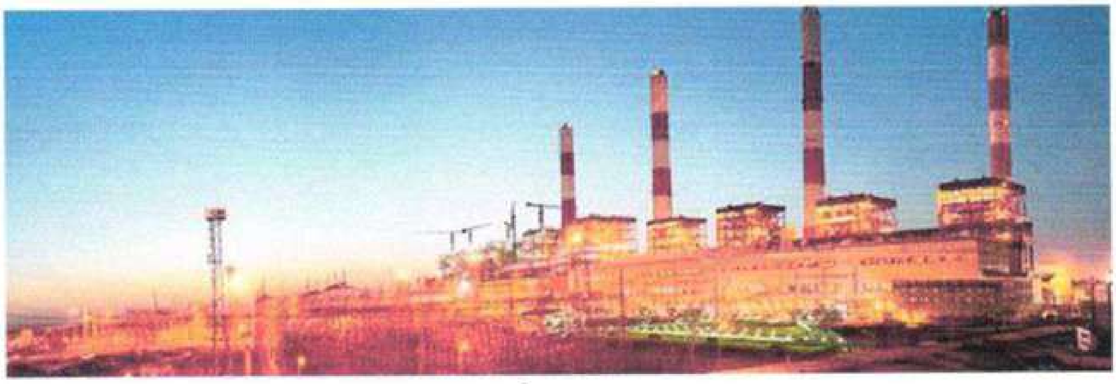
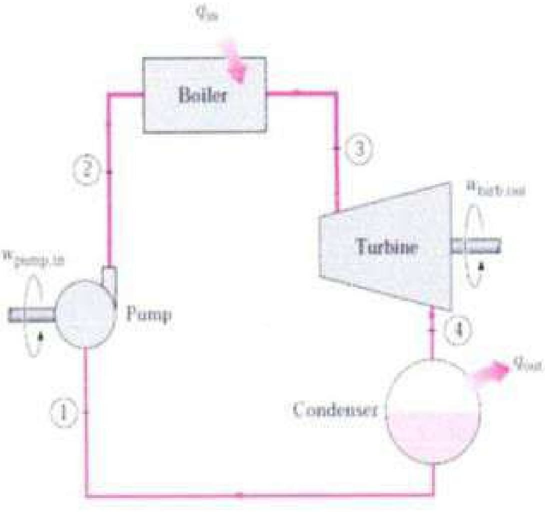
6

VAPOR POWER CYCLES





Course Contents

6.1 Performance Parameters of Vapor Power Cycle

a) Thermal Efficiency

Thermal efficiency is given by,

$$\eta = \frac{Net\ work\ done\ in\ the\ cycle}{Heat\ supplied\ in\ the\ cycle} = \frac{w_{net}}{q_1}$$

b) Work Ratio

The work ratio for a power plant is defined as ratio of the net work output of the cycle to the work developed by the turbine. It is expressed as,

$$Work\ ratio = \frac{w_{net}}{w_t}$$

$$\therefore Work\ ratio = \frac{w_t - w_p}{w_t} = 1 - \frac{w_p}{w_t}$$

A low work ratio implies large pump work. Larger the pump work, lower the work ratio.

c) Steam Rate or Specific Steam Consumption (SSC)

It is defined as the flow rate of steam per unit of power developed (kWh).

$$SSC = \frac{Steam\ flow\ rate}{Power\ output}$$

$$SSC = \frac{3600}{w_{net}}; \frac{kg}{kWh}$$

Where, w_{net} is in kJ/kg.

d) Heat Rate

Thermal efficiency can be expressed as heat rate, which is a measure of the rate of heat input q_1 required to produce unit work output (1kW).

$$Heat\ rate = \frac{3600 \times q_1}{w_{net}}$$

$$\therefore Heat\ rate = \frac{3600}{\eta_{th}}; kJ/kWh$$

6.2 The Carnot Vapor Cycle

- The Carnot cycle is the most efficient cycle operating between two specified temperature limits. The Carnot cycle is an ideal cycle for vapor power plants. However, the Carnot cycle is not a suitable model for power cycles, as there are so many practical difficulties are associated with it (discussed later).

- Fig. 6.1 shows P-v, T-S, h-S and schematic diagram of the Carnot cycle when steam is used as the working substance.

