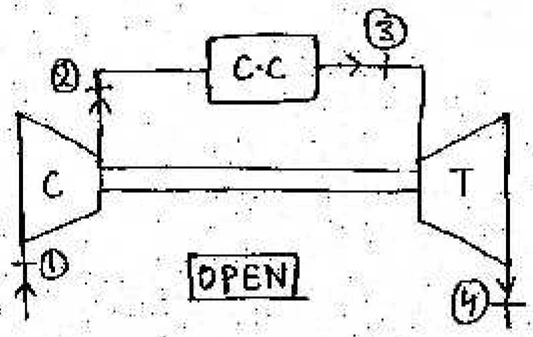
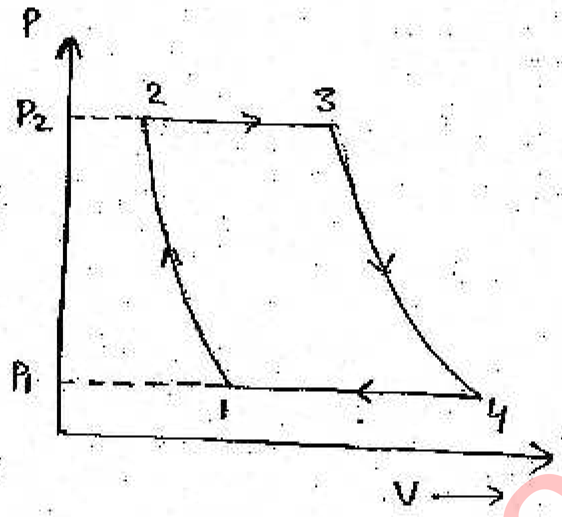
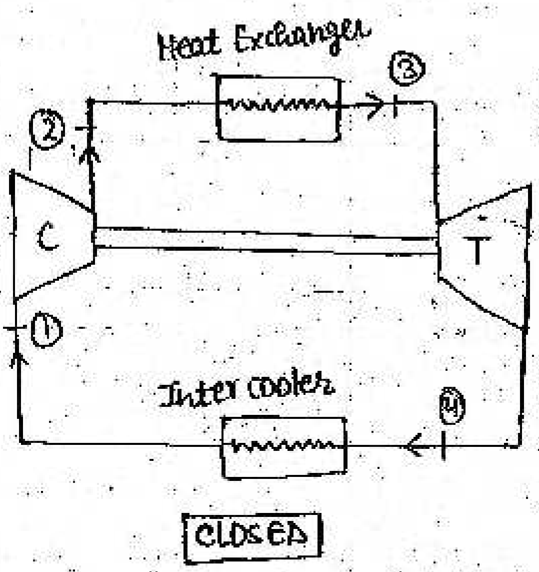
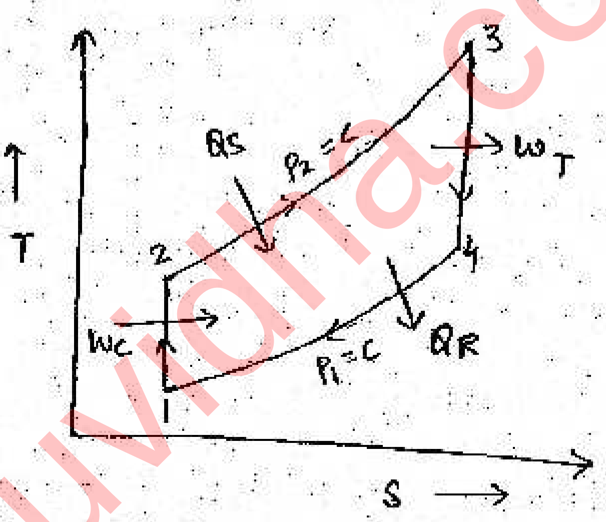
GAS TURBINE









Brayton cycle is the practical working cycle in Gas turbine plant and it consist of four process.

1) Process 1-2 → Reversible adiabatic compression in compressor from lower to higher pressure.

2) Process 2-3 → constant pressure Heat addition process either directly in the combustion chamber or indirectly in the Heat exchanger.

3) process 3-4 → Reversible adiabatic expansion in the turbine from Higher pressure to lower pressure.

