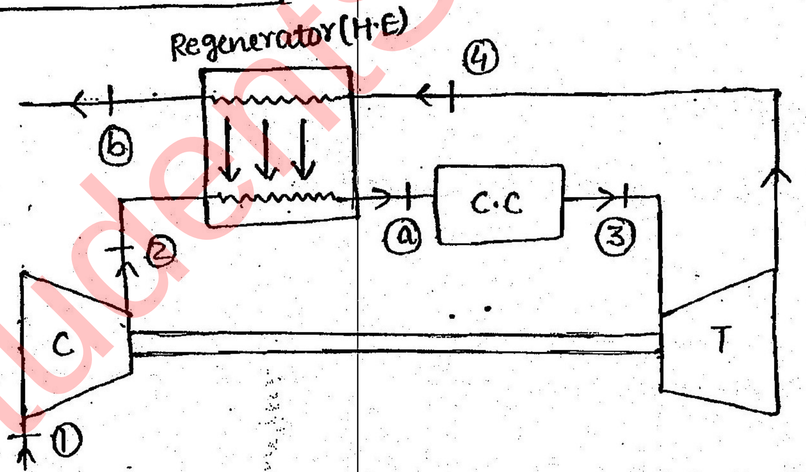
REGENERATION



Regeneration is the process in which the high temp. gas at the exit of turbine is utilized for Heating the cold air coming out from the compressor and entering the combustion chamber.

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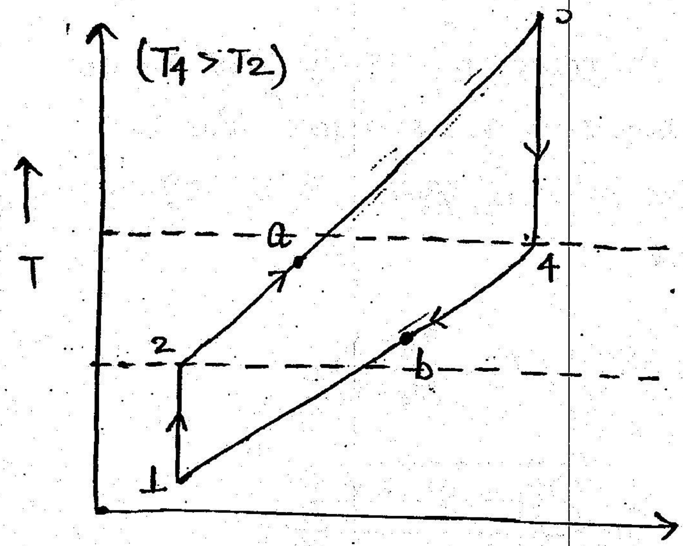


Effectiveness or thermal ratio or Degree of Regeneration :-

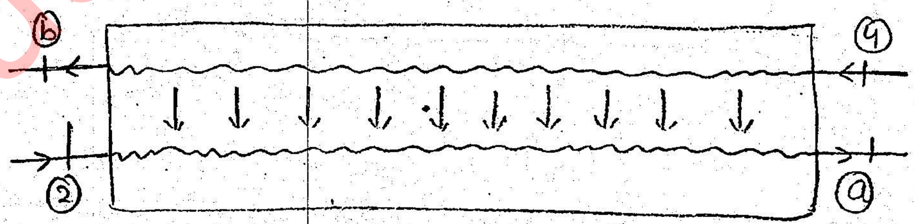
It is the term used to indicate the capacity of Heat exchanger in transferring heat from hot body to cold body. It is the ratio of actual temp. rise to the max^m temp. rise possible in a heat exchanger.

$$\epsilon = \frac{\text{Actual temp. Rise}}{\text{Maximum temp. Rise}}$$

$$\boxed{\epsilon = \frac{T_a - T_2}{T_4 - T_2}} \qquad \boxed{\epsilon \approx 70\% \text{ to } 80\%}$$

Effects of Regeneration :-

- No change in compressor or turbine output.
- W_{net} same.
- $Q_S \downarrow$
- $Q_R \downarrow$
- $T_{mA} \uparrow$
- $T_{mR} \downarrow$
- $\eta \uparrow$



$(T_a = T_b)$ when Heat exchanger made infinitely long.

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Ideal Regenerative Cycle :-

In an ideal Regenerative cycle cold air is heated upto turbine exit temp. in a Heat exchanger. It is possible for an infinitely large Heat exchanger and at that point effectiveness becomes 100% and

