SSC-JE 2025

Staff Selection Commission

Junior Engineer Examination

Mechanical Engineering

Power Plant

Well Illustrated **Theory** *with*

Solved Examples and **Practice Questions**

MADE EASY PUBLICATIONS

Power Plant

Contents

CHAPTER 01

Rankine Cycle

1.1 Introduction

A steam power plant continuously converts the energy stored in fossil fuels or fissile fuels into shaft work and ultimately into electricity. The working substance is water which is some times in the liquid phase and sometimes in the vapour phase. The fluid is undergoing a cyclic process, there will be no net change in its internal energy over the cycle $(\oint dE = 0)$ and consequently the net energy transferred to the unit mass of the fluid as heat during the cycle must equal the net energy transfer as work from the fluid.

$$\Sigma Q_{net} = \Sigma W_{net} \qquad \text{(First law of thermodynamics for a cycle)}$$

$$Q_1 - Q_2 = W_T - W_P$$

where,

Q_1 = heat transferred to the working fluid kJ/kg

Q_2 = heat rejected from the working fluid kJ/kg

W_T = work transferred from the working fluid kJ/kg

W_P = work transferred into the working fluid kJ/kg

$$\eta_{cycle} = \frac{W_{net}}{Q_1} = \frac{W_T - W_P}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

NOTE : Working substance in steam power plant – water.
Working substance in steam turbines – steam.

1.2 Rankine Cycle

It is the practical cycle used in steam power plants.

- This cycle contains four processes:
  - **For steam boiler:** reversible constant pressure heating process of water
  - **For turbine:** reversible adiabatic expansion of steam.
  - **For condenser:** reversible constant pressure heat rejection
  - **For pump:** reversible adiabatic compression.

- When all these four processes are ideal the cycle is an ideal cycle, called a **Rankine cycle**.

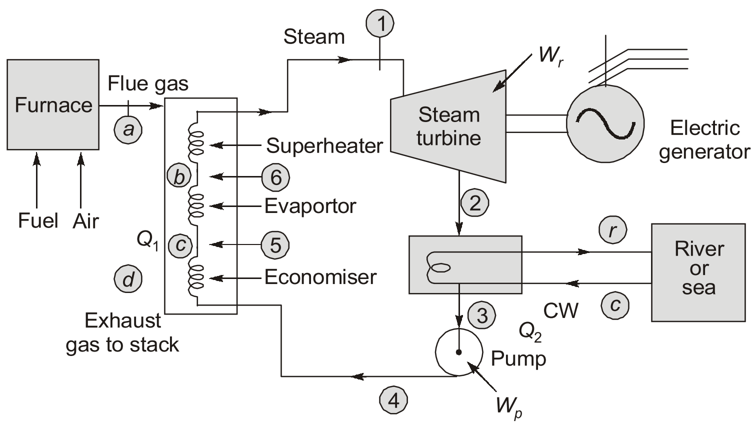

Figure 1.1

- Now,

  For 1 kg of fluid, the steady flow energy equation to each processes:

  For boiler, $Q_1 = h_1 - h_4$

  For turbine, $W_T = h_1 - h_2$

  For condenser, $Q_2 = h_2 - h_3$

  For pump, $W_P = h_4 - h_3$

  Efficiency of Rankine cycle

$$\eta = \frac{W_{net}}{Q_1} = \frac{W_T - W_P}{Q_1} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

$$W_P = h_4 - h_3 = -\int_3^4 \nu d_p \;; \qquad \nu \rightarrow \text{specific volume of liquid at 3}$$

  Volume of liquid at 3.

  Since, $\nu_{\text{steam or gas}} >> \nu_{\text{liquid}}$

  $\therefore$ $W_p >>> W_T$

  So, W_p is often neglected.

- **Steam rate:** The capacity of a steam plant is often expressed in terms of steam rate or specific steam consumption. It is defined as the rate of steam flow (kg/s) required to produce unit shaft output (1 kW).

$$\text{Steam rate} = \frac{1}{W_{net}}\text{kg/kWs} = \frac{3600}{W_{net}}\text{ kg/kWh}$$

  It varies from 3 to 5 kg/kWh

- **Heat rate:** The cycle efficiency is sometimes expressed alternatively as heat rate which is the rate of heat input (kJ/s) required to produce unit shaft output (1 kW)

$$\text{Heat rate (H.R.)} = \frac{Q_1}{W_T - W_P} = \frac{1}{\eta}\frac{\text{kJ}}{\text{kWs.}}$$