4) Process 4-1 → constant pressure heat rejection process either directly to atmosphere or indirectly in an inter-

Advantages of closed cycle :-

- It is more efficient b/w the same maximum and minimum temp
- Better working fluid having better properties like He, Ar can be used.
- It can work below atmospheric pressure.
- Any lower grade fuel can be used as working substance is not mixed with fuel.
- No problem of turbine blade erosion.

90% used → open cycle
20% used → closed cycle

Disadvantages :-

- Cycle becomes complicated, costly and bulky.
- Absolute leak proofing of below atmospheric cycle is very difficult.
- Due to bulky can not be used for aircraft application.

Air standard assumptions :-

- Air is the working substance throughout and its chemical composition does not change.
- Cp, Cv and γ value remain constant irrespective of temperature. ← cold air assumption
- Changes in kinetic and potential energy is negligible.
- There is no loss of pressure while flow takes place through various component.
- There is no heat loss to the surrounding during compression and expansion process.

(1) compressor work (Wc) :-

Process 1-2

By S.F.E.E ① & ②

$$h_1 + \cancel{\frac{V_1^2}{2}} + \cancel{Z_1 g} + \cancel{Q_{1-2}} = h_2 + \cancel{\frac{V_2^2}{2}} + \cancel{Z_2 g} + W_{1-2}$$

$\boxed{V_1 = V_2}$ $\boxed{Z_1 = Z_2}$ $\boxed{Q_{1-2} = 0}$ $W_{1-2} = -W_C$

(adiabatic)

$$h_1 = h_2 - W_C$$

$$\boxed{W_C = h_2 - h_1 = C_p(T_2 - T_1)}$$

2) Heat supplied (Q_s):-

Process 2-3

$$h_2 + \cancel{\frac{V_2^2}{2}} + \cancel{Z_2 g} + Q_{2-3} = h_3 + \cancel{\frac{V_3^2}{2}} + \cancel{Z_3 g} + \cancel{W_{2-3}}^{0}$$

$V_2 = V_3$, $Z_2 = Z_3$, $W_{2-3} = 0$, $Q_{2-3} = Q_s$

$$h_2 + Q_s = h_3$$

$$\boxed{Q_s = h_3 - h_2 = C_p(T_3 - T_2)}$$

3) Turbine work (W_T):-

Process 3-4

$$h_3 = h_4 + W_T$$

$[V_3 = V_4 , Z_3 = Z_4 , Q_{3-4} = 0]$

$$\boxed{W_T = h_3 - h_4 = C_p(T_3 - T_4)}$$

4) Heat Rejected (Q_R):-

Process 4-1 :-

$$h_4 - Q_R = h_1$$

$$\boxed{Q_R = h_4 - h_1 = C_p(T_4 - T_1)}$$

Now

$$W_{net} = W_T - W_C$$

$$W_{net} = (h_3 - h_4) - (h_2 - h_1)$$

$$= (h_3 - h_2) - (h_4 - h_1)$$

$$\boxed{W_{net} = Q_S - Q_R = W_T - W_C}$$

[WK] $E_{in} = E_{out}$

$$Q_S + W_C = W_T + Q_R$$

$$\boxed{Q_S - Q_R = W_T - W_C}$$

Process 1-2 :-

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

$$\boxed{\text{Pressure Ratio} = r_p = \frac{P_2}{P_1}}$$

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

Process 3-4 :-

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

as $P_3 = P_2$ and $P_4 = P_1$

$$\frac{T_3}{T_4} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\frac{T_3}{T_4} = (r_p)^{\frac{\gamma-1}{\gamma}} = \frac{T_2}{T_1}$$