$$\boxed{\epsilon = 100\%, \ T_a = T_4, \ T_b = T_2}$$

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

$$\eta = 1 - \frac{T_b - T_1}{T_3 - T_a}$$

Now

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

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

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

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

$$\eta = 1 - \frac{T_1}{T_3} \cdot \frac{T_2}{T_1}$$

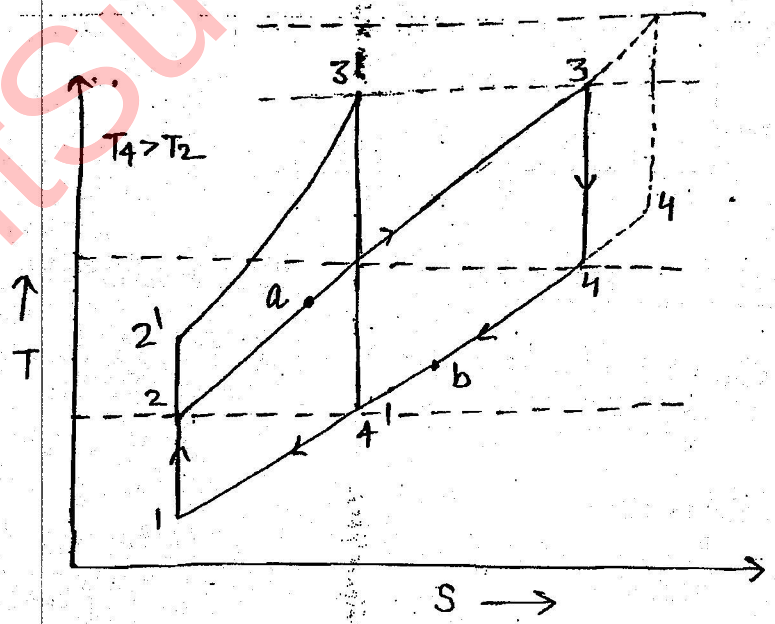
$$\boxed{\eta_{ideal\ Reg.} = 1 - \frac{T_1}{T_3}(r_p)^{\frac{\gamma-1}{\gamma}}}$$

(i) $r_p \uparrow \longrightarrow \eta \downarrow$

(ii) $\gamma \uparrow \longrightarrow \eta \downarrow$

(iii) $T_1 \uparrow \longrightarrow \eta \downarrow$

(iv) $T_3 \uparrow \longrightarrow \eta \uparrow$



⊛ Beyond certain region use of Regenerative becomes ineffective because of compressor outlet temp. becomes more than turbine outlet temp.

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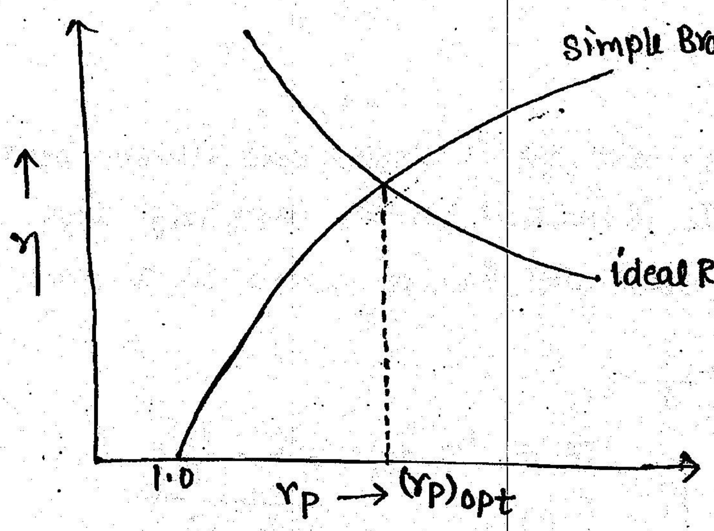
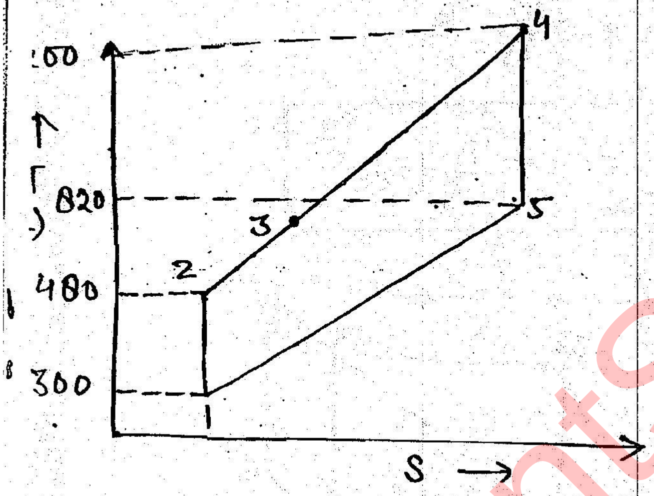


Q. Determine the efficiency for the actual gas turbine cycle as shown below where temp. are given in K. also find the η when the Regenerator is installed with an effectiveness of 0.7.



