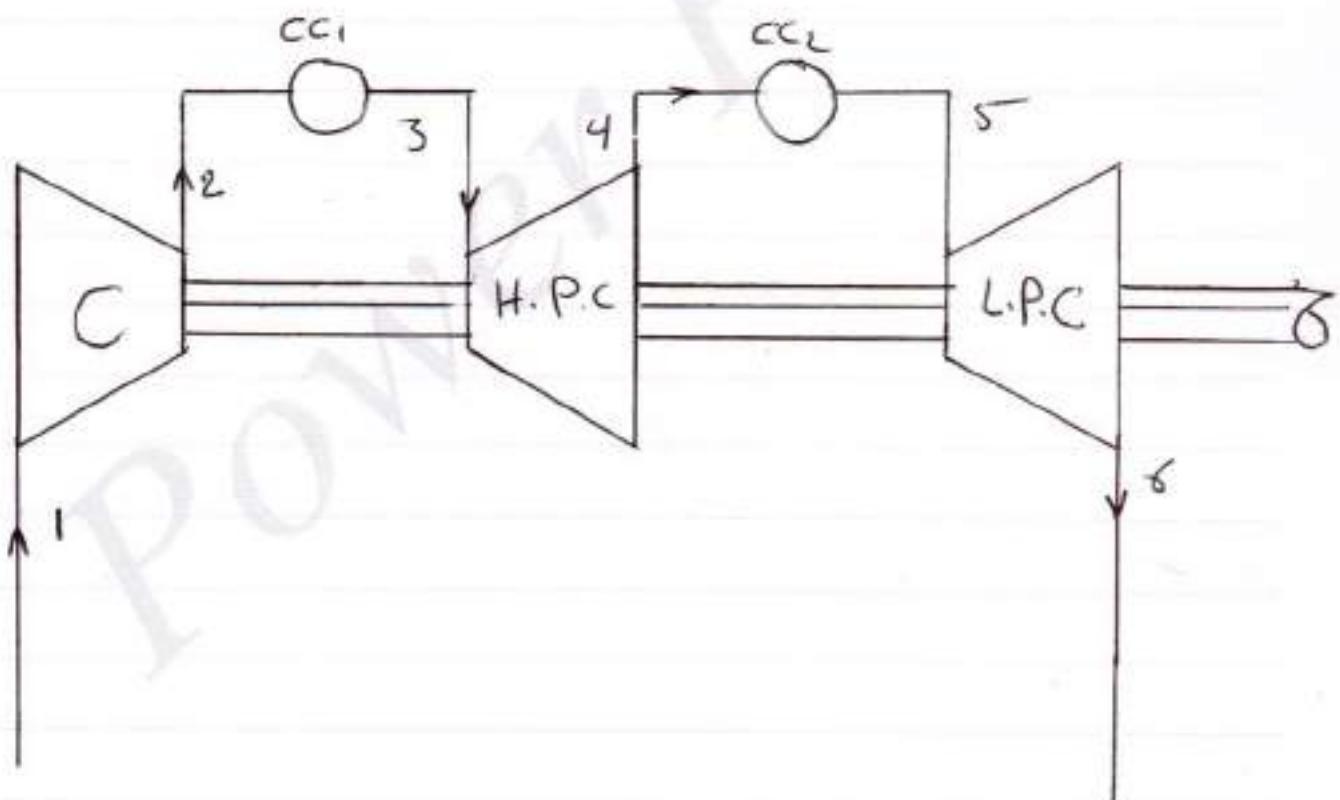


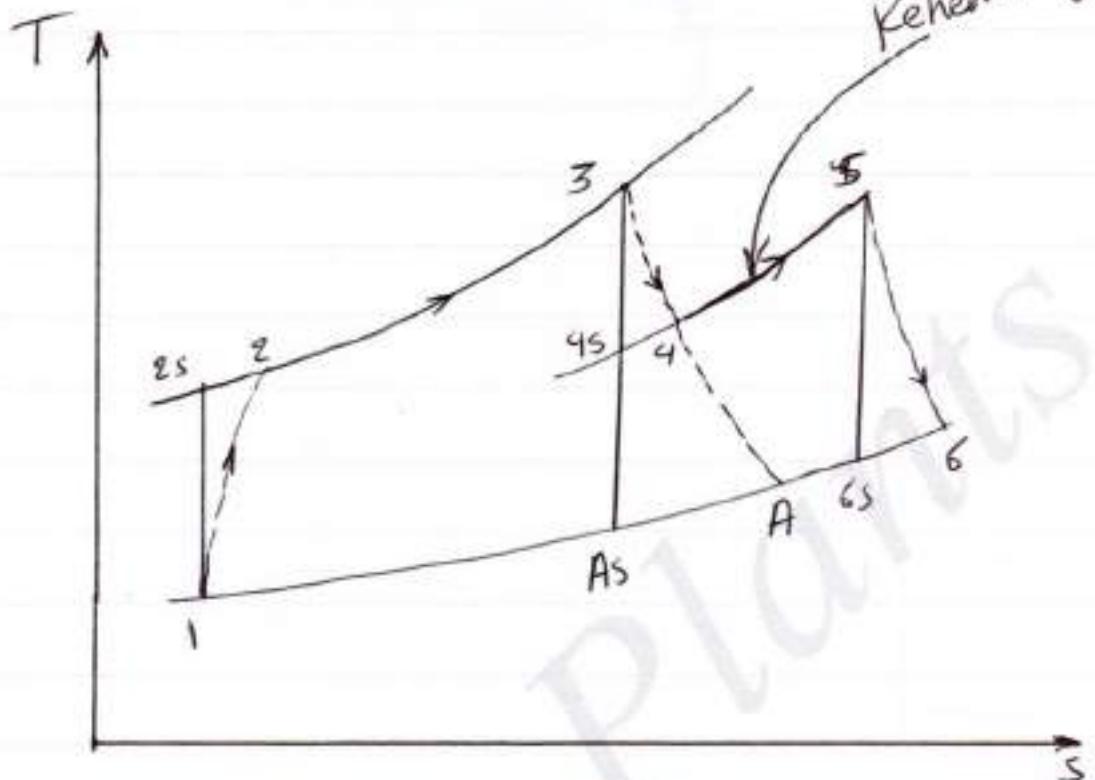
# Power Plants

## Reheating

In order to maximize the work available from the simple gas turbine cycle, enthalpy of fluid entering gas turbine is increased. Also, expand its expansion up to the lowest possible enthalpy value.



# Power Plants



- 1-2 : Air is compressed across the compressor
- 2-3 : Heat is added through first Combustion chamber
- 3-4 : Air is expanded across H.P. turbine
- 4-5 : Air is reheated by adding heat through the Second Comb. chamber.
- 5-6 : Air is expanded across L.P. turbine

The Work of the two stages turbine is greater than that of single expansion.

$$\therefore (T_3 - T_4) + (T_5 - T_6) > (T_3 - T_A)$$

## Power Plants

$$W_c = CP_a (T_2 - T_1)$$

$$W_{net} = W_{H.P.T} + W_{L.P.T} - W_c$$

$$W_{H.P.T} = CP_g (T_3 - T_4)$$

$$W_{L.P.T} = CP_g (T_5 - T_4)$$

For perfect reheating,  $T_3 = T_5$

$$\begin{aligned} Q_{add} &= Q_{add cc_1} + Q_{add cc_2} \\ &= CP_g (T_3 - T_2) + CP_g (T_5 - T_4) \end{aligned}$$

So, Efficiency for Reheat cycle

$$\eta_{reheat} = \frac{CP_g [(T_3 - T_4) + (T_5 - T_6)] - CP_a (T_2 - T_1)}{CP_g [(T_3 - T_2) + (T_5 - T_4)]}$$

