Mechanical Engineering

Power Plant Engineering

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016
E-mail: infomep@madeeasy.in
Contact: 011-45124660, 8860378007
Visit us at: www.madeeasypublications.org

Power Plant Engineering

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CHAPTER 03

Analysis of Steam Cycles

3.1 Introduction

Steam power plants work on the basis of some thermodynamic cycle, such as Carnot cycle and Rankine cycle. Carnot cycle is an ideal and most efficient cycle but is not practically feasible. Coal based power stations are using Rankine cycle.

A steam power plant continuously converts the chemical energy of the fossile fuels or fissile fuels into mechanical energy and ultimately into electrical energy. The working substance is water which is some times in the liquid phase and sometimes in the vapour phase.

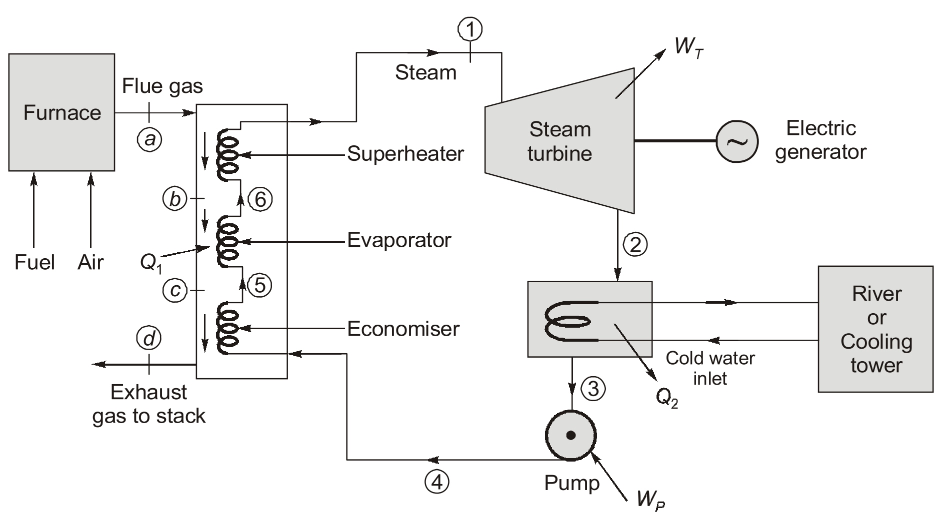


Fig. 3.1

3.2 Carnot Cycle

This cycle was proposed by Sadi Carnot. Under Carnot cycle the working substance receives heat at temperature and rejects at another temperature. The cycle consists of **two isothermal** processes and **two reversible adiabatic** processes, as shown in **fig 3.2.**

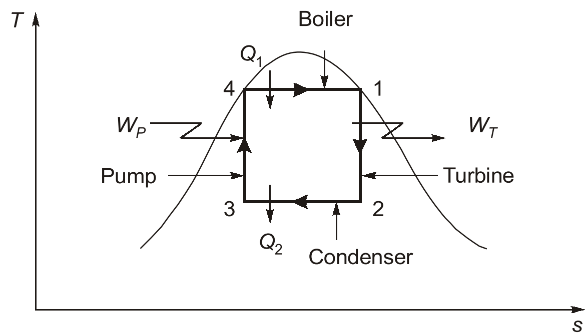


Fig. 3.2

Process 1–2: Isentropic (reversible adiabatic) expansion.

Process 2–3: Reversible isothermal heat rejection

Process 3–4: Isentropic (reversible adiabatic) compression

Process 4–1: Reversible isothermal heat addition

All the above processes of Carnot cycle are reversible hence the entire cycle is also reversible. The same can also be represented by a heat engine which operates between two thermal reservoirs maintained at temperature T_1 and T_2 and produces the work W.

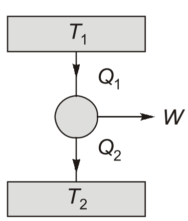


Fig. 3.3

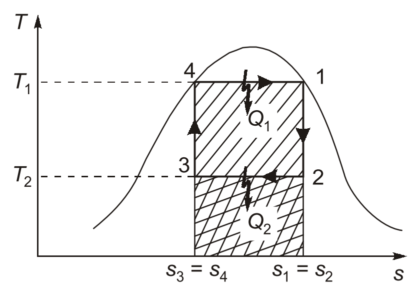


Fig. 3.4

The single line hatched area enclosed by points 1, 2, 3, 4 represents the net heat ($Q_1 - Q_2$) or net work ($W_T - W_P$) interaction, and the double line or crossed hatched area represents heat rejection, (Q_2).

For a substance undergoing a cyclic change, cyclic integral of work is equal to the cyclic integral of heat. Thus,

$W_T - W_P = Q_1 - Q_2$, and efficiency (η) can be represented by

$$\eta = \frac{\text{Net work}}{\text{Heat supplied}} = \frac{W_T - W_P}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2(s_2 - s_3)}{T_1(s_1 - s_4)} = 1 - \frac{T_2}{T_1}$$

Since the area under a process on T-s diagram represents the heat interaction.