$$\boxed{\frac{T_2}{T_1} = \frac{T_3}{T_4}}$$

Efficiency :-

$$\eta = \frac{W_{net}}{Q_S}$$

$$\eta = \frac{Q_S - Q_R}{Q_S}$$

$$\eta = 1 - \frac{Q_R}{Q_S}$$

$$\eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

$$\eta = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}$$

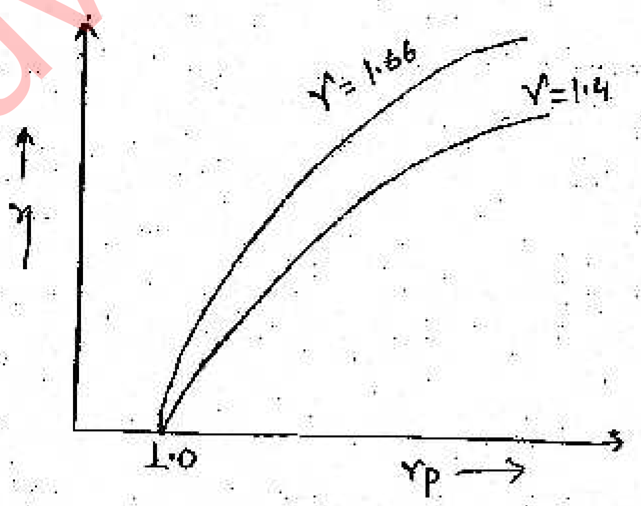
(As temp. ratio is equal).

$$\left(\frac{T_2}{T_1} = \frac{T_3}{T_4}\right) \Rightarrow \left[\frac{T_4}{T_1} = \frac{T_3}{T_2}\right]$$

$$\eta = 1 - \frac{T_1}{T_2}$$

$$\eta = 1 - \frac{1}{(T_2/T_1)}$$

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



(*) for a simple Brayton cycle η increases with increase in pressure ratio and γ value

Backwork Ratio (r_{bw}) :-

$$r_{bw} = \frac{-\text{ve work in a cycle}}{+\text{ve work in a cycle}}$$

$$\boxed{r_{bw} = \frac{W_C}{W_T}}$$

Gas turbine → 40% to 60%

Steam P.P → 1 to 2% (Pump work is less. Volume is less $= vdp$)

) Work Ratio (r_w) :-

$$r_w = \frac{\text{Net work in a cycle}}{+\text{ve work in a cycle}}$$

$$r_w = \frac{W_{net}}{W_T} = \frac{W_T - W_C}{W_T} = 1 - \frac{W_C}{W_T}$$

$$\boxed{r_w = 1 - r_{bw}}$$

Gas turbine → 40% to 60%

Steam P.P → 98% to 99%

Air rate :-

It is the mass flow rate of air required to produced 1 kw power output.

$$\boxed{AR = \frac{\dot{m}_a \rightarrow kg/s}{P \rightarrow kw}}$$

$$\boxed{P = \dot{m}_a \cdot W_{net}} \quad W_{net} \rightarrow KJ/kg$$

$$\therefore \boxed{AR = \frac{1}{W_{net}}} \quad \frac{kg}{KJ} \text{ OR } \frac{kg}{kw \cdot s}$$

$$\boxed{AR = \frac{3600}{W_{net}}} \quad kg/kwh$$

$W_{net} \rightarrow KJ/kg$ of air

Specific Fuel consumption

OR

Fuel Rate :-

It is the mass flow rate of fuel required to produced 1 kw power output.

$$\boxed{sfc = \frac{\dot{m}_f \rightarrow kg/s}{P \rightarrow kw}}$$

$$\boxed{P = \dot{m}_a W_{net}}$$

$$sfc = \frac{\dot{m}_f}{\dot{m}_a \cdot W_{net}}$$

$$\boxed{sfc = \frac{1}{(A/F) \cdot W_{net}}}$$

$A/F \simeq 50:1$ to $80:1$

$$\boxed{sfc = \frac{3600}{(A/F) \cdot W_{net}}} \quad kg/kwh$$

Q: A Brayton cycle has a pressure ratio 4 and inlet condition are 1 bar, 27°c. Find the mass flow rate of air required for 800 kW power output if the maximum temp. in the cycle is 1000°c. Take $\gamma = 1.4$ and $C_p = 1\ kJ/kgK$.

$\frac{P_2}{P_1} = 4$, $T_1 = 300K$, $T_3 = 1273K$

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

$T_2 = 445.79K$

$\frac{T_2}{T_1} = \frac{T_3}{T_4}$

$T_4 = 856.68K$

$P = \dot{m}_a C_p[(T_3-T_4)-(T_2-T_1)]$

$800 = \dot{m}_a \cdot 1[(1273-856.68) - (445.79-300)]$

$\boxed{\dot{m}_a = 2.95\ kg/s}$

Q: Air enters the compressor of a gas turbine working on brayton cycle at 1 bar and 27°c. The pressure ratio is 4. calculate the maximum temp. in the cycle when the back work ratio is 0.4.

$r_p = 4$, $T_1 = 300K$, $P_1 = 1\ bar$.