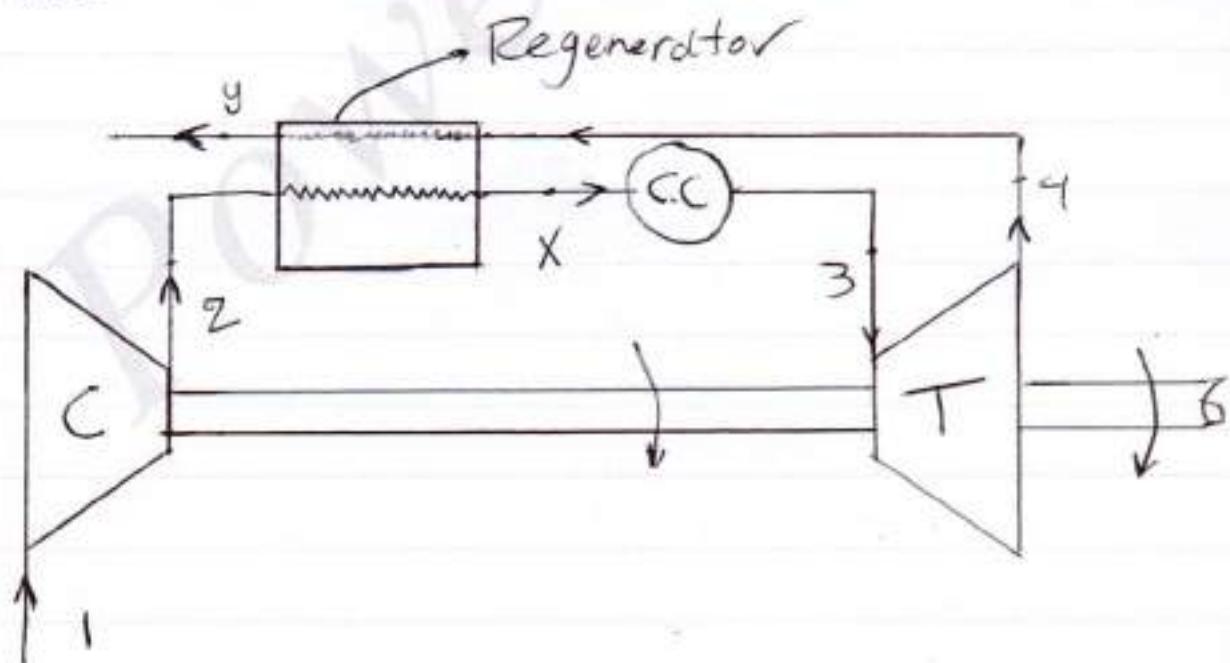
*Mohamed Ameen*

# Power Plants

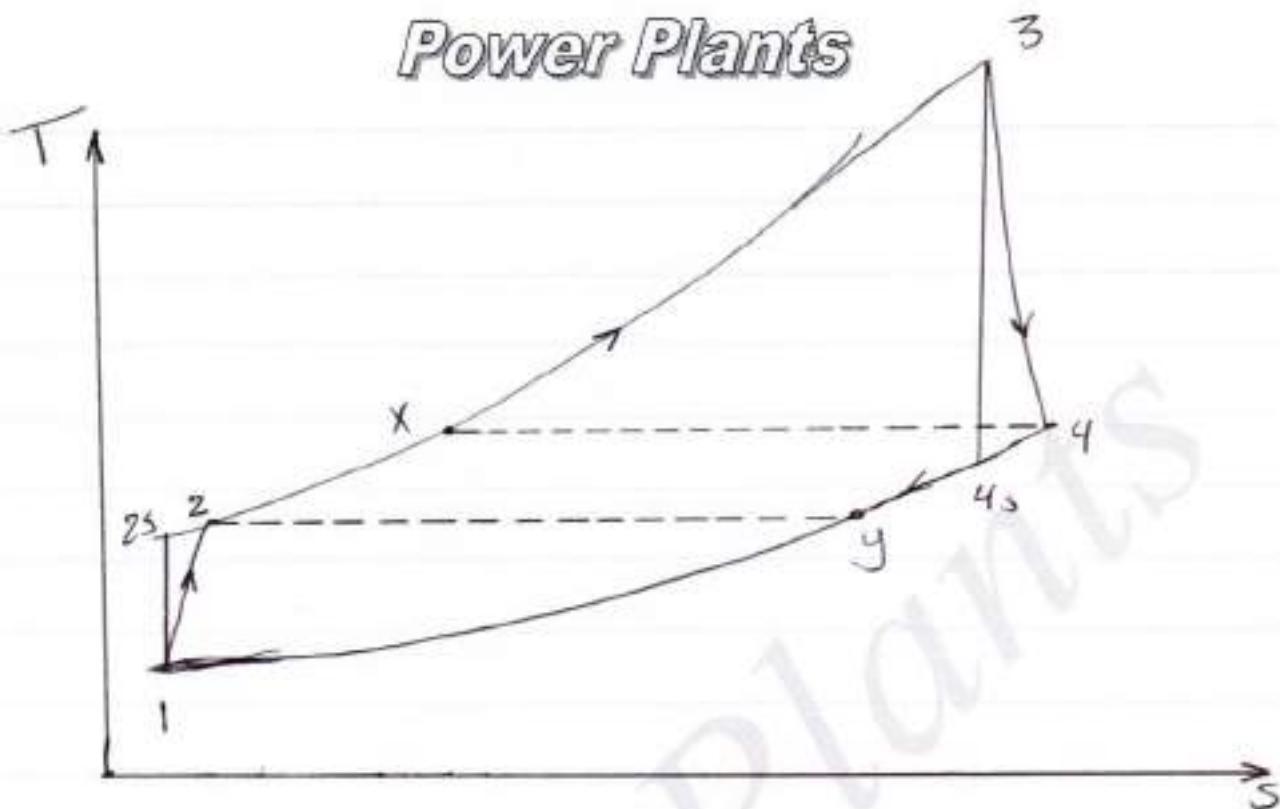
## Regeneration

The turbine exhaust temperature of a gas turbine is normally above ambient temperature. Accordingly, the hot turbine exhaust has a potential for using. One way of utilizing this potential is by means of a heat exchanger called a regenerator.