1.3 Economiser, Evaporator and Superheater

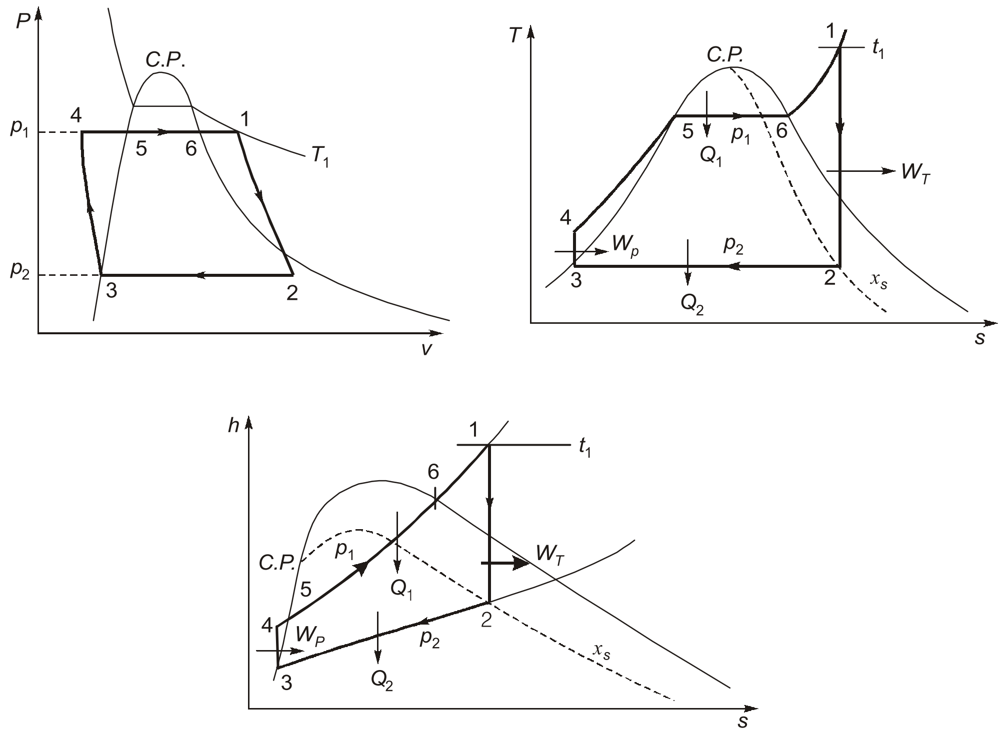

Figure 1.2

- Water is first heated sensibly in the economiser in the liquid phase at a certain pressure till it becomes saturated liquid.
- Economiser heats the feedwater (sensibly) by using the heat of exhaust flue gases. This reduces the fuel consumption in the boiler.

$$Q_{Eco} = h_5 - h_4$$

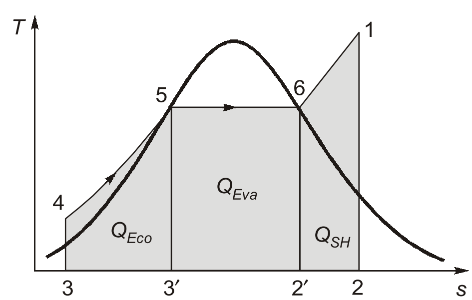

Figure 1.3

- In the evaporator there is phase change or boiling by absorbing the latent heat of vapourization at that pressure

$$Q_{Evo} = h_6 - h_5 = h_{fg}$$

- The saturated vapour is further heated at constant pressure in the superheater to superheated state

$$Q_{SH} = h_1 - h_6$$

- As the pressure increases, the latent heat decreases and so the heat absorbed in the evaporator decreases and the fraction of the total heat absorbed in the superheater increases.

- For steam generators operating above the critical pressure there is no evaporator or boiling section. because enthalpy of vaporization becomes zero at critical point. However, there is a transition zone where all the liquid on being heated suddenly flashes into vapour.

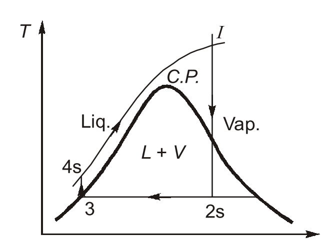

Figure 1.4: Rankine Cycle with Supercritical Pressure

Example 1.1 The function of economizer in a boiler is to

(a) Superheat the steam
(b) Reduce fuel consumption
(c) Increase steam pressure
(d) Maintain saturation temperature

[ESE : 2011]

Solution: **(b)**

Economiser extracts heat flow the flow gases to heat feed water and reduces fuel consumption.