3.2.1 Limitations of Carnot Cycle

1. Termination of condensation process is not practically feasible at point 3 from where compression leads to point 4 on saturation line, *i.e.*, water in saturated condition and needs only latent heat for conversion into vapour.
2. During compression of the mixture of steam and water in the pump from point 3 to point 4, steam is getting condensed and vanishes at the end of compression. When steam gets converted into water, a large difference in specific volume causes cavitation over the impellers. The cavitation damage the impeller due to which impeller requires frequent replacement.

3. Any pump cannot suck the mixture of water and its vapour at state point 3 and deliver saturated liquid at state point 4, which is the need of Carnot cycle.
4. If exhaust steam from turbine is completely cooled in condenser, then transfer of heat at constant temperature (6′–4) and infinite pressure gradient is not possible. **Addition of heat at constant temperature is possible only within the dome**. Outside the dome, i.e., either in sub-cooled region or superheat region this is not possible.

3.3 Rankine Cycle

Limitation of Carnot cycle can be overcome by complete condensation of vapour up to point 3′ (shown as in figure 3.5) as a large amount of cooling water is supplied in the condenser. The water thus formed is pumped to point 4′ and sent to the boiler for **addition of sensible and latent heat** to get it converted into steam. The area under 3′–4′–4 is sensible heat addition and area under 4–1 is latent heat addition. The cycle thus formed by the process 1–2–3′–4′–4–1 becomes Rankine cycle, which is being used in thermal power plants with modifications to induce superheaters, regenerator and reheater.

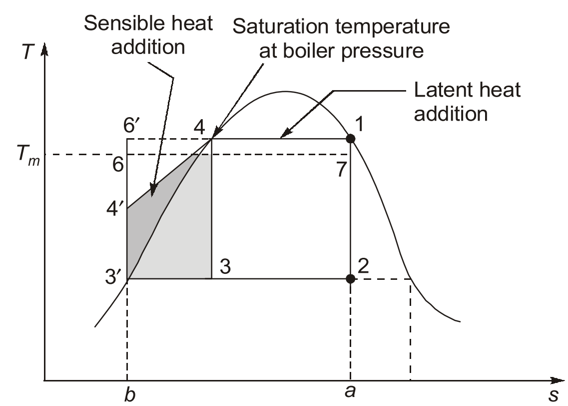


Fig. 3.5

This cycle contains four processes:

- **Boiler: Reversible constant pressure heating process** of water
- **Turbine: Reversible adiabatic expansion** of steam.
- **Condenser: Reversible constant pressure heat rejection**
- **Pump: Reversible adiabatic compression**.

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

3.3.1 Calculation of Mean Temperature (T_m)

In the Rankine cycle, heat is added reversibly at a constant pressure but at infinite temperatures. If T_m is the mean temperature of heat addition, then

Heat added: $$q_1 = h_1 - h_4' = T_m(s_2 - s_3')$$

or $$T_m = \frac{h_1 - h_4'}{s_2 - s_3'}$$

3.3.2 Comparison of Carnot and Rankine Cycles

Efficiency of Carnot cycle, $$\eta_C = 1 - \frac{T_2}{T_1}$$

For comparison, let us assume that the entire heat addition in Rankine cycle also takes place at some imaginary temperature T_m, i.e., area b–4′–4–1–a–b = area b–6–7–a–b. Thus, the equivalent cycle with heat addition at constant temperature becomes 7–2–3′–6–7, with heat addition at T_m and heat rejection at T_2. The efficiency of this equivalent cycle becomes:

$$\eta_R = 1 - \frac{T_2}{T_m}, \quad \text{where } T_m < T_1$$

Since T_m is lower than T_1 in Rankine cycle, the efficiency of Rankine is lower than the efficiency of Carnot cycle $\eta_R < \eta_C$.

NOTE

Lower is the condenser pressure, the higher will be the efficiency of the Rankine cycle. Since it is fixed so $\eta_{Rankine} = f(T_m)$ only.

The **higher the mean temperature of heat addition, the higher will be the cycle efficiency**.

3.3.3 Analysis of Rankine Cycle

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,

$$\eta = \frac{w_{net}}{q_1} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

The pump work is small compared to the turbine work and is often neglected.

Isentropic Cycle

$$\text{Work ratio} = \frac{\text{Net work}}{\text{Turbine work}} = \frac{w_{net}}{w_T}$$

Do You Know?

Critical temperature and pressure of water are 374°C and 221.2 bar. At all temperature above the critical, it is impossible to liquefy water vapour by using pressure, no matter how great the pressure is employed.

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).