A regenerator allows the air exiting the compressor to be preheated before entering the combustor, thereby reducing the amount of fuel that must be burned in the combustor.



## Power Plants



The regenerator shown is a counterflow heat exchanger. Ideally, no frictional pressure drop occurs in either stream.

The turbine exhaust gas is cooled from state 4 to state y while the air exiting the compressor is heated from state 2 to state x.

If there is no losses in the heat exchanger, Then,

$$m_a C_{Pa} (T_x - T_2) = m_g C_{Pg} (T_4 - T_y)$$

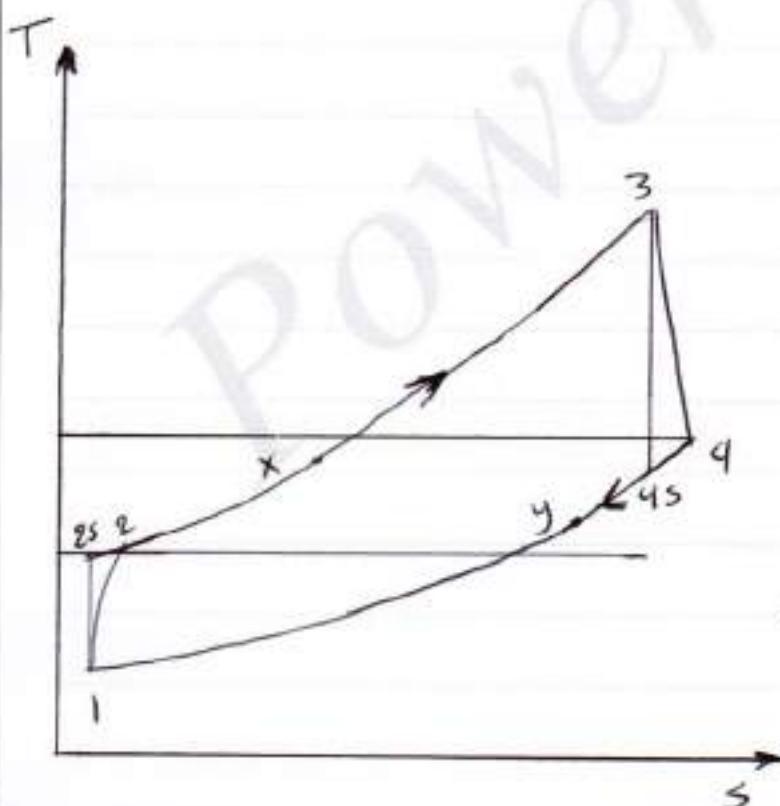
## Power Plants

which means the heat given up by the gases must be equal to the heat received by the air.

$$\begin{array}{l} T_4 = T_x \\ T_y = T_2 \end{array} \quad \left. \begin{array}{l} \\ \end{array} \right\} \text{For ideal heat exchanger}$$

In practice, this is impossible

$$T_4 > T_x, \quad T_y > T_2$$



## Power Plants

Heat exchanger effectiveness

It is defined as heat received by the air to the maximum possible heat which could be transferred from the gases in the heat exchanger

Therefore,

$$\text{Effectiveness } \epsilon = \frac{m_a C_p (T_x - T_2)}{m_a C_p (T_4 - T_2)}$$

Thermal ratio

$$\text{Thermal ratio} = \frac{\text{temperature rise of the air}}{\text{Max. temperature difference available}}$$

$$= \frac{T_x - T_2}{T_4 - T_2}$$

$$Q_{\text{add}} (\text{without HX}) = C_p g (T_3 - T_2)$$

$$Q_{\text{add}} (\text{with HX}) = C_p g (T_3 - T_x)$$

## Power Plants

It is obvious that

$$Q_{\text{add}}(\text{with HX}) < Q_{\text{add}}(\text{without HX})$$

$$W_{\text{net}} = CP_g(T_3 - T_4) - CP_a(T_2 - T_1)$$

$$\eta_{\text{regen.}} = \frac{CP_g(T_3 - T_4) - CP_a(T_2 - T_1)}{CP_g(T_3 - T_x)}$$

