' figure of most most important parameter based on material properties.

z increases

η increases

$$z = \frac{\alpha_{pn}^2}{k_p + k_n}$$

$$K = k_p + k_n$$

$$R = R_p + R_n$$

$$R.K = \left[\frac{e_p L_p}{A_p} + \frac{e_n L_n}{A_n} \right] \left[\frac{k_p A_p}{L_p} + \frac{k_n A_n}{L_n} \right]$$

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

$$\Rightarrow R.K = \left[\frac{e_p}{r_p} + \frac{e_n}{r_n} \right] [k_p r_p + k_n r_n]$$

$$\frac{d R.K}{d (r_n/r_p)} = 0$$

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

$$\boxed{\frac{r_n}{r_p} = \left[\frac{k_p f_n}{f_p \cdot k_n} \right]^{1/2}}$$

On substitution,

$$R.K_{\min} = k_p f_p + k_p f_n \left[\frac{k_n f_p}{k_p f_n} \right]^{1/2}$$

$$+ k_n f_p \left[\frac{k_p f_n}{k_n f_p} \right]^{1/2} + k_n f_n$$

$$= (\sqrt{f_n k_p} + \sqrt{k_n f_n})^2$$

We don't want high thermal conductivity as we want to maintain the temperature difference. And we ^{also} want low resistivity.

So, we need low thermal conductivity but ~~for~~ high electrical conductivity. Some semiconductors are ~~a~~ good options ~~for this~~ for this.

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

$$\frac{d\eta}{dm} = 0 \quad m_{op} = \left[1 + z \left(\frac{T_1 + T_0}{2} \right) \right]^{\frac{1}{2}}$$

$$m_{op+1} = \frac{z}{m_0 - 1} \cdot \frac{T_1 + T_0}{2}$$

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

$$W_L = \frac{m}{1-m^2} = \frac{\alpha p n^2 (T_1 - T_0)^2}{R_p + R_n}$$

$$\frac{dW_L}{dm} = 0 \quad \text{for maximum power}$$

$$m \rightarrow 1$$

$$\dot{w}_L = \frac{1}{4} \cdot \frac{\alpha_{pn}^2 (T_1 - T_0)^2}{R_p + R_n}$$

$$\eta = \frac{T_1 - T_0}{T_1} \cdot \frac{m_o - 1}{m_o + \frac{T_0}{T_1}}$$

$$\eta \text{ for max power} = \frac{T_1 - T_0}{T_1} + \frac{1}{\varphi - \frac{1}{2} \frac{T_1 - T_0}{T_1} + \frac{4}{ZT_1}}$$