$r_{bw} = \frac{T_2-T_1}{T_3-T_4}$

$\frac{T_2}{T_1} = \frac{T_3}{T_4}$

$r_{bw} = \frac{T_2-T_1}{T_3 - \frac{T_3 T_1}{T_2}}$

$= \frac{T_2-T_1}{\frac{T_3(T_2-T_1)}{T_2}}$

$\boxed{r_{bw} = \frac{T_2}{T_3}}$

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

$T_2 = 445.79K$

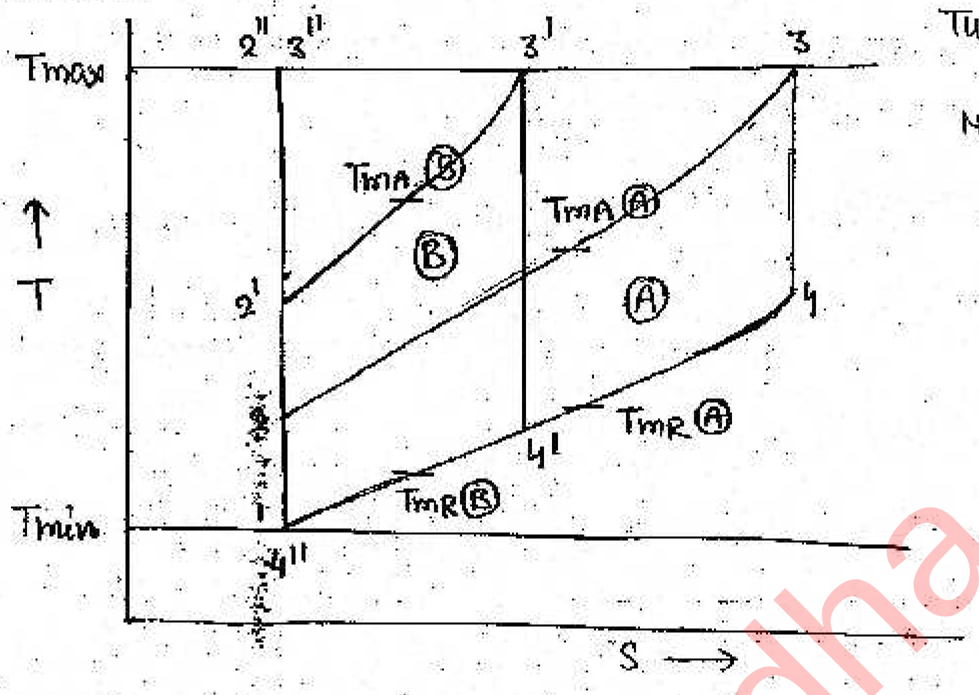
Now $T_3 = \frac{T_2}{r_{bw}}$

$T_3 = \frac{445.79}{0.4}$

$\boxed{T_3 = 1114.5\ K}$

Effect of pressure ratio on efficiency and Net work output :-

LECTURE-2
14/09/2016



Turbine blade
↓
Nimonic alloy

In actual working gas turbine cycle work b/w two temp. limit one the max^m temp. that depends upon the metullergical conditions of turbine blade and second the min^m temp. that depends upon the atmospheric condition.

when $r_p = 1$ both efficiency η and W_{net} will be zero. As r_p is increased both start increasing and η becomes maximum when the compression process end at max^m temp. limit. At this point η becomes equal to carnot but the net work out again become zero.

Pressure ratio for maximum efficiency :-

$$\boxed{(r_p)_{max} = \left(\frac{T_{max}}{T_{min}}\right)^{\frac{\gamma}{\gamma-1}}}$$

Now

$$\eta = 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}} \Rightarrow \boxed{\eta_{max} = 1 - \frac{T_{min}}{T_{max}} = \eta_{carnot}}$$

increases with $r_p \uparrow$, because

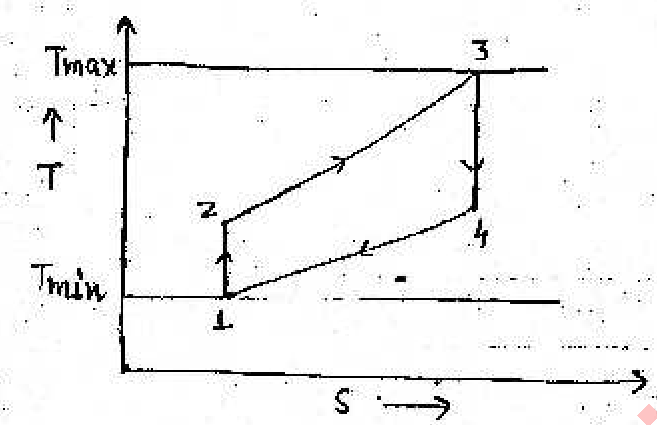
As $r_p \uparrow$ $\quad T_{mA} \xrightarrow{\text{approach}} T_{max}$