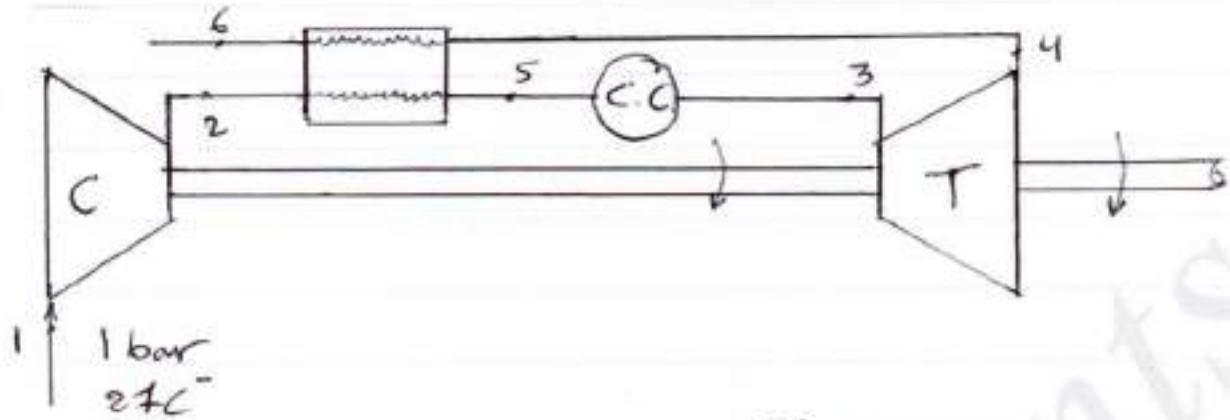
Ex/ In a gas turbine, air is supplied at 1 bar, 27°C into compressor having compression ratio of 8. The air leaving combustion chamber is heated upto 1100 K and expanded upto 1 bar. A heat exchanger having effectiveness of 0.8 is fitted at exit of turbine for heating the air before its inlet into combustion chamber. Assume that,

$$CP = 1.0032 \text{ kJ/(kg.K)} \text{ (for all processes)}$$

$$\gamma_a = 1.506, \gamma_g = 1.396$$

Determine : Specific work output of the plant  
thermal efficiency of the plant.  
Work ratio

# Power Plants



$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{1-1/6}{1+1/6}}$$

$$T_2 = 300 + (8)^{\frac{0.506}{1.506}}$$

$$T_2 = \frac{603.32}{100} K$$

$$T_3 = 1100 K$$

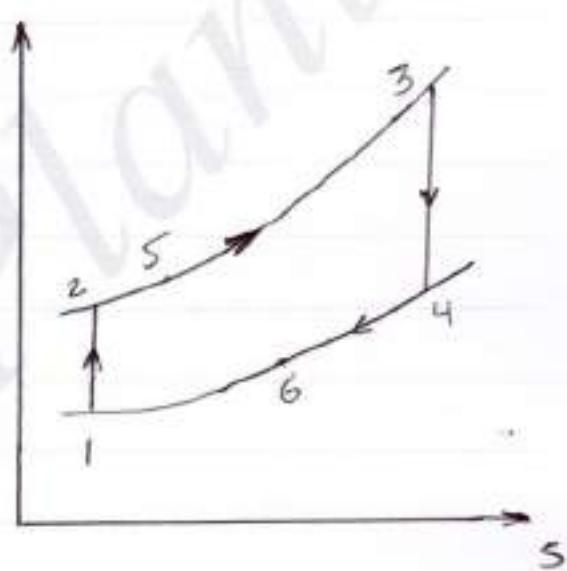
$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{1-1/6}{1+1/6}} \Rightarrow T_4 = \frac{1100}{(8)^{\frac{0.346}{1.346}}}$$

$$T_4 = 644.53 K$$

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

$$0.8 = \frac{T_5 - 603.32}{644.53 - 603.32}$$

$$\Rightarrow T_5 = 636.28 K$$



## Power Plants

$$W_c = CP_a(T_2 - T_1)$$
$$= 1.0032 (603.32 - 300) = 304.3 \text{ KJ/Kg}$$

$$W_t = CP_g(T_3 - T_4)$$
$$= 1.0032 (1100 - 644.53) = 456.93 \text{ KJ/Kg}$$

$$W_{net} = W_t - W_c = 152.6 \text{ KJ/Kg} \text{ (specific work output)}$$

$$\gamma_{\text{cycle}} = \frac{W_{net}}{Q_{add}}$$

$$Q_{add} = CP_g(T_3 - T_5)$$
$$= 1.0032 (1100 - 636.29) = 465.2 \text{ KJ/Kg}$$

$$\gamma = \frac{152.6}{465.2} = 32.81 \%$$

$$\text{Work/Energy ratio} = \frac{W_t - W_c}{W_t} = \frac{W_{net}}{W_t}$$
$$= \frac{152.6}{456.93} = 0.334$$

## Power Plants

Ex/ A 5000 kW gas turbine generating set operates with two compressor stages with intercooling between stages; the overall pressure ratio is 9/1. A HP turbine is used to drive the compressors and a LP turbine drives the generator. The temperature of gases at entry to the HP turbine is  $650^{\circ}\text{C}$  and the gases leaving the LP turbine are passed through a heat exchanger to heat the air leaving the HP stage compressor. Gases are reheated to  $650^{\circ}\text{C}$  after expansion in HP.T. The compressors have equal pressure ratios and intercooling is complete between stages. The air inlet temperature to the unit is  $15^{\circ}\text{C}$ .