Without Regenerator

$$\eta = \frac{(T_4 - T_5) - (T_2 - T_1)}{(T_4 - T_2)}$$

$$\eta = \frac{380 - 180}{720}$$

$$\boxed{\eta = 27.7\%}$$

With Regenerator

$$\epsilon = \frac{T_3 - T_2}{T_5 - T_2} = 0.7$$

$$T_3 = 718\,K$$

$$\eta = \frac{(T_4 - T_5) - (T_2 - T_1)}{(T_4 - T_3)}$$

$$\eta = \frac{200}{(1200 - 718)}$$

$$\boxed{\eta = 41.4\%}$$

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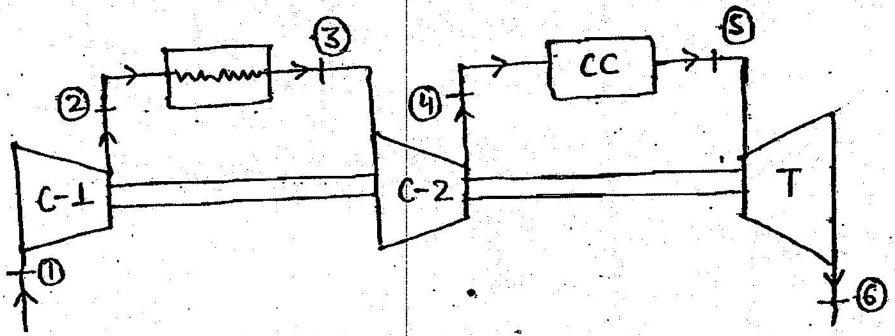
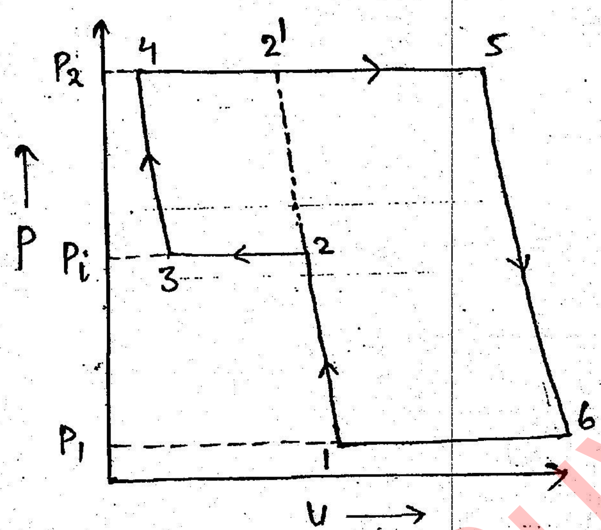
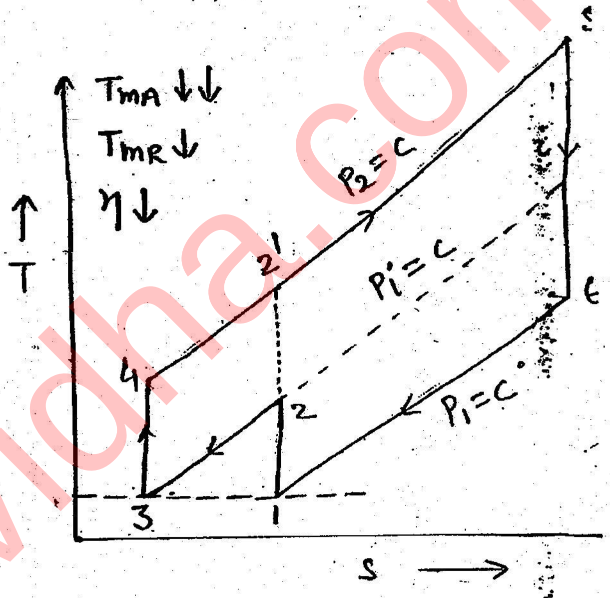
INTERCOOLING







In order to increase the net work output one method is to decrease the work input required by the compressor and this is obtained by using several stages of compression with intercooling of air in b/w the stages.

* If intercooler + Regenerator ⟶ $\eta \uparrow$ by 15 to 20%.

Effects of intercooling :-

(i) $W_c \downarrow$

(ii) W_T no change

(iii) $W_{net} \uparrow$

(iv) $Q_S \uparrow$ (4-2')

(v) $Q_R \uparrow$ (2-3)

(vi) $T_{mA} \downarrow\downarrow$

(vii) $T_{mR} \downarrow$ and $\eta \downarrow$ (by 2 to 4%)

(viii) Scope of Regeneration increases as compressor outlet temp. decreases.

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Condition for minimum compressor work for perfect intercooling

For perfect intercooling :- $(T_1 = T_3)$

$$W_c = W_{c_1} + W_{c_2}$$

$$= C_p [T_2 - T_1 + T_4 - T_3]$$

$$= C_p T_1 \left[\frac{T_2}{T_1} - 1 + \frac{T_4}{T_1} - \frac{T_3}{T_1} \right]$$

$$W_c = C_p T_1 \left[\frac{T_2}{T_1} + \frac{T_4}{T_3} - 2 \right]$$

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

let $\boxed{\frac{\gamma-1}{\gamma} = x}$

$$\frac{T_2}{T_1} = \frac{P_i^x}{P_1^x}$$

$$\frac{T_4}{T_3} = \frac{P_2^x}{P_i^x}$$

$$W_c = C_p T_1 \left[\frac{P_i^x}{P_1^x} + \frac{P_2^x}{P_i^x} - 2 \right]$$

For W_c to be minimum.