$T_{mR} \xrightarrow{\text{approach}} T_{min}$

$$\eta = \frac{W_{net} \to 0}{Q_s \to 0}$$

Indeterminate terms, we can't determine fro this formula.

Pressure ratio for maximum work output :-



$$W_{net} = C_p[T_3 - T_4 - T_2 + T_1]$$

for simple Brayton.

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \Rightarrow T_4 = \frac{T_3 \cdot T_1}{T_2}$$

$$W_{net} = C_p\left[T_3 - \frac{T_3 \cdot T_1}{T_2} - T_2 + T_1\right]$$

As T_3 & T_1 are fixed temp. limits

For W_{net} to be maximum.

$$\frac{dW_{net}}{dT_2} = 0 \left[-1 \quad - \frac{T_3 \cdot T_1(-1)}{T_2^2}\right] = 0$$

$$\boxed{T_2 = \sqrt{T_3 \cdot T_1}}$$

$$T_4 = \frac{T_3 \cdot T_1}{T_2}$$

$$\boxed{T_4 = \sqrt{T_3 \cdot T_1} = T_2}$$

$$W_{net} = C_p[T_3 - T_4 - T_2 + T_1]$$

for $(W_{net})_{max}$.

$$T_2 = T_4 = \sqrt{T_3 \cdot T_1}$$

$$(W_{net})_{max} = C_p[T_3 - 2\sqrt{T_3 \cdot T_1} + T_1]$$

$$\boxed{(W_{net})_{max} = C_p\left[\sqrt{T_3} - \sqrt{T_1}\right]^2}$$

$$(r_p)_{opt} = \left(\frac{T_2}{T_1}\right)^{\frac{1}{\left(\frac{\gamma-1}{\gamma}\right)}}$$

Now as $T_2 = \sqrt{T_3 \cdot T_1}$

$$(r_p)_{optimum} = \left(\frac{\sqrt{T_3 \cdot T_1}}{T_1}\right)^{\frac{1}{\left(\frac{\gamma-1}{\gamma}\right)}}$$

$$= \left(\sqrt{\frac{T_3}{T_1}}\right)^{\frac{1}{\left(\frac{\gamma-1}{\gamma}\right)}}$$

$$\boxed{(r_p)_{opt} = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}}} = \sqrt{(r_p)_m}$$