Assume that:  $\gamma_c$  for both compressors is 0.8  
 $\gamma_t = \gamma_{+} =$  turbines is 0.85

The heat exchanger thermal ratio is 0.75.

A mechanical efficiency of 98% can be assumed for both the power shaft and the compressor/turbine shaft. Determine:-

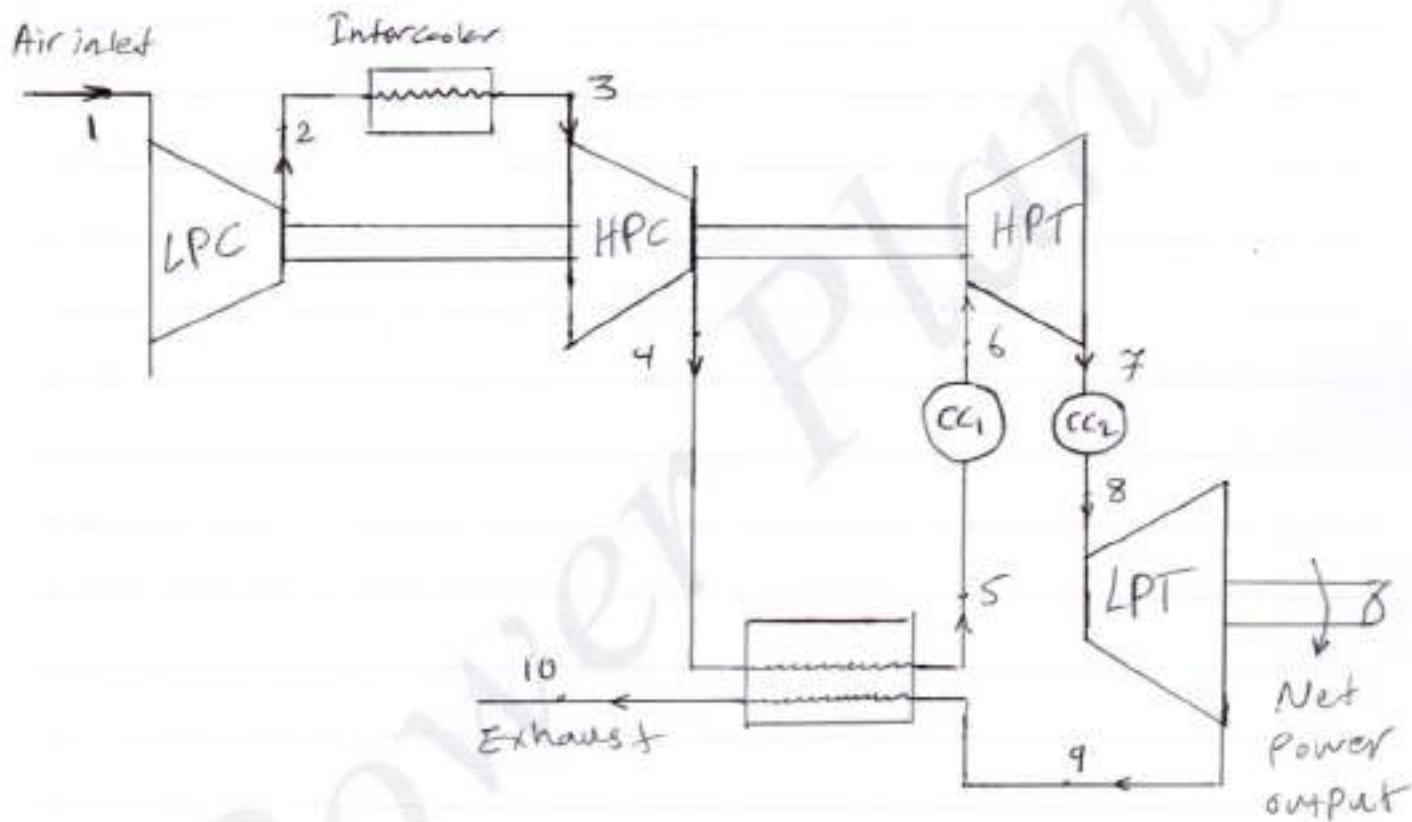
- (i) the cycle efficiency
- (ii) the work ratio
- (iii) the mass flow rate.