$$\frac{dW_c}{dP_i} = 0$$

$$\frac{x P_i^{x-1}}{P_1^x} + \frac{(-x) P_2^x}{P_i^{x+1}} = 0$$

$$\frac{P_i^{x-1}}{P_1^x} = \frac{P_2^x}{P_i^{x+1}}$$

$$P_i^{2x} = P_1^x P_2^x$$

$$\boxed{P_i = \sqrt{P_2 P_1}}$$

OR

$$\boxed{\frac{P_i}{P_1} = \frac{P_2}{P_i}}$$

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

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

→ $T_3 = T_1$ & $\frac{P_2}{P_i} = \frac{P_i}{P_1}$

$$\boxed{T_4 = T_2}$$

as $T_3 = T_1$

& $T_4 = T_2$

$W_{c_1} = W_{c_2}$

Perfect intercooling

(1) $T_3 = T_1$

(2) $P_i = \sqrt{P_2 \cdot P_1}$

(3) $T_4 = T_2$

(4) $W_{c_1} = W_{c_2}$

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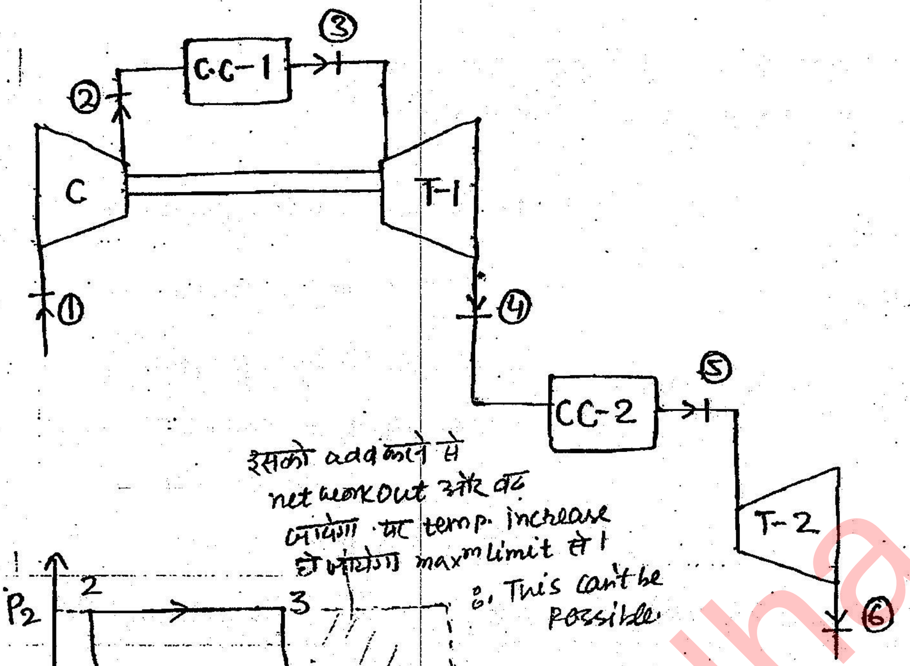
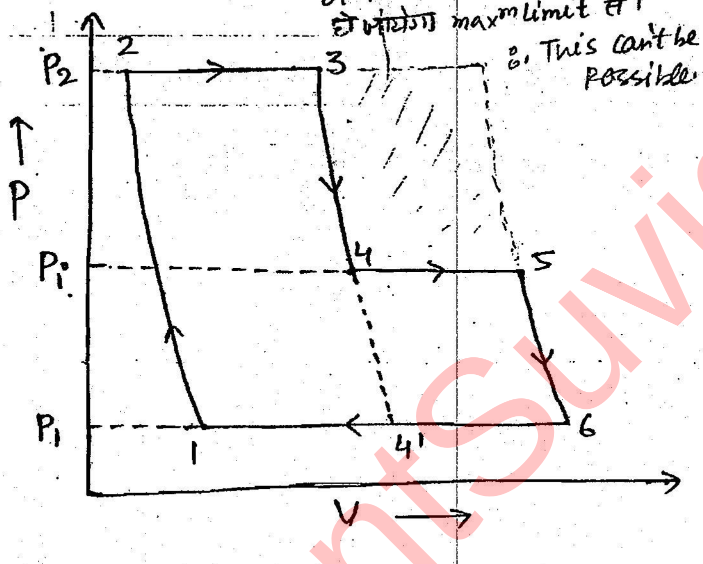
REHEATING

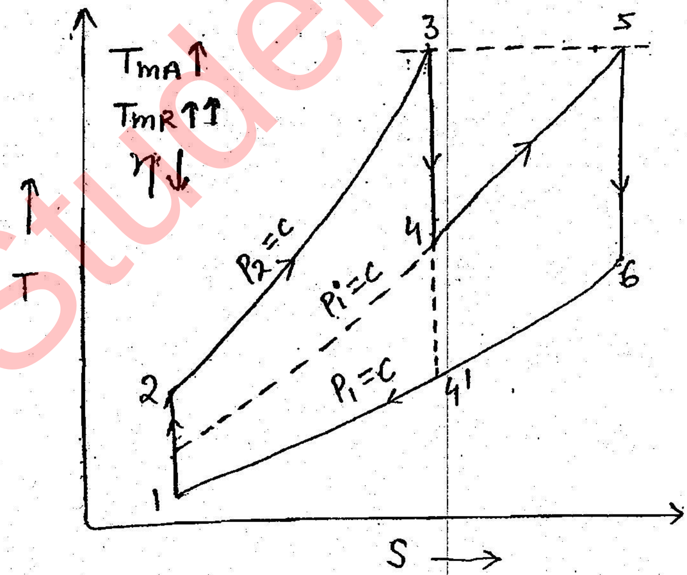
LECTURE-3
15/09/2016





$\uparrow W_{net} = \uparrow W_T - W_c$

* Net workoutput of the cycle can be increased by increasing the output of the turbine and this is achieved by using several stages of expansion with Reheating in b/w stages.