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

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)

Heat rate: $$\text{H.R.} = \frac{3600}{\eta_{th}} = \frac{3600\, q_1}{w_{net}} \text{ kJ/kWh}$$

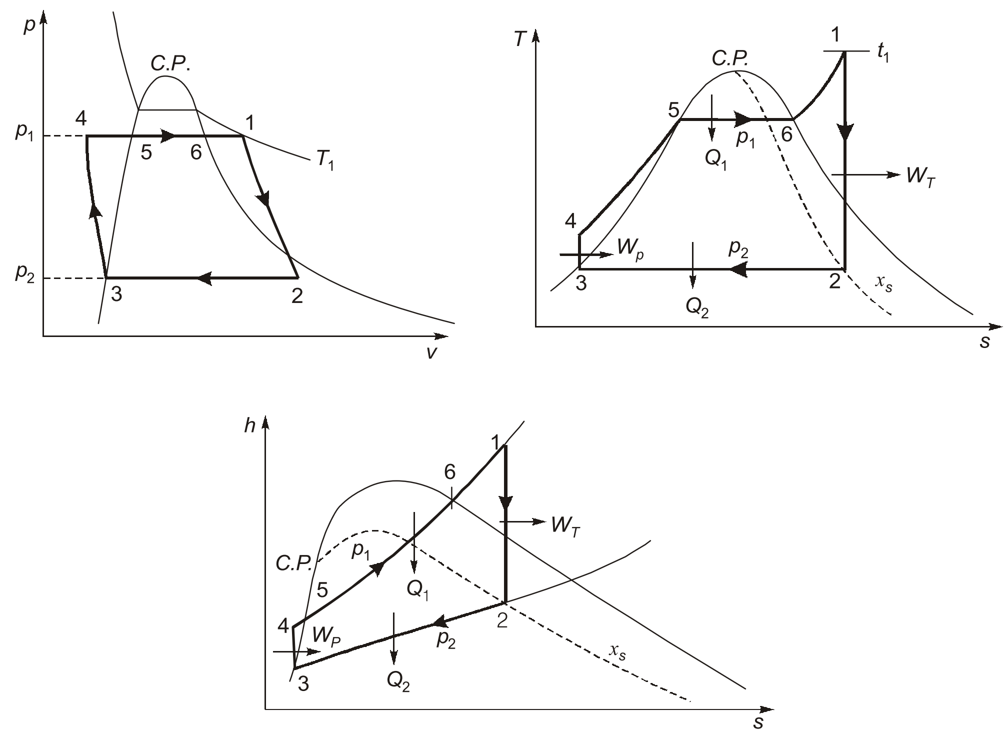


Fig. 3.6

Water is first heated sensibly in the economiser in the liquid phase at a certain pressure till it becomes saturated liquid.

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

In the evaporator there is phase change or boiling with state changing 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 gaseous phase.

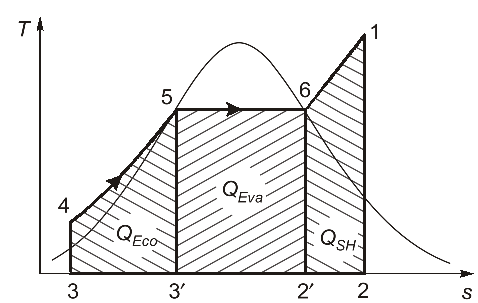


Fig. 3.7

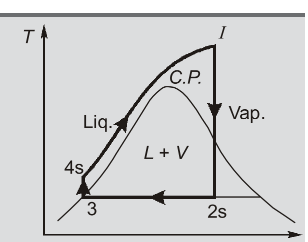
$$q_{SH} = h_1 - h_6$$

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.

NOTE

For steam generators operating above the critical pressure there is no evaporator or boiling section.

However, there is a transition zone where all the liquid on being heated suddenly flashes into vapour.



Rankine cycle with supercritical boiler pressure leaving the condenser is subcooled by 6.3°C. The boiler is sized for a mass flow rate of 20 kg/s. Determine the rate at which heat is added in the boiler, the power required to operate the pumps, the net power produced by the cycle and the thermal efficiency.

[Ans. 59,660 kW, 122 kW, 18,050 kW, 30.3%]

Q.3 The closed feedwater heater of a regenerative Rankine cycle is to heat 7000 kPa feedwater from 260°C to a saturated liquid. The turbine supplies bleed steam at 6000 kPa and 325°C to this unit. This steam is condensed to a saturated liquid before entering the pump. Calculate the amount of bleed steam required to heat 1 kg of feedwater in this unit.

[Ans. 0.0779 kg/s]

Q.4 A steam power plant operates on an ideal regenerative Rankine cycle with two open feedwater heaters. Steam enters the turbine at 10 MPa and 600°C and exhausts to the condenser at 5 kPa. Steam is extracted from the turbine at 0.6 and 0.2 MPa. Water leaves both feedwater heaters as a saturated liquid. The mass flow rate of steam through the boiler is 22 kg/s. Show the cycle on a T-s diagram, and determine

(a) the net power output of the power plant and

(b) the thermal efficiency of the cycle

[Ans. (a) 30.5 MW, (b) 47.1%]

Note: *Use steam table if required.*

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