

# ESE 2019

UPSC ENGINEERING SERVICES EXAMINATION

## Main Examination

*Thoroughly  
Revised and  
Updated*

**19** Years  
Previous Solved Papers

# Mechanical Engineering

Topicwise **Conventional** Solved Questions

## Paper-I

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### **Mechanical Engineering Topicwise Conventional Solved Questions : Paper-1**

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## Director's Message

During the last few decades of engineering academics, India has witnessed geometric growth in engineering graduates. It is noticeable that the level of engineering knowledge has degraded gradually, while on the other hand competition has increased in each competitive examination including GATE and UPSC examinations. Under such scenario higher level efforts are required to take an edge over other competitors.



**B. Singh** (Ex. IES)

The objective of MADE EASY books is to introduce a simplified approach to the overall concepts of related stream in a single book with specific presentation. The topic-wise presentation will help the readers to study & practice the concepts and questions simultaneously.

The efforts have been made to provide close and illustrative solutions in lucid style to facilitate understanding and quick tricks are introduced to save time.

*Following tips during the study may increase efficiency and may help in order to achieve success.*

- Thorough coverage of syllabus of all subjects
- Adopting right source of knowledge, i.e. standard reading text materials
- Develop speed and accuracy in solving questions
- Balanced preparation of Paper-I and Paper-II subjects with focus on key subjects
- Practice online and offline modes of tests
- Appear on self assessment tests
- Good examination management
- Maintain self motivation
- Avoid jumbo and vague approach, which is time consuming in solving the questions
- Good planning and time management of daily routine
- Group study and discussions on a regular basis
- Extra emphasis on solving the questions
- Self introspection to find your weaknesses and strengths
- Analyze the exam pattern to understand the level of questions
- Apply shortcuts and learn standard results and formulae to save time

**B. Singh** (Ex. IES)

CMD, MADE EASY Group

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# 4

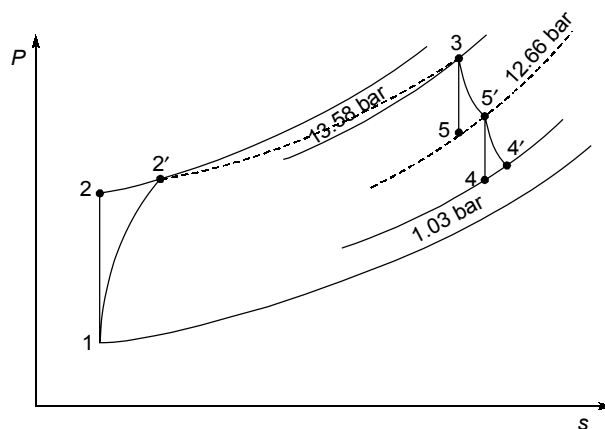
# Power Plant Engineering

**Revised Syllabus of ESE:** Rankine and Brayton cycles with regeneration and reheat, Fuels and their properties, Flue gas analysis, Boilers, Steam turbines and other power plant components like condensers, air ejectors, electrostatic precipitators and cooling towers – their theory and design, types and applications.

## 1. Gas Turbine

- Q.1 A simple open cycle gas turbine has a compressor turbine and a free power turbine. It develops electrical power output of 250 MW. The cycle takes in air at 1 bar and 288 K. The total compressor pressure ratio is 14. The turbine inlet temperature is 1500 K. The total to total isentropic efficiency of compressor and turbine at 0.86 and 0.89, respectively. The mechanical efficiency of each shaft is 0.98. Combustion efficiency is 0.98 while combustor pressure loss is 3% of compressor delivery pressure. The exhaust pressure loss is 0.03 bar. Alternator efficiency is 0.98. Take calorific value of fuel equal to 42,000 kJ/kg,  $c_{pa} = 1.005$  kJ/kgK and  $c_{pg} = 1.15$  kJ/kgK. Calculate the following: (i) air-fuel ratio, (ii) specific work output, (iii) specific fuel consumption, (iv) mass flow rate of air, (v) cycle thermal efficiency. [20 marks : 2004]

Solution:



$$\text{Electrical power} = 250 \text{ MW}$$

$$\begin{aligned} \therefore \text{Power output at turbine shaft} &= \frac{\text{Electrical power}}{\text{alternator efficiency} \times \text{mechanical efficiency}} \\ &= \frac{250}{0.98 \times 0.98} \Rightarrow 260.308 \text{ MW} \end{aligned}$$

$$T_2 = T_1(14)^{\frac{\gamma-1}{\gamma}} = 288(14)^{\frac{0.4}{1.4}} = 612.15 \text{ K}$$

$$T_2' = T_1 + \frac{(T_2 - T_1)}{\eta_c} = 288 + \frac{(612.15 - 288)}{0.86} = 664.92 \text{ K}$$

In combustion chamber:

$$\dot{m}_a c_{pa} T_2' + \dot{m}_f \cdot \text{c.v.} \times 0.98 = (\dot{m}_a + \dot{m}_f) c_{pg} \cdot T_3$$

$$\frac{\dot{m}_f}{\dot{m}_a} (\text{c.v.} \times 0.98 - c_{pg} T_3) = (c_{pg} T_3 - c_{pa} T_2')$$

$$\frac{\dot{m}_f}{\dot{m}_a} = \frac{1.15 \times 1500 - 1.005 \times 664.92}{(42000 \times 0.98 - 1.15 \times 1500)} = 0.02679$$

Compressor is run by compressor turbine.

$$\frac{\dot{m}_a c_{pa} (T_2' - T_1)}{\eta_{\text{shaft}}} = (\dot{m}_a + \dot{m}_f) c_{pg} (T_3 - T_5')$$

$$\frac{1.005 \times (664.92 - 288)}{0.98} = (1 + 0.02679) \times 1.15 (1500 - T_5')$$

$$T_5' = 1172.651$$

$$\eta_t = \frac{T_3 - T_5'}{T_3 - T_5}$$

$$0.89 = \frac{1500 - 1172.651}{1500 - T_5}$$

$$T_5 = 1132.193$$

$$\frac{T_3}{T_5} = (r_p')^{\frac{0.33}{1.33}}$$

$$\frac{1500}{1132.193} = (r_p')^{\frac{0.33}{1.33}}$$

$$r_p' = 1.0722$$

$$\frac{p_3}{p_5} = 1.0722 \Rightarrow p_5 = 12.665 \text{ bar}$$

During process 3 to 4

$$T_4 = \frac{T_5'}{\left(\frac{12.66}{1.03}\right)^{\frac{0.33}{1.33}}} = 629.242 \text{ K}$$

From turbine efficiency

$$\eta_t = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$T_4' = 1500 - 0.89 (1500 - 629.242) = 725.025 \text{ K}$$

$$\text{Turbine shaft power} = (\dot{m}_a + \dot{m}_f) c_{pg} (T_5' - T_4')$$

$$260.3082 \times 10^3 = \dot{m}_a (1 + 0.02679) \times 1.15 \times (1172.651 - 725.025)$$

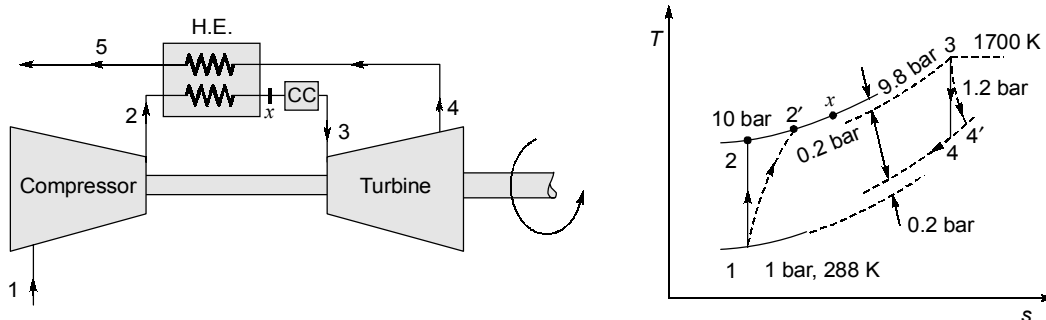
$$\dot{m}_a = 492.485 \text{ kg/s}$$

$$\dot{m}_f = 0.02679 \times 492.485 \text{ kg/s} = 13.1936 \text{ kg/s}$$

- (ii) Specific work output =  $\frac{\text{power output}}{\text{mass flow rate of air}} = \frac{250 \times 10^3}{492.485} = 507.629 \text{ kJ/kg}$
- (iii) Specific fuel consumption =  $\frac{\dot{m}_f}{\text{power output}} = \frac{13.1936 \times 3600}{250 \times 10^3} = 0.18998 \text{ kg/kWh}$
- (iv) Mass flow rate of the air,  $\dot{m}_a = 492.485 \text{ kg/s}$
- (v) Thermal efficiency of cycle,  $\eta_{th} = \frac{\text{Net output}}{\text{Heat supplied}} \times 100 = \frac{250 \times 10^3}{\dot{m}_f \times \text{c.v.} \times 0.98}$   
 $= \frac{250 \times 10^3 \times 100}{13.1936 \times 42000 \times 0.98} = 46.036\%$