1.4 Internal Irreversibility

- Internal irreversibility of Rankine cycle is caused by fluid friction, throttling and mixing.
- Due to rapid processes in pumps and the turbines and large flow rates involved, heat loss per unit mass is negligible.

  Though the assumption of adiabatic flow in them is still valid, due to fluid friction the expansion and compression processes are not reversible and entropy of the fluid in both increases.

  - The isentropic Efficiency (η_T) of the turbine is $\eta_T = \dfrac{h_1 - h_2}{h_1 - h_{2s}}$

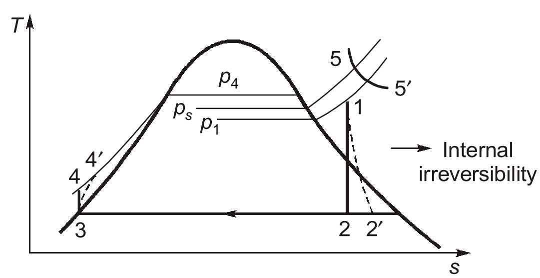

Figure 1.5

The liquid leaving the pump must be at higher pressure then turbine inlet as there is pressure drop in boiler pipes, valves etc. and reaches at P_1 from P_4 as shown above.

  - The isentropic Efficiency of the Pump, $\eta_p = \dfrac{h_{4s} - h_3}{h_4 - h_3}$.
  - The actual pump work would be, $W_p = \dfrac{h_{4s} - h_3}{\eta_P} = \dfrac{v_3(p_4 - p_3)}{\eta_P}$.

  Thus turbine produces less work and the pump absorbs more work.

NOTE : Processes in turbines and pumps in steam power plants are ADIABATIC and IRREVERSIBLE.

1.5 External Irreversibility

- External irreversibility of the Rankine cycle is caused due to the temperature differences between the combustion gases and the working fluid on the source side and the temperature- difference between the condensing working fluid and the condenser cooling water on the sink side.
- The point where minimum temperature difference occur are called pinch point.

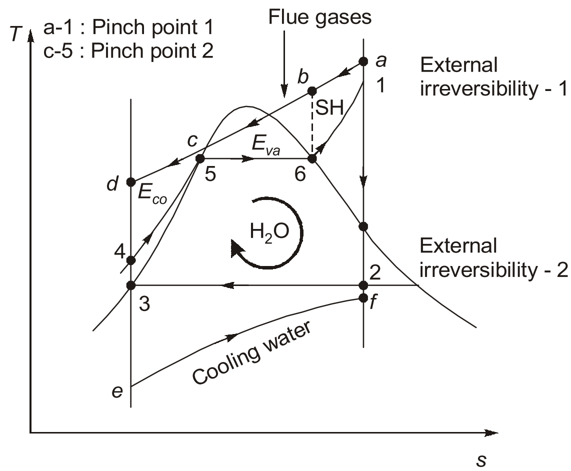

Figure 1.6

Carnot Cycle : Why it is not practical

- To compress the wet steam from state 3 will require a large work consuming compressor.
- It this case, pump work $(h_4 - h_3)$ will be large. Also it is impossible to supply heat at constant temperature from 4 to 5.

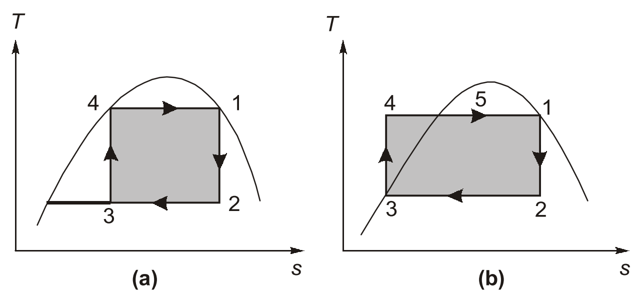

Figure 1.7

NOTE : Carnot cycle (in any of the above two cases) will have very less work ratio because of large pump work

$$\text{Work Ratio} = \frac{W_T - W_P}{W_T}$$

1.6 Mean Temperature of Heat Addition

- In the Rankine cycle, heat is added reversibly at a constant pressure but at infinite temperatures. If T_{m1} is the mean temperature of heat addition then

  Heat added is

$$Q_1 = h_1 - h_4 = T_{m_1}(s_1 - s_4)$$

$$\therefore \quad T_{m_1} = \frac{h_1 - h_4}{s_1 - s_4}$$

  Heat rejected

$$Q_2 = h_2 - h_3 = T_2(s_1 - s_4)$$

$$\eta_{\text{Rankine}} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_{m_1}}$$

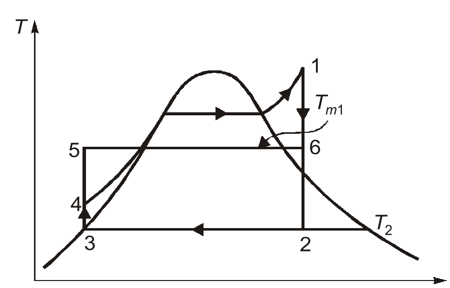

Figure 1.8

- Lower is the condenser temperature, the higher will be the Efficiency of the Rankine cycle. Since it is fixed due to ambient conditions so $\eta_{\text{Rankine}} = f(T_{m_1})$ only.
- The higher the mean temperature of heat addition, the higher will be the cycle efficiency.