# Power Plants

For air take  $C_P = 1.005 \text{ KJ/Kg}$ ,  $\gamma = 1.4$

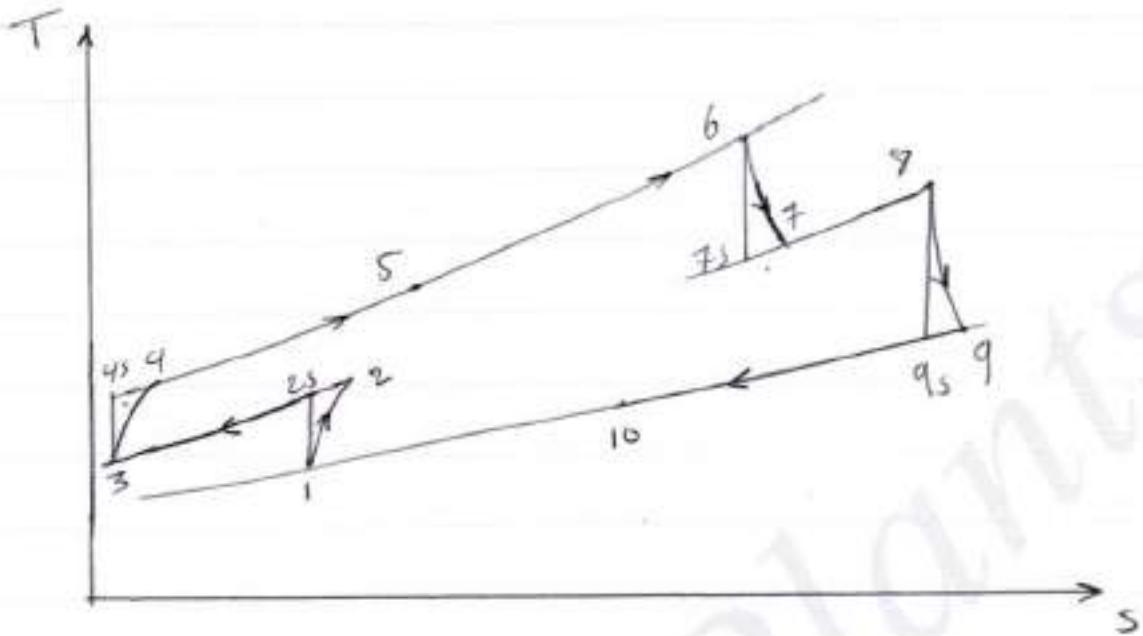
For gas take  $C_P = 1.15 \text{ KJ/Kg}$ ,  $\gamma = 1.333$

Solution :-



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## Power Plants



Since the pressure ratio and isentropic efficiency of each compressor is the same, then the work input required for each compressor is the same.

$$T_1 = T_3, \quad T_2 = T_4$$

$$\frac{T_{2s}}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}}$$

$$\frac{P_2}{P_1} = \sqrt{9} = 3$$

$$T_{2s} = 288 + (3)^{\frac{0.4}{1.4}} = 394 \text{ K}$$

## Power Plants

$$\eta_{LPC} = \frac{T_{2s} - T_1}{T_2 - T_1}$$

$$0.8 = \frac{T_{2s} - 288}{T_2 - 288} \Rightarrow T_2 = 420.5 \text{ K}$$

$$W_{EPC} = CP_a (T_2 - T_1)$$

$$= 1.005 (420.5 - 288)$$

$$= 133.1 \text{ kJ/kg} \quad [\text{For each compressor}]$$

$$T_{4s} = T_{2s} + 394$$

$$T_4 = T_2 = 420.5$$

The HP turbine is required to drive both compressors and to overcome mechanical friction

$$\begin{aligned} W_c &= W_{c1} + W_{c2} \\ &= 133.1 + 133.1 \\ &= 266.2 \text{ kJ/kg} \end{aligned}$$

$$W_{HPT} = \frac{W_c}{\eta_m} = \frac{266.2}{0.98} = 272 \text{ kJ/kg}$$

## Power Plants

Therefore,

$$272 = Cp_g (T_6 - T_7)$$

$$272 = 1.15 (923 - T_7)$$

$$T_7 = 686.5 \text{ K}$$

$$\eta_{H.P.T} = \frac{T_6 - T_7}{T_6 - T_{7s}}$$

$$0.85 = \frac{923 - 686.5}{923 - T_{7s}} \Rightarrow T_{7s} = 645 \text{ K}$$

$$\frac{T_6}{T_{7s}} = \left( \frac{P_6}{P_7} \right)^{\frac{1}{\gamma-1}} \quad \text{or} \quad \frac{P_6}{P_7} = \left( \frac{T_6}{T_{7s}} \right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{P_6}{P_7} = \left( \frac{923}{645} \right)^{\frac{1.333}{0.333}} = 4.19$$