**Q.2** An open cycle gas turbine employs a regenerative arrangement. The air enters the compressor at 1 bar and 288 K and is compressed to 10 bar with a compression efficiency of 85%. The air is heated in regenerator and then in combustion chamber till its temperature is raised to 1700 K and during the process the pressure falls by 0.2 bar. The air is then expanded in the turbine and passes to regenerator which has 75% effectiveness and cause a pressure drop of 0.2 bar. The isentropic efficiency of turbine is 86%. By sketching the gas turbine system and showing the process on  $T$ - $s$  diagram. Calculate thermal efficiency and power output if mass flow rate of air is 100 kg/s. Take mechanical and alternator efficiency as 98%,  $c_{pg} = 1.15 \text{ kJ/kgK}$  and  $c_{pa} = 1.005 \text{ kJ/kgK}$  [20 marks : 2005]

**Solution:**



Given data: Regenerative arrangement

$P_1 = 1 \text{ bar}$ ;  $T_1 = 288 \text{ K}$ ;  $P_2 = 10 \text{ bar}$ , Maximum temperature = 1700 K

Effectiveness of regenerator,  $\epsilon = 75\%$ ,  $\eta_t = 86\%$ ,  $\eta_{\text{thermal}} = ?$ , Power output = ?, Mass = 100 kg/s

$\eta_m = 98\%$ ,  $\eta_g = 98\%$ ,  $c_{pg} = 1.15 \text{ kJ/kgK}$ ,  $c_{pa} = 1.005 \text{ kJ/kgK}$

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

$$\frac{T_2}{288} = \left( \frac{10}{1} \right)^{\frac{0.4}{1.4}}$$

$$T_2 = 556.04 \text{ K}$$

$$\eta_c \Rightarrow 0.85 = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.85 = \frac{556.04 - 288}{T_2' - 288}$$

$$T_2' = 603.24 \text{ K}$$

also

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

$$\frac{1700}{T_4} = \left(\frac{9.8}{1.2}\right)^{\frac{\gamma-1}{\gamma}} \quad \left[ \begin{array}{l} \therefore R = c_{pg} - c_{vg}, 0.287 = 1.15 - c_{vg} \\ c_{vg} = 0.863 \\ \therefore \gamma = \frac{c_{pg}}{c_{vg}} = 1.33 \end{array} \right]$$

$$\frac{1700}{T_4} = \left(\frac{9.8}{1.2}\right)^{\frac{0.33}{1.33}}$$

$$T_4 = 1009.6 \text{ K}$$

But

$$\eta_t = 0.86 = \frac{T_3 - T'_4}{T_3 - T_4} \Rightarrow \frac{1700 - T'_4}{1700 - 1009.6} = 0.86$$

$$T'_4 = 1106.26 \text{ K}$$

So,

$$\epsilon = 0.75$$

$$0.75 = \frac{T_x - T_2}{T_4 - T_2} = \frac{T_x - 603.43}{1106.26 - 603.34}$$

$$T_x = 980.53 \text{ K}$$

So,

$$W_{\text{compressor}} = \dot{m}_{\text{air}} \times (c_p)_{\text{air}} \times (T_2 - T_1) = \dot{m}_{\text{air}} \times 1.005 \times (603.34 - 288)$$

$$= \dot{m}_{\text{air}} \times 316.91 \text{ kJ/kg}$$

$$W_{\text{turbine}} = (\dot{m}_a + \dot{m}_f) \times 1.15 \times (1700 - 1106.26)$$

$$= 682.8 (\dot{m}_a + \dot{m}_f) \text{ kJ/kg}$$

But,

$$\eta_{\text{mechanical}} = 98\%$$

$$\eta_{\text{alternator}} = 98\%$$

Hence net work done by compressor

$$= \frac{316.9 \times \dot{m}_{\text{air}}}{0.98} = 323.37 \dot{m}_{\text{air}}$$

Net work done by Turbine

$$= 682.8 (\dot{m}_a + \dot{m}_f) \times 0.98 = 669.14 (\dot{m}_a + \dot{m}_f)$$

Given,

$$\dot{m}_{\text{air}} = 100 \text{ kg/s}$$

$$\dot{m}_f = ?$$

Heat supplied in the combustion chamber:

$$Q_s = (\dot{m}_f \times C.V.) \times \eta_{\text{combustion}}$$

Also

$$= (\dot{m}_a + \dot{m}_f) c_{pg} T_3 - \dot{m}_a c_{pa} T_x$$

$$\text{(Assume } C.V. = 42000 \text{ kJ/kg)}$$

$$(\dot{m}_f \times C.V.) \times \eta_{\text{combustion}} = (\dot{m}_a + \dot{m}_f) \times 1.15 \times 1700 - 100 \times 1.005 \times 980.53$$

$$\dot{m}_f \times 42000 \times 0.85 - \dot{m}_f \times 1.15 \times 1700 = 100 \times 1.15 \times 1700 - 100 \times 1.005 \times 980.53$$

$$\dot{m}_f = 2.8732 \text{ kg/s}$$

$\therefore$

$$\left(\frac{\text{Air}}{\text{Fuel}}\right)_{\text{ratio}} = \left(\frac{100}{2.8732}\right) = 34.804$$



$$(i) \quad \eta_{\text{thermal}} = \frac{\text{Net work done}}{\text{Heat supplied}} = \frac{W_T - W_C}{\dot{m}_F \times C.V.}$$

$$= \left( \frac{669.14 \times 102.42 - 323.37 \times 100}{2.8732 \times 42000} \right) \times 100\% = 30.246\%$$

$$(ii) \quad \text{Power output} = W_{\text{Turbine}} - W_{\text{compressor}}$$

$$= 669.14(\dot{m}_a + \dot{m}_f) - 323.37 \dot{m}_{\text{air}}$$

$$= 669.14(102.8732) - 323.37 \times 100 = 36196 \text{ kW} = \mathbf{36.499 \text{ MW}}$$

Q.3 Air enters the compressor of a gas turbine at 100 kPa, 300 K with a volumetric flow rate of 5 m<sup>3</sup>/s. The air is compressed in two stages to 1200 kPa with intercooling to 300 K between stages at a pressure of 350 kPa. The turbine inlet temperature is 1400 K and the expansion occurs in two stages with reheat to 1340 K between the stages at a pressure of 350 kPa. The compressor and turbine stage efficiencies are 87% and 85% respectively. Determine

- (i) the thermal efficiency of the cycle,
- (ii) the back work ratio,
- (iii) the net power developed in kW.

Draw the schematic diagram of the cycle and indicate the process on T-s diagram. Assume effectiveness of the regenerator as 80%. Assume  $c_p = 1.0045 \text{ kJ/kgK}$  for air and gas.