Effects of Reheating :-

- $W_c \rightarrow$ same
- $W_T \rightarrow \uparrow$
- $W_{net} \rightarrow \uparrow$
- $Q_S \rightarrow \uparrow$
- $Q_R \rightarrow \uparrow$
- $T_{mA} \rightarrow \uparrow$
- $T_{mR} \rightarrow \uparrow\uparrow$
- $\eta \rightarrow \downarrow$

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- Pmean ↓
- Scope of Regeneration increases because of turbine exit temp. increases.
- Wnet ↑ [For the same power output mass flow rate will be less. so power plant will be compact.]

$$\boxed{N = \frac{120 f}{p}}$$

f → frequency
p → No. of poles.

In india
$$\text{max}^m \text{ speed} = \frac{120 \times 50}{2} = \underline{\underline{3000 \text{ rpm}}}$$

* In india → 50 Hz frequency
* In USA → 60 Hz frequency.
* if you change frequency that doesnot effect on η. ∴ η doesn't depend on frequency.

Condition for maximum Turbine output with perfect Reheating :-

Perfect Reheating :- $(T_3 = T_5)$

$$W_T = W_{T_1} + W_{T_2}$$

$$W_T = C_p [T_3 - T_4 + T_5 - T_6]$$

$$= C_p T_3 \left[1 - \frac{T_4}{T_3} + \frac{T_5}{T_3} - \frac{T_6}{T_3}\right]$$

$$W_T = C_p T_3 \left[1 - \frac{T_4}{T_5} + 1 - \frac{T_6}{T_5}\right]$$

$$W_T = C_p T_3 \left[2 - \frac{T_4}{T_5} - \frac{T_6}{T_5}\right]$$

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

Let $\boxed{\left(\frac{\gamma-1}{\gamma}\right) = x}$

$$\frac{T_3}{T_4} = \frac{P_2^x}{P_i^x}$$

$$\frac{T_5}{T_6} = \frac{P_i^x}{P_1^x}$$

$$W_T = C_p T_3 \left[2 - \frac{P_i^x}{P_2^x} - \frac{P_1^x}{P_i^x}\right]$$

* For perfect Reheating

① $T_5 = T_3$

②. $P_i = \sqrt{P_2 \cdot P_1}$ or $\frac{P_i}{P_1} = \frac{P_2}{P_i}$

③ $T_4 = T_6$

④ $W_{T_1} = W_{T_2}$

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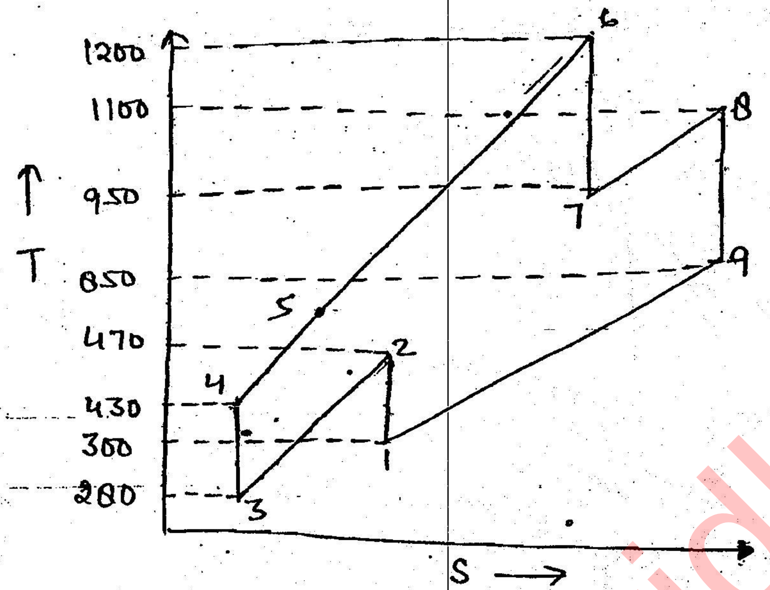
Ques. Actual gas turbine cycle with intercooling and Reheating is as given below. Find the η of the cycle when the temp. are given in Kelvin also find the η when a regenerator is installed with an effectiveness of 0.7.



• without Regenerator :-

$$\eta = \frac{W_{T_1} + W_{T_2} - W_{C_1} - W_{C_2}}{Q_{S_1} + Q_{S_2}}$$

$$\eta = \frac{(T_6 - T_7) + (T_8 - T_9) - (T_2 - T_1) - (T_4 - T_3)}{(T_6 - T_4) + (T_8 - T_9)}$$

$$\eta = \frac{250 + 250 - 170 - 150}{770 + 150}$$

$$\boxed{\eta = 19.56\%}$$

• With Regeneration :-

$$\epsilon = 0.7 = \frac{T_5 - T_4}{T_9 - T_4}$$

$$T_5 = 724K$$

$$\eta = \frac{(T_6 - T_7) + (T_8 - T_9) - (T_2 - T_1) - (T_4 - T_3)}{(T_6 - T_5) + (T_8 - T_9)}$$