$$\frac{P_6}{P_9} = \frac{P_6}{P_7} \cdot \frac{P_8}{P_9}, \quad P_7 = P_8$$

$$\frac{P_8}{P_9} = \frac{4.19}{4.19} = 2.147$$

## Power Plants

$$\frac{T_8}{T_{9s}} = \left( \frac{P_8}{P_9} \right)^{\frac{1}{\gamma}}$$

$$T_{9s} = \frac{923}{(2.147)^{\frac{1.333}{1.333}}} = 762.6 \text{ K}$$

$$\eta_{LPT} = \frac{T_8 - T_9}{T_8 - T_{9s}}$$

$$0.85 = \frac{923 - T_9}{923 - 762.9} \Rightarrow T_9 = 786.7 \text{ K}$$

$$\begin{aligned}\text{Net work output} &= CP_g (T_8 - T_9) * 0.98 \\ &= 1.15 (923 - 786.7) * 0.98 \\ &= 153.7 \text{ kJ/kg}\end{aligned}$$

$$\text{Thermal ratio} = \frac{T_5 - T_4}{T_9 - T_4}$$

$$0.75 = \frac{T_5 - 420.5}{786.7 - 420.5}$$

$$T_5 = 695.2 \text{ K}$$

## Power Plants

$$\text{Heat supplied} = CP_3(T_6 - T_5) + CP_9(T_8 - T_7)$$
$$= 1.05 [(923 - 695.2) + (923 - 686.5)]$$
$$= 534 \text{ kJ/kg}$$

$$\eta_{\text{cycle}} = \frac{W_{\text{net}}}{Q_{\text{added}}} = \frac{153.7}{534} = 28.8\%$$

$$\text{Work ratio} = \frac{\text{Work net}}{\text{gross work}}$$

$$\text{gross work} = W_{H.P.T} + W_{C.P.T}$$

$$= 272 + \frac{153.7}{0.98} = 429 \text{ kJ/kg}$$

$$\text{Work ratio} = \frac{153.7}{429} = 0.358$$

$$\text{Output} = m * W_{\text{net}}$$

$$m = \frac{5000}{153.7} = 32.6 \text{ kg/s}$$

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# Power Plants

## Sheet 2

Q<sub>1</sub>/ A gas turbine has an overall pressure ratio of 5 and maximum cycle temperature of 550 °C. The turbine drives the compressor and an electric generator, the mechanical efficiency of the drive being 97%. The ambient temperature is 20 °C and air enters the compressor at rate of 15 kg/s:  $\gamma_c = 80\%$ .

$$\gamma_t = 83\%$$

$$CP_a = 1.005, \gamma = 1.4$$

$$CP_g = 1.15, \gamma = 1.33$$

Determine : Power output, Cycle efficiency  
Work ratio

$$(660.3 \text{W}, 12.1\%, 0.169)$$

Q<sub>2</sub>/ In a marine gas turbine unit, a HP stage turbine drives the compressor, and a LP stage turbine drives the propeller through suitable gearing. The overall pressure ratio is 4/1, the mass flow rate is 60 kg/s

## Power Plants

Maximum temperature is  $650^{\circ}\text{C}$ , and the air intake conditions are 1.01 bar and  $25^{\circ}\text{C}$ .

$$\gamma_c = 0.8, \gamma_{H.P.T} = 0.83, \gamma_{L.P.T} = 0.85$$

The mechanical ~~losses~~ efficiency of both shafts is 98%. Calculate:

- (i) Pressure between turbine stages
- (ii) Cycle efficiency
- (iii) Shaft Power

$$(1.57 \text{ bar} / 14.9\% \times 4560 \text{ W})$$

Q3/ For the same unit in Q2, calculate cycle efficiency when a heat exchanger is fitted. Assume a thermal ratio of 0.75 ( $23.4\%$ )

Q4/ In a gas turbine generating set, two stages of compression are used with an intercooling between stages. The HP turbine drives the HP compressor, and LP turbine drive the LP compressor and the generator. The exhaust from the LP turbine passes through a heat exchanger which transfers heat to the air leaving the HP compressor. There is

## Power Plants

a reheat combustion chamber between turbine stages which rises the gas temperature to  $600^{\circ}\text{C}$ , which is also the gas temperature at entry to the HP turbine. The overall pressure ratio is 10/1, each compressor having the same pressure ratio, and the air temperature at entry to the unit is  $20^{\circ}\text{C}$ . The heat exchanger thermal ratio may be taken as 0.7 and intercooling is complete between compressor stages.

Assume isentropic efficiencies of 0.8 for both compressor stages, and 0.85 for turbine stages and 2% of the work of each turbine is used in overcoming friction. Calculate:

- (i) Power output for a mass flow rate of 115 kg/s
- (ii) Overall efficiency of the plant.

(14460 kW, 25.7%)