[20 marks : 2006]

Solution:

Given data:  $P_1 = 100 \text{ kPa}$ ;  $P_2 = 350 \text{ kPa}$ ;  $P_4 = 1200 \text{ kPa}$ ;  
 $T_1 = T_3 = 300 \text{ K}$ ;  $T_5 = 1400 \text{ K}$ ;  $T_7 = 1340 \text{ K}$ ;  $\eta_c = 0.87$ ;  
 $\eta_t = 0.85$ ;  $\epsilon = 0.8$

$$\frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} = \left( \frac{350}{100} \right)^{0.4}$$

$$T_2 = 300 \times 1.43 = 429.11 \text{ K}$$

Now 
$$\frac{T_2 - T_1}{T_2' - T_1} = 0.87 \eta_c$$

$$\Rightarrow \frac{429.11 - 300}{T_2' - 300} = 0.87 = \eta_c$$

$$T_2' = 448.4 \text{ K}$$

$$\frac{T_4}{T_3} = \left( \frac{P_4}{P_3} \right)^{0.4}$$

$$\Rightarrow T_4 = 300 \times 1.422 = 426.6 \text{ K}$$

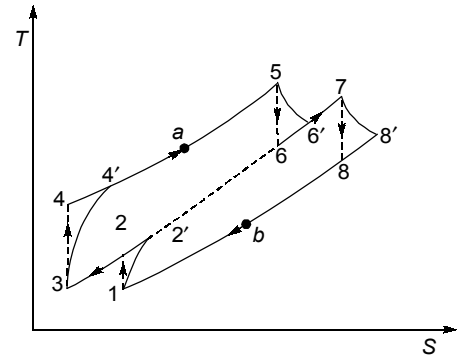
$$\frac{T_4 - T_3}{T_4' - T_3} = 0.87 = \eta_c$$

$$\Rightarrow \frac{426.6 - 300}{T_4' - 300} = 0.87$$

$$T_4' = 445.50 \text{ K}$$

Now  $T_5 = 1400 \text{ K}$

$$\frac{T_6}{T_5} = \left( \frac{P_6}{P_5} \right)^{0.4} = \left( \frac{350}{1200} \right)^{0.4} = 0.703$$



$$T_6 = 1400 \times 0.703$$

$$= 984.55 \text{ K}$$

$$\frac{T_5 - T_6'}{T_5 - T_6} = 0.85 = \eta_t$$

$$\frac{1400 - T_6'}{1400 - 984.55} = 0.85$$

$$T_6' = 1046.87 \text{ K}$$

$$T_7 = 1340 \text{ K}$$

$$\frac{T_8}{T_7} = \left(\frac{100}{350}\right)^{0.4} \Rightarrow T_8 = 936.82 \text{ K}$$

$$\frac{T_7 - T_8'}{T_7 - T_8} = 0.85 = \eta_t$$

$$\Rightarrow T_7 - T_8' = 342.703 \text{ K}$$

$$T_8' = 997.30 \text{ K}$$

$$\dot{m} = \rho \dot{v}$$

$$\rho = \frac{P}{RT} = \frac{100 \times 10^3}{287 \times 300} = 1.161 \text{ kg/m}^3$$

$$\begin{aligned} \text{Work done by turbine} &= \dot{m} c_p (T_5 - T_6') + \dot{m} c_p (T_7 - T_8') \\ &= 1.161 \times 5 \times 1.005 \times [(1400 - 1046.87) + (1340 - 997.3)] \\ &= 1.161 \times 5 \times 1.005 \times [353.13 + 342.703] = 4059.50 \text{ kJ/s} \\ &= 4059.507 \text{ kW} \end{aligned}$$

$$\begin{aligned} \text{Work done by compressor} &= \dot{m} c_p (T_2' - T_1) + \dot{m} c_p (T_4' - T_3) \\ &= \dot{m} c_p [(448.4 - 300) + (445.50 - 300)] \\ &= 1.161 \times 5 \times 1.005 [148.4 + 145.50] = 1.161 \times 1.005 \times 293.92 \times 5 \\ &= 1714.737 \text{ kJ} \end{aligned}$$

$$\text{Now for regeneration} \quad \varepsilon = \frac{T_a - T_4'}{T_8' - T_4'}$$

$$0.8 = \frac{T_a - 445.52}{997.29 - 445.50}$$

$$T_a = 886.94 \text{ K}$$

$$\begin{aligned} \text{Heat supplied} &= Q = \dot{m}_a c_p (T_5 - T_a) + \dot{m}_a c_p (T_7 - T_6') \\ &= 1.161 \times 5 \times 1.005 [1400 - 886.94 + 1340 - 1046.87] \\ &= 4703.3 \text{ kW} \end{aligned}$$

$$(i) \quad \text{Thermal efficiency} = \frac{W_T - W_c}{Q_s} = \frac{4059.50 - 1714.73}{4703.3} = \mathbf{49.85\%}$$

$$(ii) \quad \text{Work ratio} = \frac{\text{Net work done}}{\text{work done by turbine}} = \frac{4059.50 - 1714.73}{4059.50} = \mathbf{0.5776}$$

$$(iii) \quad \text{Back work ratio} = \frac{\text{Work done by compressor}}{\text{Work done by turbine}} = \frac{1714.73}{4059.50} = \mathbf{0.4223}$$

$$(iv) \quad \text{Net power developed: } P = 4059.50 - 1714.73 = \mathbf{2344.77 \text{ kW}}$$

Q.4 In an open-cycle gas turbine plant, the air enters at 15°C and 1 bar, and is compressed in a compressor to a pressure ratio of 15. The air from the exit of compressor is first heated in a heat exchanger which is 75% efficient by turbine exhaust gas and then in a combustor to a temperature of 1600 K. The same gas expands in a two stage turbine such that the expansion work is maximum. The exhaust gas from h.p. turbine is reheated to 1500 K and then expands to l.p. turbine. The isentropic efficiencies of compressor and turbine may be taken as 86% and 88% respectively. The mechanical efficiencies for compressor and turbine are 97% each. The alternator efficiency is 98%. The output of turbo-alternator is 250 MW. Work out the following:

- Sketch the system and show the process on  $T$ - $s$  diagram.
- The cycle thermal efficiency.
- The work ratio.
- The specific power output.
- The mass flow rate of air.

[15 marks : 2007]

Solution:

Given data:

$$T_1 = 288 \text{ K}, P_1 = 1 \text{ bar}, \frac{P_2}{P_1} = 15$$

Effectiveness = 75%, Maximum temperature = 1600 K

Entry temperature of second stage

Turbine = 1500 K;  $\eta_c = 86\%$ ,  $\eta_t = 88\%$ ,

$(\eta_{\text{mechanical}})_{\text{turbine}} = (\eta_{\text{mechanical}})_{\text{compressor}} = 97\%$

$\eta_{\text{alternator}} = 98\%$ ,

Output of turbo alternator = 250 MW

$$\frac{T_{2s}}{T_1} = \left( \frac{P_{2s}}{P_1} \right)^{\frac{\gamma-1}{\gamma}}; \quad \frac{T_{2s}}{288} = \left( \frac{15}{1} \right)^{\frac{0.4}{1.4}}$$

$$T_{2s} = 624.33 \text{ K}$$

$$\eta_{\text{compressor}} = 0.86 = \frac{T_{2s} - T_1}{T_2 - T_1} = \frac{624.33 - 288}{T_2 - 288}$$

$$T_2 = 679 \text{ K}$$

$$P_4 = P_5 = \sqrt{P_2 P_1}$$

$$P_5 = P_4 = \sqrt{15}$$

$$P_5 = P_4 = 3.87 \text{ bar}$$

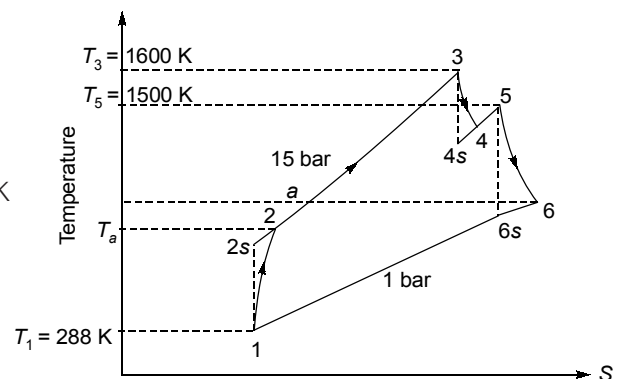
(3 – 4s) and (5 – 6s)

$$\frac{T_3}{T_{4s}} = \left( \frac{P_3}{P_{4s}} \right)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore \frac{1600}{T_{4s}} = \left( \frac{15}{3.87} \right)^{\frac{0.4}{1.4}} \Rightarrow T_{4s} = 1086.6 \text{ K}$$

$$\frac{T_5}{T_{6s}} = \left( \frac{P_5}{P_{6s}} \right)^{\frac{\gamma-1}{\gamma}}$$

$$\frac{1500}{T_{6s}} = \left( \frac{3.87}{1} \right)^{\frac{0.4}{1.4}} \Rightarrow T_{6s} = 1018.9 \text{ K}$$



$$\begin{aligned} \text{At} \quad \eta_t &= 88\% \\ \eta_t &= 0.88 = \left( \frac{T_3 - T_4}{T_3 - T_{4s}} \right) \\ 0.88 &= \frac{1600 - T_4}{1600 - 1086.6} \Rightarrow T_4 = 1148.2 \text{ K} \\ \frac{T_5 - T_6}{T_5 - T_{6s}} &= 0.88 \\ 0.88 &= \frac{1500 - T_6}{1500 - 1018.9} \Rightarrow T_6 = 1076.6 \text{ K} \\ \text{Effectiveness} &= 0.75 = \frac{T_a - T_2}{T_6 - T_2} \\ 0.75 &= \frac{T_a - 679}{1076.7 - 679} \\ T_a &= 977.24 \text{ K} \\ \therefore W_{\text{compressor}} &= \frac{c_p(T_2 - T_1)}{\eta_{\text{mech}}} = \frac{1.005(679 - 288)}{0.97} = 405.10 \text{ kJ/kg} \\ W_{\text{Turbine}} &= [c_p(T_3 - T_4) + c_p(T_5 - T_6)] \eta_{\text{mech}} \\ &= [1.005(1600 - 1148.2) + 1.005(1500 - 1076.6)] \times 0.97 = 853.18 \text{ kJ/kg} \end{aligned}$$