$$\eta = \frac{\overset{25+}{225} + 250 - 170 - 150}{(1200 - 724) + 150}$$

$$\boxed{\eta = 28.7\%}$$

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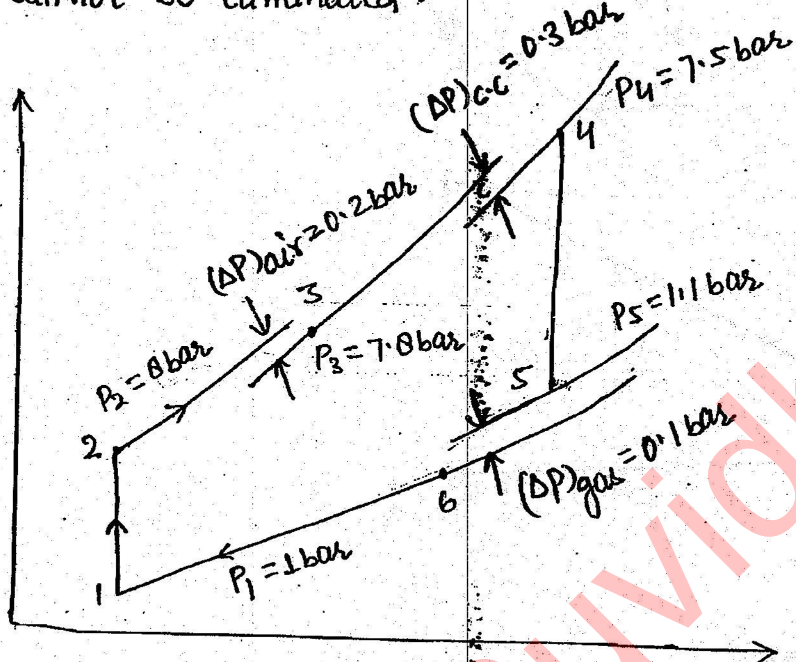
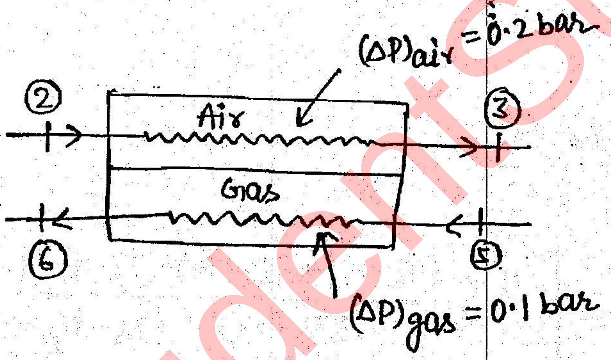
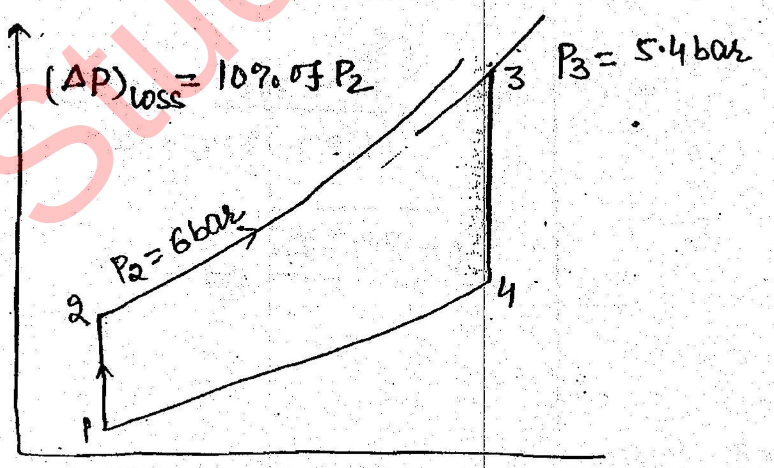
ACTUAL GAS TURBINE :-

1) Pressure losses :-

There is always loss of pressure during flow through heat exchanger, combustion chamber and duct connecting various components. These losses can be minimized by proper duct design but can not be eliminated.







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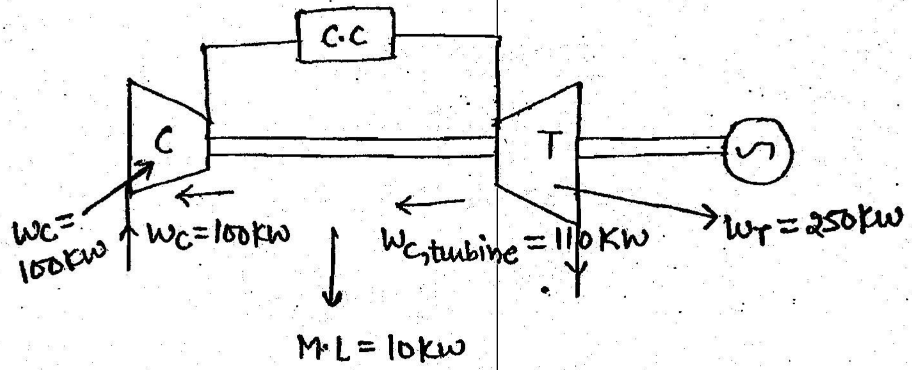
(2) Mechanical losses :-