NOTE : In winters or colder regions, $T_2 \downarrow \Rightarrow \eta_{Rankine} \uparrow$

1.7 Effect of Superheat

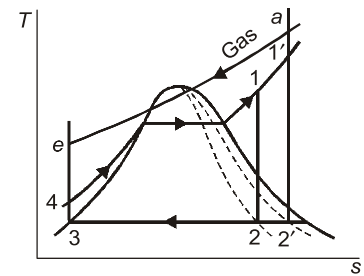

Figure 1.9 : Superheating at same inlet pressure

(a) Mean temperature of heat addition is increased, hence efficiency is increased.

(b) The quality of steam at turbine exhaust is increased as the expansion line shifts to right. Hence performance of turbine is improved.

- The maximum temperature of steam that can be used is fixed from metallurgical considerations.
- As the operating steam pressure at which heat is added in the boiler increases, the mean temperature of heat addition increases. But when the turbine inlet pressure increases the ideal expansion line of steam shifts to the left and the moisture content of steam in the later stages of the turbine is high and strike the blade with high velocity and erode their edges, as a result of which the life of the blades decreases.

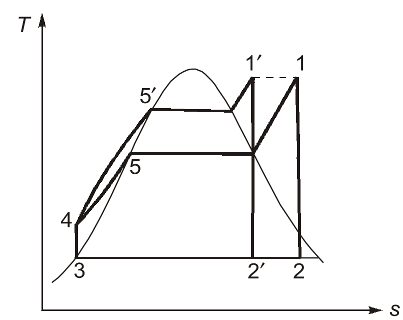

Figure 1.10 : Superheating at increased inlet pressure and same inlet temperature

$$T_1' = T_1$$
$$P_1' > P_1$$
$$x_2' < x_2$$

- At turbine exhaust quality of steam should not fall below 90% to avoid blade erosion.

1.8 Reheating of Steam

- Reheating is done to utilize higher boiler pressure while maintaining better quality of steam at turbine exhaust.
- In reheating, the expansion of steam from initial state 1 to condenser pressure is carried out in two or more steps.
- Initially the steam is expanded from state 1 to 2s in high pressure (HP) turbine, then reheated from 2s to 3 in a reheater and then expanded from 3 to 4s in low pressure (LP) turbine.

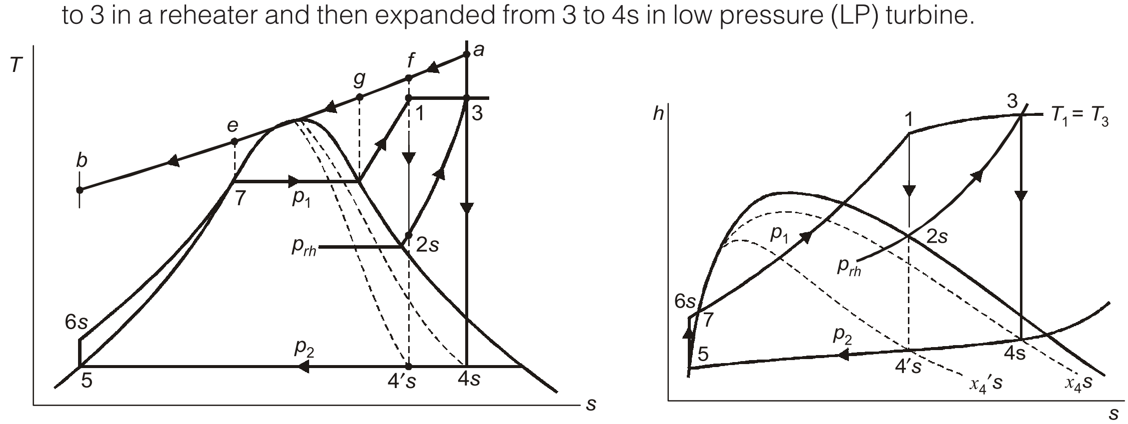

Figure 1.11

$$Q_1 = h_1 - h_{6s} + h_3 - h_{2s}$$
$$Q_2 = h_{4s} - h_5$$
$$W_T = h_1 - h_{2s} + h_3 - h'_{4s}$$
$$W_p = h_{6s} - h_5$$
$$\eta = \frac{(h_1 - h_{2s} + h_3 + h_{4s}) - (h_{6s} - h_5)}{h_1 - h_{6s} + h_3 - h_{2s}}$$