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

$$\boxed{\eta_{opt} = 1 - \sqrt{\frac{T_1}{T_3}}}$$

Maximum power or work :-

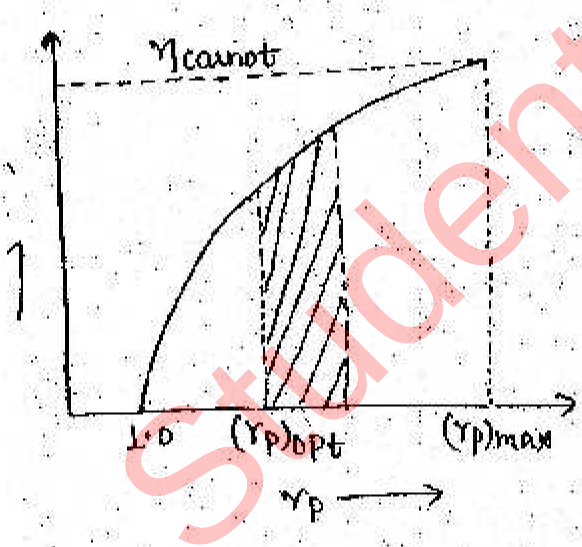
$T_3 = T_{max}$, $T_1 = T_{min}$

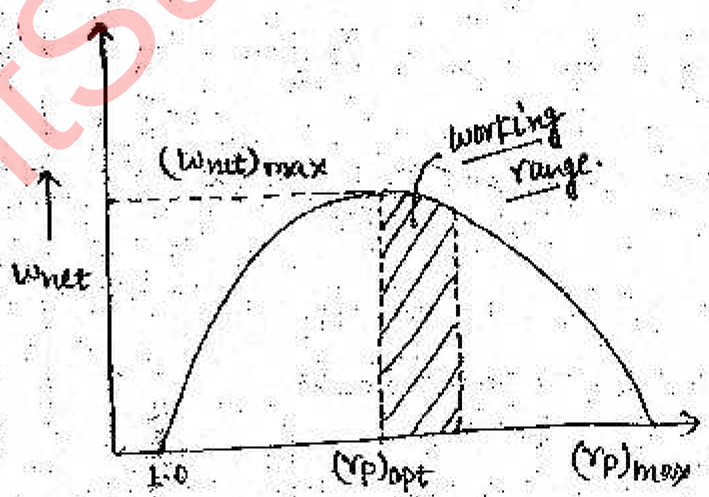
$$T_2 = T_4 = \sqrt{T_{max} \cdot T_{min}}$$

$$(w_{net})_{max} = c_p\left[\sqrt{T_{max}} - \sqrt{T_{min}}\right]^2$$

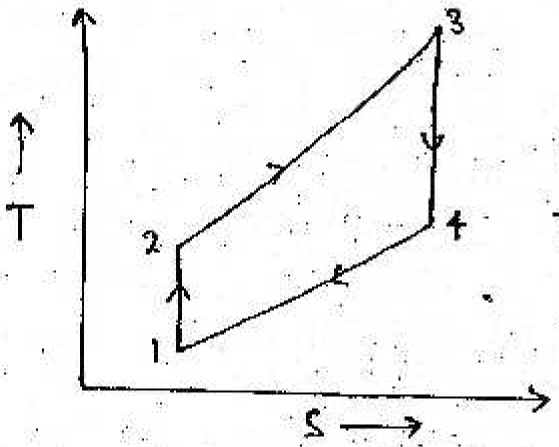
$$(r_p)_{opt} = \left(\frac{T_{max}}{T_{min}}\right)^{\frac{\gamma}{2(\gamma-1)}} = \sqrt{(r_p)_{max}}$$

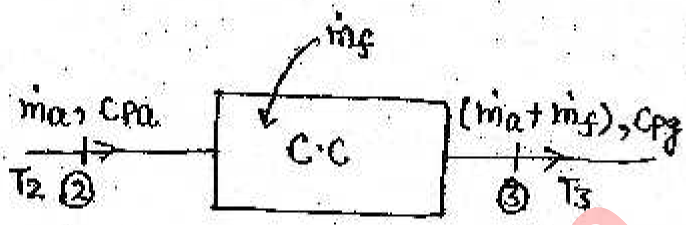
$$\eta_{opt} = 1 - \sqrt{\frac{T_{min}}{T_{max}}}$$





Combustion chamber :-





In open cycle gas tubine air is mixed with fuel in the combustion chamber to release energy. Under ideal condition the energy relased by burning of fuel should be exactly equal to enthalpy rise of gas.

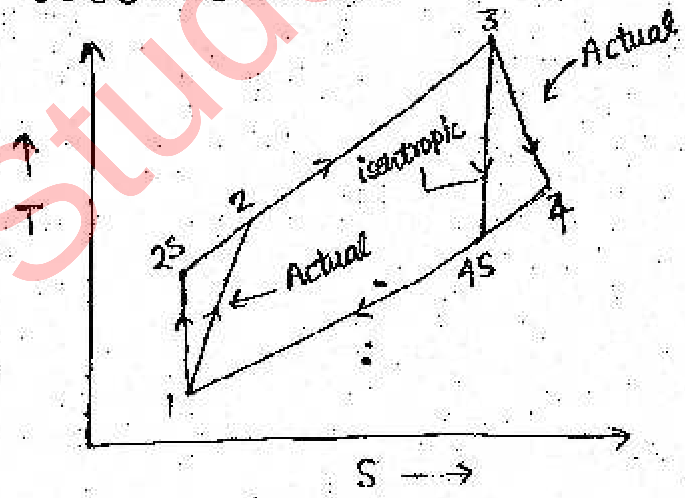
CV → calorific value

Heat Released by fuel = Enthalpy rise of gas

$$\boxed{\dot{m}_f \cdot C.V. \cdot \eta_{combustion} = (\dot{m}_a+\dot{m}_f) C_{pg} T_3 - \dot{m}_a C_{pa} T_2}$$ ← Exact Solution

$$\boxed{\dot{m}_f \cdot C.V. \cdot \eta_{combustion} = (\dot{m}_a+\dot{m}_f) C_{pa} (T_3 - T_2)}$$ ← Approximate Solution (objective)