Heat supplied:

$$\begin{aligned} \therefore q_{\text{supplied}} &= mc_p(T_3 - T_a) + mc_p(T_5 - T_4) \\ &= 1 \times 1.005 [(1600 - 977.24) + (1500 - 1148.3)] \\ &= 979.33 \text{ kJ/kg} \\ \text{(ii)} \quad \eta &= \frac{W_{\text{net}}}{Q_s} = \frac{W_T - W_C}{Q_s} = \frac{853.18 - 405.10}{979.33} = 0.4575 = \mathbf{45.75\%} \\ \text{(iii)} \quad \text{Work ratio} &= \frac{\text{Net work done}}{\text{work done by turbine}} = \frac{853.18 - 405.10}{853.18} = \mathbf{0.5252 = 52.52\%} \\ \text{(iv)} \quad \text{Specific power output} &= \text{Net work done} = 853.18 - 405.10 = 448.08 \text{ kJ/kg} \\ \text{(v)} \quad \text{Mass flow rate} \quad \frac{250 \times 10^3}{\eta_{\text{alternator}}} &= \dot{m} \times \text{net work done} \\ \frac{250 \times 10^3}{0.98} &= \dot{m} \times 448.08 \\ \dot{m} &= \mathbf{569.32 \text{ kg/s}} \end{aligned}$$

**Q.5** A two stage compression with intercooling in between stages and a single stage turbine with regeneration is employed in an open cycle gas turbine plant. Air at 1 bar and 15°C enters the compressor and the maximum pressure ratio is 5 and the maximum temperature in the cycle is 800°C. The rate of air flow through the cycle is 250 kg/sec and the calorific value of the fuel used is 42 MJ/kg. The isentropic efficiencies of both the compressors is 0.8 and the effectiveness of the regenerator is 0.7, and the isentropic efficiency of the turbine is 0.9. The combustion efficiency is 0.95, the mechanical efficiency is 0.96 and the generator efficiency is 0.75. Take  $c_p$  of air = 1.005 kJ/kgK and  $\gamma = 1.4$  and for gases  $c_p = 1.08$  kJ/kgK and  $\gamma = 1.33$ .

Assuming perfect intercooling and neglecting pressure and heat losses, determine

- (i) the air fuel ratio
- (ii) the cycle efficiency
- (iii) the power supplied by the plant
- (iv) the specific fuel consumption and the fuel consumption per hour

[15 marks : 2008]

**Solution:**

Given:  $P_1 = 1$  bar, Maximum pressure ratio = 5 bar,  $T_1 = 288$  k,  $T_5 = 800^\circ\text{C} = 1073$  K

$\dot{m}_a = 250$  kg/s, C.V. = 42 MJ/kg,  $\eta_{\text{combustion}} = 0.95$ ;  $\eta_c = 0.8$ ,  $\eta_{\text{mechanical}} = 0.96$ ,  $\eta_t = 0.9$

$\eta_{\text{generator}} = 0.75$ ;  $\epsilon = 0.7$

For air  $c_{pa} = 1.005$ ;  $\eta = 1.4$

For gases  $c_{pg} = 1.08$ ;  $\eta = 1.33$

1 - 2 = 1st stage compression

3 - 4 = 2nd stage compression

5 - 6 = Turbine works

2 - 3 = Intercooling process

4 - a = Heat provided by Regenerator

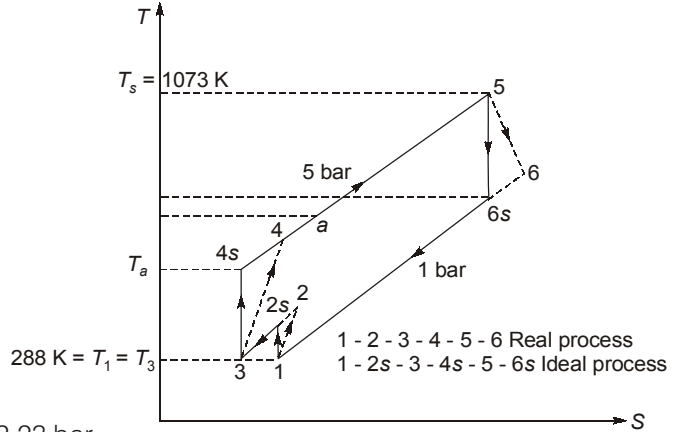
a - 5 = Actual heat addition combustion process

Due to perfect intercooling

$$P_2 = P_3$$

$$= \sqrt{P_1 P_4} = \sqrt{1 \times 5} = 2.23 \text{ bar}$$

$$T_1 = T_3 = 288 \text{ K}$$



**Case-II:**

Isentropic compression process

$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}; \quad \frac{T_{2s}}{288} = \left(\frac{2.23}{1}\right)^{\frac{0.4}{1.4}}$$

$$T_{2s} = 362.14 \text{ K}$$

$$\eta_c = 0.8 = \frac{T_{2s} - T_1}{T_2 - T_1} \Rightarrow \frac{362.14 - 288}{T_2 - 288} = 0.8$$

$$T_2 = 380.67 \text{ K}$$

∴ Similarly (3 - 4s) → Isentropic process

$$\frac{T_{4s}}{T_3} = \left(\frac{P_{4s}}{P_3}\right)^{\frac{\gamma-1}{\gamma}}; \quad \frac{T_{4s}}{288} = \left(\frac{5}{2.23}\right)^{0.4/1.4}$$

$$T_{4s} = 362.14 \text{ K}$$

$$\eta_c = 0.8 = \left(\frac{T_{4s} - T_3}{T_4 - T_3}\right) = 0.8 = \frac{362.14 - 288}{T_4 - 288}$$

$$T_4 = 380.67 \text{ K}$$

∴ Now (5 - 6s) → Isentropic expansion process

$$\frac{T_5}{T_{6s}} = \left(\frac{P_5}{P_{6s}}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{5}{1}\right)^{\frac{0.33}{1.33}}$$

$$\frac{1073}{T_{6s}} = \left(\frac{5}{1}\right)^{\frac{0.33}{1.33}}$$

$$T_{6s} = 719.73 \text{ K}$$

$$\eta_t = 0.9 = \left(\frac{T_5 - T_6}{T_5 - T_{6s}}\right) \Rightarrow 0.9 = \left(\frac{1073 - T_6}{1073 - 719.73}\right)$$

$$T_6 = 755.05 \text{ K}$$

$$\text{So, effectiveness} \quad 0.7 = \frac{T_a - T_4}{T_6 - T_4} = \frac{T_a - 380.67}{755.05 - 380.67}$$

$$T_a = 642.736 \text{ K}$$

$$\begin{aligned} \text{Work done by compressor} &= W_{CI} + W_{CII} = \dot{m}_a c_{\text{pair}} (T_2 - T_1) + \dot{m}_a c_{\text{pair}} (T_4 - T_3) \\ &= \dot{m}_a c_{\text{pair}} [(T_2 - T_1) + (T_4 - T_3)] = 250 \times 1.005 [(380.67 - 288) + (380.67 - 288)] \\ &= 46566.675 \text{ kW} \end{aligned}$$

$$\eta_{\text{mech}} = 0.96$$

$$\text{Net work done by compressor} = \frac{46566.675}{0.96} = 48506.95 \text{ kW}$$

$$\text{Heat supplied} = \dot{m}_f \times C.V. \times 10^6 \times \eta_{\text{combustion}} = \dot{m}_f \times 42000 \times 0.95$$