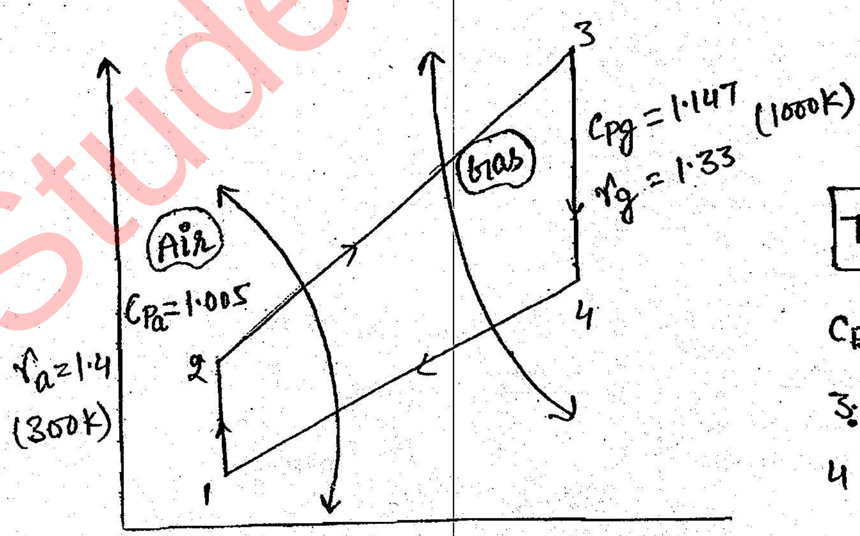
Compressor is driven by turbine and while transmission of power from turbine to compressor some part of energy is lost out in intermediate gear, connecting shaft and bearing known as mechanical losses.
Due to these losses the net workoutput of the cycle always decreases

$$\boxed{\eta_{mech} = \frac{W_C}{W_{C,turbine}}}$$

$$W_{net} = W_T - W_{C,turbine}$$

$$\boxed{W_{net} = W_T - \frac{W_C}{\eta_{mech}}}$$

(3) C_p, C_v and γ value does not remain constant with temperature.



$$\boxed{T\uparrow,\ C_P\uparrow,\ C_v\uparrow,\ \gamma\downarrow}$$

$C_P - C_V$	=	R	$\gamma = \frac{C_P}{C_V}$
3 - 2	=	1	$\gamma = 1.5$
4 - 3	=	1	$\gamma = 1.33$

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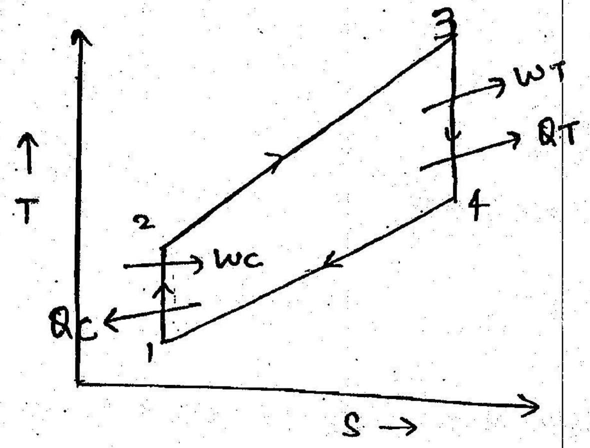
(4) There is loss of energy in the compressor and turbine during compression and expansion process :-