Isentropic Efficiency :-



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

$$\downarrow\downarrow \eta = 1 - \frac{Q_R\uparrow}{Q_S\downarrow}$$

▶ Due to internal irreversibility i.e friction compressor required more work and turbine produces less work output.

Compressor

$$\eta_c = \frac{\text{Isentropic work}}{\text{Actual work}}$$

$$\boxed{\eta_c = \frac{T_{2s} - T_1}{T_2 - T_1}}$$

$$\boxed{\eta_c \simeq 80 \text{ to } 85\%}$$

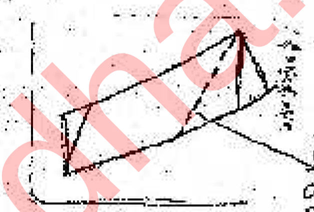
Turbine

$$\eta_T = \frac{\text{Actual work}}{\text{Isentropic work}}$$

$$\boxed{\eta_T = \frac{T_3 - T_4}{T_3 - T_{4s}}}$$

$$\boxed{\eta_T \simeq 85 \text{ to } 90\%}$$

Now $\eta = 1 - \frac{Q_R}{Q_S}$ $$\boxed{\eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}}$$



but the condition is that process should be non-adiabatic. In non-adiabatic process we remove the heat from the cycle and entropy = -ve

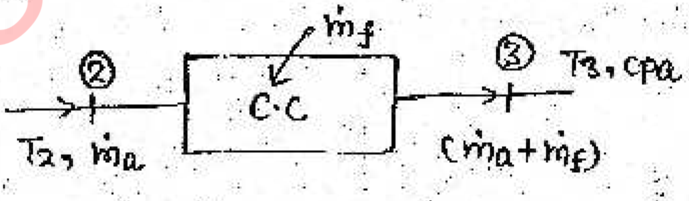
: Find the required A/F in a gas turbine where $\eta_c = 80\%$ and $\eta_T = 85\%$ and $T_{max} = 875°C$. The working fluid can be taken as air with $c_p = 1$ kJ/kgK and $\gamma = 1.4$. Air enters the compressor at 1 bar at 20°C the pressure ratio is 4 and the fuel has calorific value is 42 MJ/kg. There is a loss of 10% of CV in combustion chamber.

$$\frac{T_{2s}}{T_1} = (r_p)^{\frac{\gamma-1}{\gamma}}$$

$$T_{2s} = 445.79 \text{ K}$$

$$\eta_c = 0.8 = \frac{T_{2s} - T_1}{T_2 - T_1}$$

$$T_2 = 482.24 \text{ K}$$



$$\dot{m}_f \cdot CV \cdot \underset{0.9}{\eta_c} = (\dot{m}_a + \dot{m}_f)(T_3 - T_2) c_{pa}$$

$$\boxed{\frac{\dot{m}_a}{\dot{m}_f} = 55.77}$$

Q. A gas turbine unit develop a power of 1500 kW and air at 1 bar 20°C enters the compressor and the pressure ratio is 6. The max^m temp at the turbine inlet is 900°C. $\eta_c = 80\%$ and $\eta_{cycle} = 24\%$ then determine —

(i) η_T

(ii) $\dot{m}_a$

$T_2 = 537.84\,K$

$\eta_{cycle} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 0.24$

$T_4 = 775.77\,K$

$\frac{T_3}{T_{4s}} = (r_p)^{\frac{\gamma-1}{\gamma}}$

$T_{4s} = 703.62\,K$

(i) $\eta_T = \frac{T_3 - T_4}{T_3 - T_{4s}}$

$\boxed{\eta_T = 84.5\%}$

(ii) $P = \dot{m}_a\, c_p\left[(T_3 - T_4) - (T_2 - T_1)\right]$

$\boxed{\dot{m}_a = 9.84\ kg/s}$