By energy balance equation, the

$$\dot{m}_f \times C.V. \times \eta_{\text{combustion}} = (\dot{m}_a + \dot{m}_f) c_{pg} T_5 - \dot{m}_a c_{pa} (T_a)$$

$$\dot{m}_f \times 42000 \times 0.95 = (250 + \dot{m}_f) \times 1.08 \times 1073 - 250 \times 1.005 \times 642.736$$

$$\therefore 1158.8 \dot{m}_f + 128222.58 = \dot{m}_f \times 42000 \times 0.95$$

$$\dot{m}_f = 3.3097 \text{ kg/s}$$

$$\begin{aligned} W_{\text{turbine}} &= (\dot{m}_a + \dot{m}_f) c_{pg} (T_6 - T_5) = (250 + 3.3097) \times 1.08 (1073 - 755.05) \\ &= 86.983 \text{ MW} \end{aligned}$$

$$W_{\text{net}} = W_T - W_C = 86.983 - 48.506 = 38.477 \text{ MW}$$

$$(i) \quad \frac{\dot{m}_a}{\dot{m}_f} = \frac{250}{3.3097} = 75.5355$$

$$(ii) \quad \text{cycle efficiency} = \frac{W_{\text{net}}}{Q_s} = \frac{38.477}{\dot{m}_f \times \eta_{\text{comb}} \times C.V.} = \frac{38.477}{3.3027 \times 0.95 \times 42} \approx 0.29 = 29.20\%$$

$$(iii) \quad \text{Power supplied by plant} = W_{\text{net}} \times \eta_{\text{generator}} = 38.477 \times 0.75 = 28.857 \text{ MW}$$

$$(iv) \quad \text{Specific fuel consumption} = \frac{\dot{m}_f}{W_{\text{net}}} = \frac{3.3097 \times 3600}{38.477 \times 10^3} = 0.3096 \text{ kg/kWh}$$

**Q.6 Define air rate, specific power and the cycle work ratio in a gas turbine. What is the significance of these parameters? [5 marks : 2012]**

**Solution:**

**Air Rate:** Mass of air supplied per second and in gas turbine cycle for combustion of fuel is called as air rate.

**Specific Power:** Specific power is defined as power output per unit mass of air supplied/sec.

**Work Ratio:** In gas turbine cycle work is produced in turbine at the same time work is also consumed in compressor. So network output is given as

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

Work ratio is ratio of network to turbine work

$$WR = \frac{W_{\text{net}}}{W_T}$$

Air rate is significant in deciding the size of the compressor and specific power decides the efficiency of the combustion process. Also it tells complete combustion is taking place or not work ratio is significant in deciding the ratio between compressor work and turbine work and hence efficiency of the cycle.

**Q.7** A gas turbine utilizes two-stages centrifugal compressor. The pressure ratios for the first and second stages are 2.5 and 2.1 respectively. The flow of air is 10 kg/s, this air being drawn at 1.013 bar and 20°C. If the temperature drop in the intercooler is 60°C and the isentropic efficiency is 90% for each stage, calculate:

- (i) the actual temperature at the end of each stage and
- (ii) the total compressor power.

Assume  $\gamma = 1.4$  and  $c_p = 1.005$  kJ/kgK for air

[10 marks : 2012]

Solution:

Given:  $\dot{m} = 10$  kg/s,  $\frac{P_2}{P_1} = 2.5$ ,  $\frac{P_3}{P_2} = 2.1$ ,  $P_1 = 101.3$  kPa,  $T_1 = 293$  K,  $T_2 - T_3 = 60^\circ\text{C}$  and  $\eta_c = 0.9$

For isentropic compression

$$T_{2s} = T_1 \left( \frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} = 293(2.5)^{0.4/1.4}$$

or  $T_{2s} = 380.68$  K

$$\frac{T_{2s} - T_1}{T_2 - T_1} = 0.9 \Rightarrow \frac{380.68 - 293}{T_2 - 293} = 0.9$$

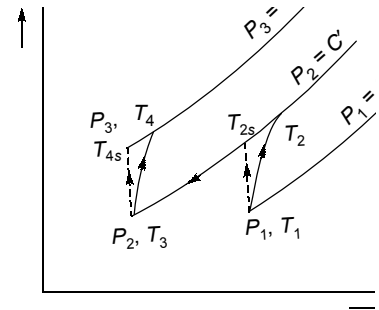
$$T_2 = 390.43$$
 K

$$T_3 = (390.43 - 60) = 330.43$$
 K

$$T_{4s} = T_3 \left( \frac{P_3}{P_2} \right)^{\frac{\gamma-1}{\gamma}} = 408.45$$
 K;  $\frac{T_{4s} - T_3}{T_4 - T_3} = 0.9 = \eta_c$

$$T_4 = 417.12$$
 K

$$\begin{aligned} \text{Compressor power} &= \dot{m}c_p [(T_2 - T_1) + (T_4 - T_3)] = 10 \times 1.005 [390.43 - 293 + 417.12 - 330.43] \\ &= 1850.3055 \text{ kW} \end{aligned}$$



**Q.8** A gas turbine engine with regeneration operates with two stages of compression and two stages of expansion. The pressure ratio across each stage of compressor and turbine is 3.5. The air enters each stage of the compressor at 300 K and each stage of the turbine at 1200 K. The compressor and turbine efficiencies are 78 and 86 percent, respectively. The effectiveness of the regenerator is 72 percent. Determine the back work ratio and the thermal efficiency of the cycle, assuming constant specific heats for air at room temperature.

[20 marks : 2013]

[10 marks : 2016]

Solution:

Given:  $T_1 = T_3 = 300$  K,  $T_6 = T_8 = 1200$  K,  $r_p = 3.5$   
(for each compression and expansion stage)

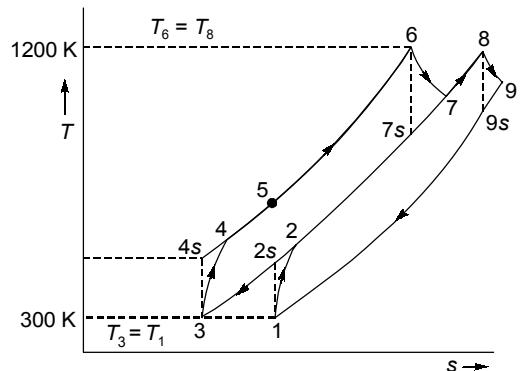
$\eta_c = 0.78$ ,  $\eta_t = 0.86$ ,  $\epsilon = 0.72$

$$\frac{T_{2s}}{T_1} = \left( r \right)^{\frac{\gamma-1}{\gamma}} = (3.5)^{\frac{1.4-1}{1.4}} = (3.5)^{0.286}$$

$\therefore T_{2s} = 300 \times (3.5)^{0.286} = 429.11$  K

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

So,  $T_2 = \frac{T_{2s} - T_1}{\eta_c} + T_1 = \frac{429.26 - 300}{0.78} + 300$



or

$$T_2 = 465.52 \text{ K}$$

$$\frac{T_{4s}}{T_3} = (r_p)^{\frac{\gamma-1}{\gamma}} = (3.5)^{\frac{1.4-1}{1.4}} = (3.5)^{0.286}$$

⇒

$$T_{4s} = 429.11 \text{ K}$$

$$0.78 = \frac{T_{4s} - T_3}{T_4 - T_3}$$

$$T_4 = 465.52 \text{ K}$$

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

$$0.72 = \frac{T_5 - 465.52}{T_9 - 465.52} \quad \dots(i)$$

$$\frac{T_6}{T_{7s}} = (3.5)^{\frac{0.4}{1.4}}$$

⇒

$$T_{7s} = 838.9 \text{ K}$$

$$\eta_T = \frac{T_6 - T_7}{T_6 - T_{7s}}; \quad 0.86 = \frac{1200 - T_7}{1200 - 838.9}$$

$$T_7 = 889.49 \text{ K} = T_9 = 889.49 \text{ K}$$

∴

$$0.72 = \frac{T_5 - 465.52}{889.49 - 465.52}$$

$$T_5 = 770.78 \text{ K}$$

$$W_{\text{net}} = (W_{T_1} + W_{T_2}) - (W_{C_1} + W_{C_2}) = [(h_6 - h_7) + (h_8 - h_9)] - [(h_2 - h_1) + (h_4 - h_3)]$$

$$= 2c_p [(T_6 - T_7) - (T_2 - T_1)] = 2 \times 1.005 [(1200 - 889.49) - (465.52 - 300)]$$

$$= 291.42 \text{ kJ/kg}$$

$$Q_S = (h_6 - h_5) + (h_8 - h_7) = c_p [T_6 - T_5 + T_8 - T_7]$$

$$= 1.005 [1200 - 770.78 + 1200 - 889.49] = 743.42 \text{ kJ/kg}$$

$$(i) \quad \text{Back work ratio} = \frac{W_C}{W_T} = \frac{2(T_2 - T_1)}{2(T_6 - T_7)} = \frac{465.52 - 300}{1200 - 889.49} = \mathbf{0.533}$$

$$(ii) \quad \eta = \frac{W_{\text{net}}}{Q_S} = \frac{291.42}{743.42} \times 100\% = \mathbf{39.19\%}$$