- The net work output of the plant increases with reheat, and hence the steam rate decreases. Reheating also improves the quality at turbine exhaust.
- With reheating, cycle efficiency decreases or increases depending upon whether mean temperature of heating addition in process $2s - 3$ is higher than that in $6s - 1$.
- By increasing the number of reheats, still higher steam pressure could be used, but the mechanical stresses increases in much higher proportion than the pressure because of prevailing high temperature. In that way the maximum steam pressure gets fixed and more than two reheats results in cycle complication and increases capital cost that are not justified by improvement in the cycle efficiency.
- The optimum reheat pressure for most of the modern power plant is 0.2 to 0.25 of the initial steam pressure.
- For too low a reheat pressure the exhaust steam may even be in the-supersaturated state, which is not good for the condenser.

NOTE : With reheating
1. Quality at turbine exhaust ↑ ⇒ Erosion of blades ↓
2. Condenser load ↑
3. Work output ↑
4. Efficiency may or may not increase

"To increase the dryness fraction at exhaust is the main aim" of reheating.

Example 1.2 If a re-heater is added to a Rankine Cycle, then usually:

(a) the net work and efficiency decreases
(b) the net work increases and efficiency remains same
(c) the net work and efficiency increases
(d) the net work remains same and efficiency increases

[SSC-JE : 2015]

Solution: **(c)**

Efficiency may increase or decrease but net work always increases.

1.9 Regeneration

- With the help of regeneration, the mean temperature of heat addition is increased by decreasing the amount of heat added at low temperatures (liquid phase) in the economiser section.
- In regeneration, the energy is exchanged internally between the expanding fluid in turbine and compressed fluid (after pump work) before heat addition.
- A well known gas cycle that uses regeneration is the Stirling cycle comprising two reversible isotherms and two reversible isochores. Ideal stirling cycle has the same efficiency as the carnot cycle.

- In the Ideal regenerative cycle the condensate after leaving the pump circulates around the turbine casing so that heat is transferred from the vapour expanding in the turbine to the condensate circulating around it. It is assumed that this heat transfer process is reversible.

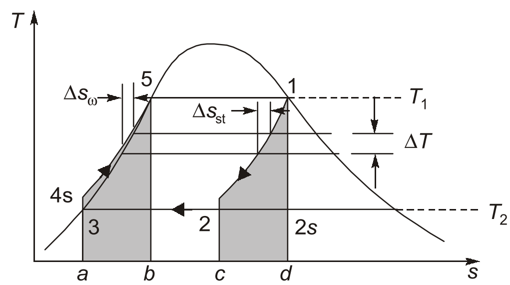

Figure 1.12: Ideal Regenerative Cycle

$$\Delta T(\text{water}) = -\Delta T(\text{steam})$$

$$Q_1 = h_1 - h_5 = T_1 (s_1 - s_5)$$

$$Q_2 = h_2 - h_3 = T_2 (s_2 - s_3)$$

for reversible heat transfer:

$$\Delta s_{univ} = \Delta s_{water} + \Delta s_{steam} = 0$$

$$\Delta s_{water} = -\Delta s_{steam}$$

$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$$

Pump work remains same as in Rankine cycle i.e.

$$W_p = h_{4s} - h_3$$

- The efficiency of ideal regenerative cycle is equal to Carnot cycle.
- The net work output of the ideal regenerative cycle is thus less and hence, its steam rate will be more; although it is more efficient compared to the Rankine cycle. However the cycle is not practicable–because

❖ reversible heat transfer cannot be realized in finite time.

❖ heat exchanger in the turbine is mechanically impracticable

❖ the moisture content of the steam in the turbine is high, which leads to excessive erosion of turbine blades.

Example 1.3 In ideal regenerative cycle the temperature of steam entering the turbine is same as that of

(a) water entering the turbine (b) water leaving the turbine

(c) steam leaving the turbine (d) water at any section of the turbine

[ESE : 2008]

Solution: **(b)**

In an ideal regenerate cycle

$$\Delta T_{water} = -\Delta T_{steam}$$

Heat transfer between steam and water takes place reversibly so that decrease in temperature of steam is equal to the increase in temperature of water leaving the turbine.