Compressor :-

By SFEE ① & ②

$$h_1 - Q_C = h_2 - W_C$$

$$\boxed{W_C = (h_2 - h_1) + Q_C}$$

Turbine :-

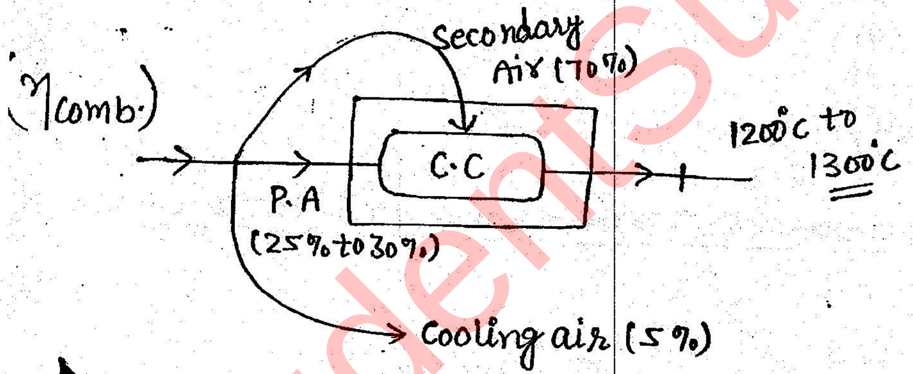
By SFEE ③ & ④

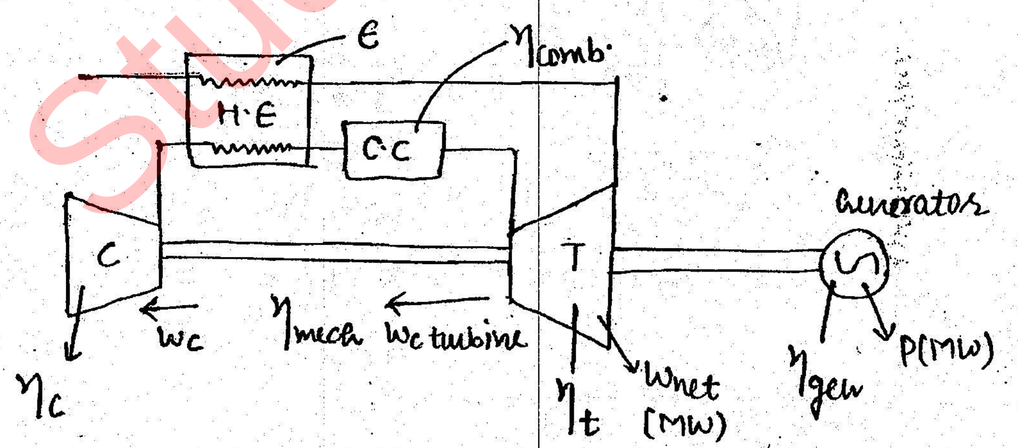
$$h_3 - Q_T = h_4 + W_T$$

$$\boxed{W_T = (h_3 - h_4) - Q_T}$$

5) Compression and expansion process are not frictionless and there is always increase in entropy due to internal irreversibility.

6) There is loss of energy due to incomplete combustion in the combustion chamber.





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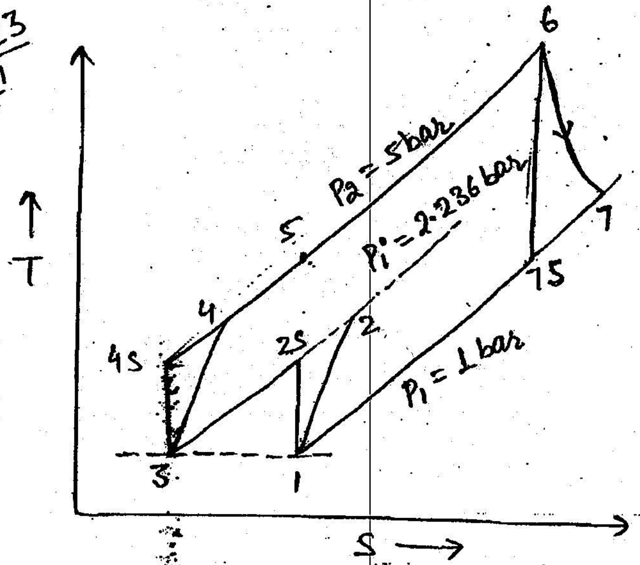
$$\boxed{\eta_{gen} = \frac{P(MW)}{W_{net}(MW)}}$$

Ques-23
P-37



$T_1 = 288\,K$

$$\frac{T_{2s}}{T_1} = (2.236)^{\frac{\gamma_a - 1}{\gamma_a}}$$

$T_{2s} = 362.4\,K$

$$\eta_{c_1} = 0.8 = \eta_{c_2} = \frac{T_{2s} - T_1}{T_2 - T_1}$$

$T_2 = 381.05 = T_4$

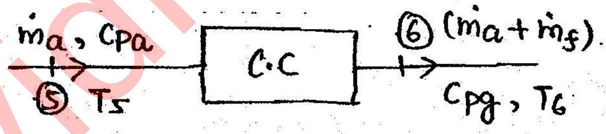
$$\eta_T = 0.9 = \frac{T_6 - T_7}{T_6 - T_{7s}}$$

$T_7 = 755.05\,K$

$$\epsilon = 0.7 = \frac{T_5 - T_4}{T_7 - T_4}$$

$T_5 = 642.8\,K$

$$\boxed{\frac{T_6}{T_{7s}} = (5)^{\frac{\gamma_g - 1}{\gamma_g}}}$$



$$\dot{m}_f \cdot CV \cdot \eta_{comb} = (\dot{m}_a + \dot{m}_f) C_{pg} \cdot T_6 - \dot{m}_a \cdot C_{pa} \cdot T_5$$

$$\dot{m}_f = \frac{\dot{m}_a (C_{pg} \cdot T_6 - C_{pa} \cdot T_5)}{(CV \cdot \eta_{comb} - C_{pg} \cdot T_6)}$$

$\dot{m}_f = 3.308\ kg/s$

① $A/F = \frac{\dot{m}_a}{\dot{m}_f} = \frac{250}{3.308} = \boxed{75.57}$

② $W_c = 2\,W_{c_1}$

$= 2 \times \dot{m}_a \cdot C_{pa} (T_2 - T_1)$

$W_c = 46.75\ MW$

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$$W_T = (\dot{m}_a + \dot{m}_f)\, C_{pg} (T_6 - T_7)$$

$$W_T = 86.90 \text{ MW}$$

$$W_{net} = W_T - \frac{W_C}{\eta_{mech}}$$

$$W_{net} = 38.29 \text{ MW}$$

$$Q_S = \dot{m}_f \cdot CV \cdot \eta_{comb}$$

$$Q_S = 132.1 \text{ MW}$$

$$\eta = \frac{W_{net}}{Q_S} = \frac{38.29}{132.1}$$

$$\boxed{\eta = 29\%}$$

(3) $\eta_{gen} = \frac{P}{W_{net}}$

$$P = 0.75 \times 38.29$$

$$\boxed{P = 28.7 \text{ MW}}$$

(4) $Sfc = \frac{\dot{m}_f}{W_{net}(kW)}$

$$Sfc = \frac{3.308 \times 3600}{38.29 \times 10^3}$$

$$\boxed{Sfc = 0.311 \text{ kg/kWh}}$$

Student

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