**Q.9** In a gas turbine plant, air at 10°C and 1.0 bar is compressed to 12 bar with isentropic efficiency of 80%. The air is heated first in the regenerator and then in the combustion chamber till its temperature is raised to 1400°C, and during this process the pressure falls by 0.2 bar. The air is then expanded in the turbine, and then passes through the regenerator, which has an effectiveness of 0.75 and causes a pressure drop of 0.2 bar. Isentropic efficiency of the turbine is 85%. Determine the thermal efficiency of the plant. Assume addition of heat at constant pressure. [10 marks : 2015]

**Solution:**

Given data:  $T_1 = 10^\circ\text{C} = 283 \text{ K}$ ;  $P_1 = 1 \text{ bar}$ ;  $P_2 = 12 \text{ bar}$ ;  $P_4 = 12 - 0.2 = 11.8 \text{ bar}$ ;

$P_5 = 1 + 0.2 = 1.2 \text{ bar}$ ;  $T_4 = 1400^\circ\text{C} = 1673 \text{ K}$ ;  $\eta_c = 0.8$ ;  $\eta_t = 0.85$ ,  $\epsilon = 0.75$



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

$$T_2 = 283 \left(\frac{12}{1}\right)^{0.4/1.4} = 575.6 \text{ K}$$

$$\eta_c = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.8 = \frac{575.6 - 283}{T_2' - 283}$$

$$T_2' = 648.75 \text{ K}$$

$$\frac{T_4}{T_5} = \left(\frac{P_4}{P_5}\right)^{\gamma-1/\gamma}$$

$$\frac{1673}{T_5} = \left(\frac{11.8}{1.2}\right)^{0.4/1.4}$$

$$T_5 = 870.69 \text{ K}$$

$$\eta_t = \frac{T_4 - T_5'}{T_4 - T_5}$$

$$0.85 = \frac{1673 - T_5'}{1673 - 870.69}$$

$$T_5' = 991.042$$

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

$$0.75 = \frac{T_3 - 648.75}{991.04 - 648.75}$$

$$T_3 = 905.47 \text{ K}$$

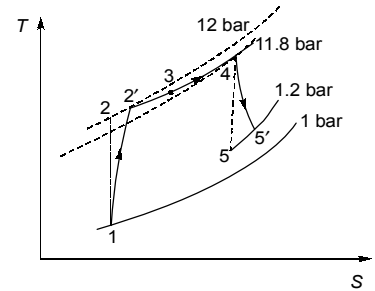
$$W_{\text{net}} = W_T - W_C = c_p [(T_4 - T_5') - (T_2' - T_1)] \\ = 1.005 [(1673 - 991.04) - (648.75 - 283)] = 317.79 \text{ kJ/kg}$$

Heat supplied,

$$Q_s = c_p (T_4 - T_3) = 1.005 (1673 - 905.47) = 771.3676 \text{ kJ/kg}$$

∴

$$\eta = \frac{W_{\text{net}}}{Q_s} = \frac{317.79}{771.3676} = 0.4119 = 41.19\%$$



Q.10 On the basis of a cold-air-standard analysis, show that the thermal efficiency of an ideal regenerative gas turbine can be expressed as

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

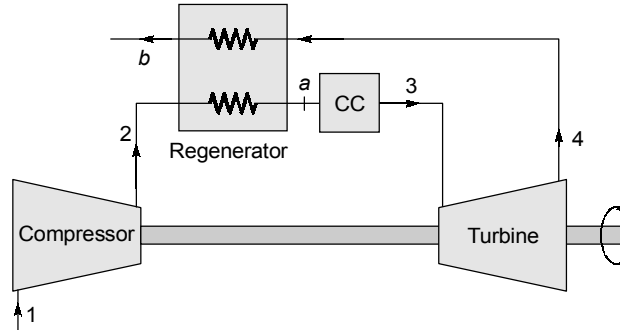
where,  $\gamma$  is the compressor pressure ratio and  $T_1$ ,  $T_3$  denote the temperatures at the compressor and turbine inlets respectively.

[10 marks : 2016]

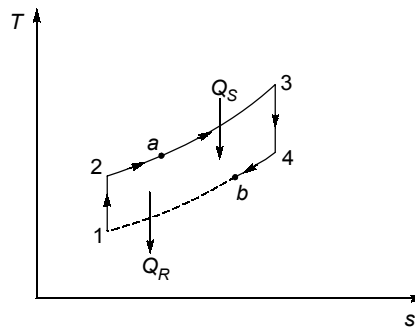
**Solution:**

Process in which turbine exhaust gases are utilized to increase the temperature of compressed air before entering the combustion chamber and heat exchanger.

It is heated in regenerator in between compressors and combustion chamber (CC).



$T_4 > T_2$  for regeneration



Effectiveness is ratio of actual temperature rise of air to the maximum possible rise in a regenerator.

$$\epsilon = \frac{\text{Actual temperature rise}}{\text{maximum temperature rise}} = \frac{T_a - T_2}{T_4 - T_2}$$

In ideal regenerative cycle work on ideal regenerator with an effectiveness of 100% and in that case compressed air is heated upto turbine exit temperature in regenerator.

$$\epsilon = 1$$

$\therefore$

$$T_a = T_4 \quad \text{and} \quad T_b = T_2$$

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

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

$\therefore$

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

$\therefore$  equation (i) becomes

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

Q.11 Discuss the effect of regeneration in gas turbine cycle. Draw the cycle efficiency vs. pressure ratio curve and explain why efficiency drops with increase in pressure ratio.

[20 marks : 2017]

Solution:

**Effect of Regeneration in Gas Turbine Cycle:** The exhaust temperature of gas leaving the turbine is usually quite high. The exhaust gas from the gas turbine can be utilized to preheat the air at temperature  $T_2$  before it goes to the combustion chamber. This is called regeneration and the regenerator effectiveness  $\epsilon$  is defined as:

$$\epsilon = \frac{\text{Actual temperature rise of air}}{\text{Maximum temperature rise possible}}$$

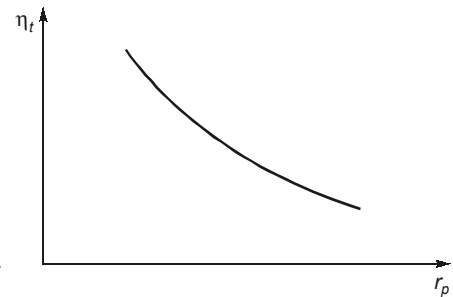
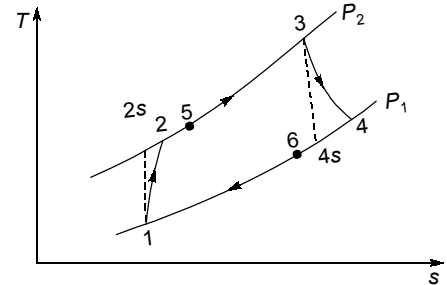
i.e. 
$$\epsilon = \frac{T_5 - T_2}{T_4 - T_2}$$

**Effects:**

- (1) Net heat addition i.e.  $Q_1 = m_a c_p (T_3 - T_5)$  and heat rejection  $Q_2 = m_a c_p (T_6 - T_1)$  both of which decrease.
- (2) Net work output ( $W_{net} = W_T - W_C$ ) remains unchanged due to regeneration.
- (3) Thus cycle efficiency  $\left( \eta = \frac{W_{net}}{Q_1} \right)$  increases with regeneration.

Cycle efficiency vs pressure ratio curve for regeneration Brayton cycle:

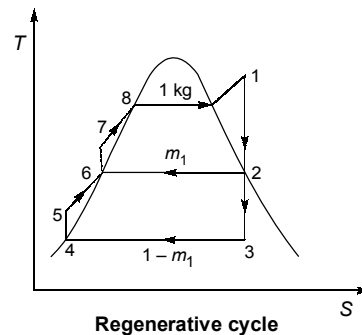
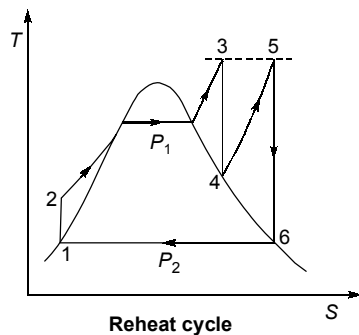
The efficiency of Brayton cycle with regeneration decreases as the pressure ratio ( $r_p$ ) increases. With the increase in pressure ratio, the temperature of air at the end of compression increase and becomes greater than the temperature of gases at the end of turbine expansion. Hence, if a regenerator is used the compressed air gets cooled and exhaust gases get heated. Thus it increases the net heat addition in the cycle and therefore efficiency reduces.



## 2. Vapour Power Cycle

Q.12 Show the Reheat cycle and regenerative feed water heating cycle on T-s diagram. Highlight their significance on the performance of steam power plant. [5 marks : 2002]

Solution:



**Significance of Reheat:** The reheat cycle has been developed to take advantage of the increased efficiency with higher pressure but the chief advantage is in decreasing to a safe value the mixture content in the low-pressure stages of the turbine.

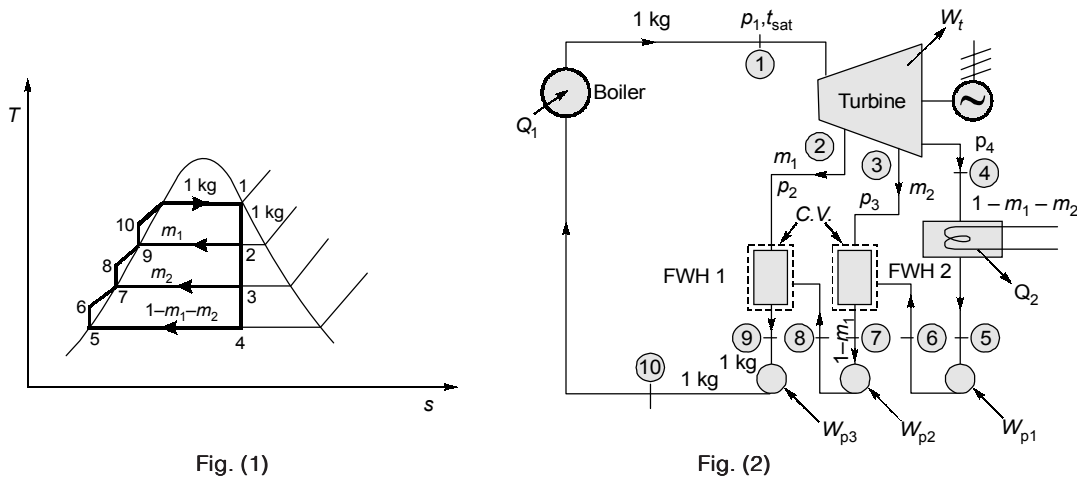
**Significance of Regenerative cycle:**

- Average temperature of heat addition is increased.
- Heating process in the boiler tends to become reversible.
- less amount of steam is passed through the low pressure stages so blade height will be less resulting in low cost of L.P. turbine.

**Q.13** What is the basic principle of regenerative feed heating in steam power plant cycle? Sketch a practical feed heating system for a 500 MW steam turbine and label it. [10 marks:2004]

**Solution:**

**Principle of Regenerative feed heating:** In a regenerative feed heating the mean temperature of heat addition is increased and the heat transfer becomes reversible due to which the thermal efficiency increases. In regeneration energy is exchanged internally between the expanding fluid in the turbine and compressed fluid before heat addition. The feed water is heated by steam extracted or bled from intermediate stages of turbine.



**Q.14** A smaller power plant produces steam at 3 MPa, 600°C in the boiler. It keeps the condenser at 45°C by transfer for 10 MW out as heat transfer. The first turbine section expands to 500 kPa and then flow is reheated followed by the expansion in the flow pressure turbine. Find the reheat temperature so the turbine output is saturated vapour. For this reheat find the total turbine power output and the boiler heat transfer. Properties of water are given in the Table below:

$t, ^\circ\text{C}$	$p, \text{kPa}$	$v_1, \text{m}^3/\text{kg}$	$v_g, \text{m}^3/\text{kg}$	$h_1, \text{kJ/kg}$	$h_v, \text{kJ/kg}$	$s_1, \text{kJ/kgK}$	$s_v, \text{kJ/kgK}$
45	9.59 ( $P_{\text{sat}}$ )	0.00101	15.252	188.42	2583.19	0.63861	8.1647
233.85	3000 ( $P_{\text{sat}}$ )	0.0012167	0.66664	1008.29	2803.99	2.6455	6.1870
600	3000	–	0.13245	–	3682.34	–	7.5084

[10 marks : 2014]

**Solution:**

From the given table,  
At 1 : 45°C,

$$x = 0, \quad h_1 = 188.42 \text{ kJ/kg}$$

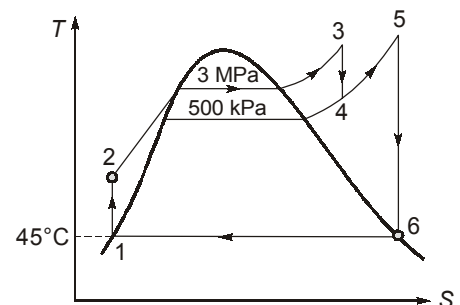
$$v_1 = 0.00101 \text{ m}^3/\text{kg}$$

$$P_{\text{sat}} = 9.59 \text{ kPa}$$

At state 3, 3 MPa, 600°C

$$h_3 = 3682.34 \text{ kJ/kg}$$

$$s_3 = 7.5084 \text{ kJ/kgK}$$



At state 6, 45°C

$$x = 1, \quad h_6 = 2583.19 \text{ kJ/kg}$$

$$s_6 = 8.1647 \text{ kJ/kgK}$$

$$h_2 = h_1 + w_{\text{pump}} = 188.42 + v_1(p_2 - p_1) = 188.42 + 0.00101(3000 - 9.59) \\ = 191.44 \text{ kJ/kg}$$

For process 3 → 4,

$$s_3 = s_4$$

(for HP turbine)

Properties at 500 kPa: (state 4) from steam table

$$T_{\text{sat}} = 151.83^\circ\text{C} = 424.98 \text{ K}$$

$$h_l = 640.21 \text{ kJ/kg}, \quad h_v = 2748.7 \text{ kJ/kg}$$

$$s_l = 1.8606 \text{ kJ/kgK}, \quad s_v = 6.8212 \text{ kJ/kgK},$$

$$c_p = 2.41267 \text{ kJ/kgK}$$

3-4 is isentropic

$$s_3 = s_4$$

$$s_3 = s_l + x(s_v - s_l)$$

$$7.5084 = 1.8606 + x(6.8212 - 1.8606)$$

$$x = 1.1385$$

∴ Point 4 is in superheated region

$$\therefore s_3 = s_v + c_{pV} \ln\left(\frac{T_4}{T_{\text{sat}}}\right)$$

$$7.5084 = 6.8212 + 2.4126 \ln\left(\frac{T_4}{424.98}\right)$$

$$T_4 = 565 \text{ K}$$

$$h_4 = h_{4v} + c_p(T_4 - T_{\text{sat}}) \\ = 2748.7 + 2.4126(565 - 424.98)$$

$$h_4 = 3086.58 \text{ kJ/kg}$$

5-6 isentropic process

$$\therefore s_5 = s_6$$

$$\therefore s_6 = s_{5v} + c_p \ln\left(\frac{T_5}{T_{\text{sat}}}\right)$$

$$8.1647 = 6.8212 + 2.4126 \ln\left(\frac{T_5}{424.98}\right)$$

$$T_5 = 741.6 \text{ K}$$

$$h_5 = h_{5v} + c_p(T_5 - T_{\text{sat}}) \\ h_5 = 2748.7 + 2.4126(741.6 - 424.98)$$

$$h_5 = 3512.75 \text{ kJ/kg}$$

Heat rejected in condenser 10 MW

$$\therefore \dot{m}(h_6 - h_1) = 10 \times 10^3$$

$$\dot{m} = \frac{10 \times 10^3}{(2583.19 - 188.42)} = 4.175 \text{ kg/s}$$

$$\therefore \text{power output} = \dot{m}[(h_3 - h_4) + (h_5 - h_6)] = 4.175(3682.34 - 3086.58 + 3512.75 - 2583.19)$$

$$\text{power} = 6368.211 \text{ kW}$$

$$\text{Heat supplied in boiler} = \dot{m}[h_3 - h_2] = 4.175(3682.34 - 191.44)$$

$$= 14574.50 \text{ kW}$$

$$\text{Heat supplied in boiler} = 14.574 \text{ MW}$$

Q.15 In a BWR type nuclear reactor, the heat of nuclear fission is transferred to water. In a reactor, water comes out of the reactor as saturated vapour at 72 bar. The steam flows through a turbine and exhausts at 0.08 bar to a condenser. The water leaves the condenser at 0.08 bar and 40°C ( $h = 176.5$  kJ/kg). The liquid water is again pumped through a pump to the nuclear reactor. Isentropic efficiency of the turbine is 70%. The plant has a capacity of 750 MW. Calculate the mass flow rate of steam circulated and the rate of heat generation.

Properties of steam:  $P = 0.08$  bar:  $h_f = 173.9$  kJ/kg,  $h_{fg} = 2403.2$  kJ/kg

$s_f = 0.5926$  kJ/kgK,  $s_{fg} = 7.6370$  kJ/kgK, At 72 bar :  $h_g = 2770.9$  kJ/kg,  $s_g = 5.8019$  kJ/kgK

[10 marks : 2015]

Solution:

Given:  $\eta_t = 0.7$ ; Power = 750 MW;  $h_{g1} = 2770.9$  kJ/kg;  $s_{g1} = 5.8019$  kJ/kgK;  $h_f = 173.9$ ; kJ/kg  
 $h_{fg} = 2403.2$  kJ/kg;  $s_f = 0.5926$  kJ/kgK;  $s_{fg} = 7.6370$  kJ/kgK;  $s_1 = s_2$

⇒

$$s_{g1} = s_{f2} + x \cdot s_{fg2}$$

⇒

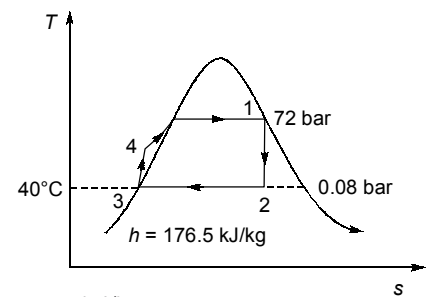
$$5.8019 = 0.5926 + x \times 7.6370$$

⇒

$$x = 0.6821$$

$$\begin{aligned} h_2 &= h_f + x h_{fg} \\ &= 173.9 + 0.6821 \times 2403.2 \\ &= 1813.15 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} w_t &= (h_1 - h_2) \times \eta_t \\ &= (2770.9 - 1813.15) \times 0.7 = 670.4 \text{ kJ/kg} \end{aligned}$$



Mass flow rate of steam

$$\dot{m} = \frac{750000}{670.4} = 1118.7 \text{ kg/s}$$

$$h_4 = h_3 = 176.5 \text{ kJ/kg} \quad (\text{Neglecting pump work})$$

Heat generated,

$$\begin{aligned} \dot{Q}_{\text{gen}} &= \dot{m}(h_1 - h_4) = 1118.7 \times (2770.9 - 176.5) = 2902.33 \times 10^3 \text{ kJ/s} \\ &= \mathbf{2902.33 \text{ MW}} \end{aligned}$$

Q.16 A simple steam power cycle uses solar energy for heat input. Water in the cycle enters the pump as saturated liquid at 40°C and is pumped to 2 bar. The water at this pressure evaporates in the steam generator and enters the turbine as saturated vapour. At the exit of the turbine, the condition of steam is 40°C with dryness fraction of 0.9. The flow rate is 150 kg/h. The instantaneous solar input is 0.58 kW/m<sup>2</sup> at a specified time. Obtain the isentropic efficiency of the turbine, net work output, cycle efficiency and the area of the solar collector needed based on the given solar input.

Following properties of steam are given:

$p$ (bar)	$T$ (°C)	$h_f$	$h_{fg}$	$h_g$	$s_f$	$s_{fg}$	$s_g$
		(kJ/kg)			(kJ/kgK)		
0.07375	40	167.53	2405.97	2573.5	0.572	7.686	8.258
2	120.2	504.7	2201.6	2706.3	1.530	5.597	7.127

Solution:

$$h_1 = 2706.3 \text{ kJ/kg}$$

$$h_3 = h_{f3} = 167.53$$

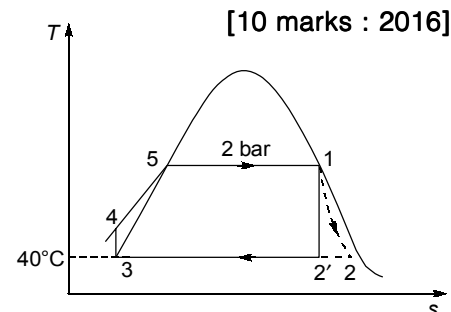
$$h_4 - h_3 = v dp$$

$$h_4 - 167.53 = v_f(200 - 7.375)$$

Since  $v_f$  is not given so neglecting pump work

so

$$h_4 - h_3 \cong 0 \quad (h_4 = h_3 = 167.53)$$



[10 marks : 2016]

$$h_2 = h_{f2} + x_2 h_{fg2} = 167.53 + 0.9 (2405.97) = 2332.90 \text{ kJ/kg}$$

$$\dot{m} = 150 \text{ kg/hr} = \frac{150}{3600} = 0.0416 \text{ kg/s}$$

Heat supplied,  $Q_s = \dot{m}(h_1 - h_4) = 0.0416(2706.3 - 167.53) = 105.61 \text{ kW}$

Calculating area required

$$\text{required area} = \frac{105.61}{0.58} = 182.09 \text{ m}^2$$

Calculating dryness fraction when isentropic expansion occurs in turbine.

$$s_{g1} = s_{f2} + x_2(s_{fg})_2$$

$$7.127 = 0.572 + x_2[7.686]$$

$$x_2 = 0.852$$

$$\therefore h'_2 = h_{f2} + x_2(h_{fg})_2 = 167.53 + 0.852(2405.97) = 2217.42 \text{ kJ/kg}$$

$$\therefore \eta_{\text{isentropic}} = \frac{h_1 - h_2}{h_1 - h'_2} = \frac{2706.3 - 2332.90}{2706.3 - 2217.42} = 0.7634 \text{ or } 76.34\%$$

$$\text{Net work output} = (h_1 - h_2)_{\text{actual}}$$

$$= 2706.3 - 2332.90 = 373.4 \text{ kJ/kg} = 0.0416 \times 373.4 = 15.53 \text{ kW}$$

$$\text{cycle } \eta = \frac{(h_1 - h_2)}{(h_1 - h_4)} = \frac{373.4}{2706.3 - 167.53} = 0.147 = \mathbf{14.7\%}$$

**Q.17 Explain the working of electrostatic precipitator and discuss variation of its collection efficiency with operating parameters like collector area, migration velocity and mass flow rate.**

[20 marks : 2017]

**Solution:**

**Electrostatic Precipitator:** The principal components of an electrostatic precipitator (ESP) are two sets of electrodes insulated from each other. The first set is composed of rows of electrically grounded vertical parallel plates, called the collection electrodes, between which the dust-laden gas flows. The second set of electrodes consists of wires, called the discharge or emitting electrodes that are centrally located between each pair of parallel plates. The wires carry a unidirectional negatively charged high-voltage current from an external DC source. The applied high voltage generates a unidirectional, non-uniform electrical field. When that voltage is high enough, a blue luminous glow called a corona, is produced around them. Electrical forces in the corona accelerate the free electrons present in the gas so that they ionize the gas molecules, thus forming more electrons and positive gas ions.

The positive ions travel to the negatively charged wire electrodes. The electrons follow the electrical field toward the grounded electrodes but their velocity decreases toward the plates. Gas molecules capture the low velocity electrons and become negative ions.

As these ions move to the collecting electrode, they collide with the fly ash particles in the gas stream and give them negative charge. The negatively charged fly ash particles are driven to the collecting plate.