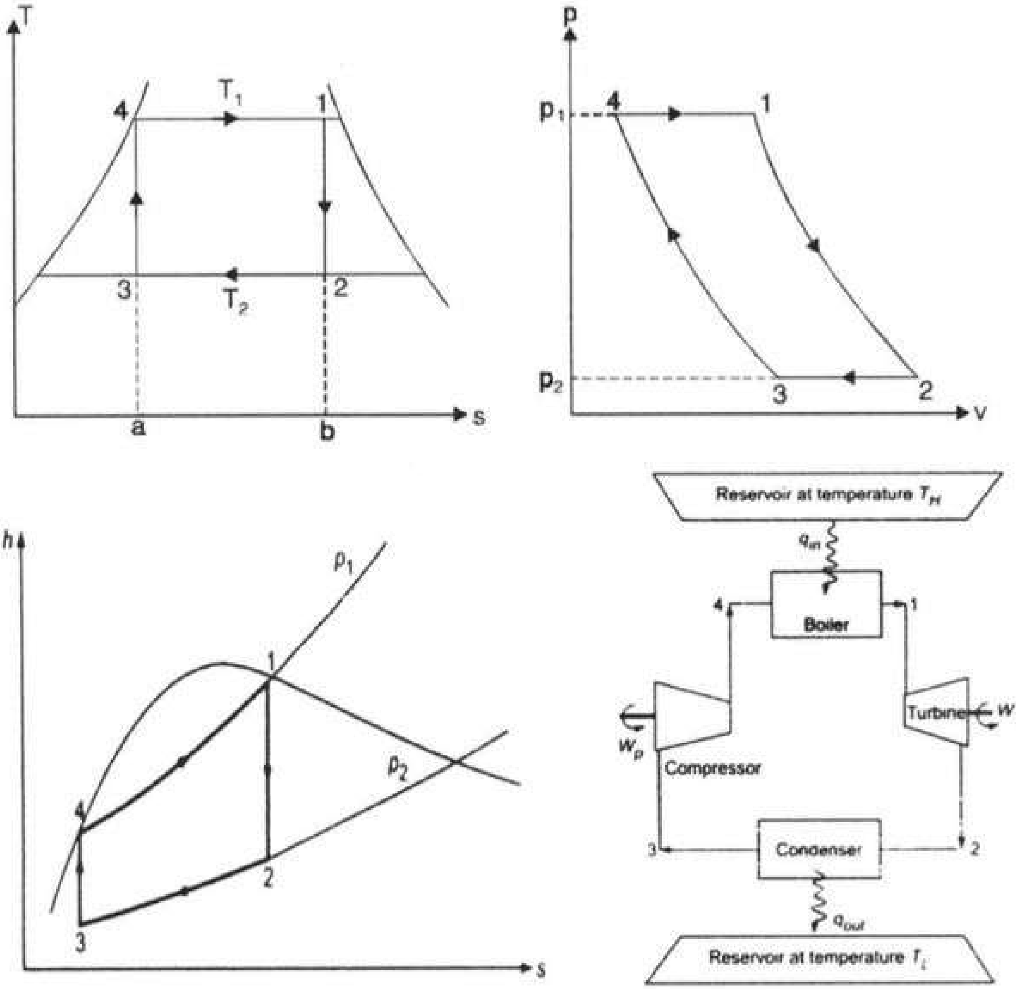


Fig. 6.1 P-v, T-S, h-S and schematic diagram of Carnot vapor cycle

- Consider 1 kg of steam as a working substance for the analysis. The cycle is composed of two isentropic and two isothermal processes. Since the working fluid is vapor, the isothermal processes are also the constant pressure processes. These processes are discussed below:

- **Process 4 – 1: Reversible isothermal heat addition in the boiler**

  Heat is supplied to the feed water (saturated water) in a boiler. Latent heat is supplied and isothermal evaporation of water takes place at constant pressure until the water gets converted into dry & saturated steam.

  Heat added isothermally at temperature T_1 is given by,

$$q_1 = h_1 - h_4$$

- **Process 1 – 2: Isentropic expansion in the turbine**

The dry & saturated steam undergoes frictionless adiabatic expansion in the steam turbine and work is done by the system$(+ve)$.

Turbine work is given by,

$$w_t = h_1 - h_2$$

- **Process 2 – 3: Controlled condensation in the condenser**

  Steam leaving the turbine is condensed isothermally at constant pressure.

  Heat rejected isothermally at temperature T_2 is given by,

$$q_2 = h_2 - h_3$$

- **Process 3 – 4: Isentropic compression in the pump (Pumping process)**

  The wet steam is compressed isentropically and it is restored to initial state point 4 and work is done on the steam$(-ve)$.

  Compressor work is given by,

$$w_c = h_4 - h_3$$

Thermal Efficiency of Carnot Vapor Cycle

- Thermal efficiency,

$$\eta = \frac{Net\ Work}{Heat\ Supplied}$$

$$\eta = \frac{w_{net}}{q_1} - - - - - - - - -(6.1)$$

- **Heat supplied** to the working fluid in a boiler,

$$q_1 = Area\ under\ the\ line\ 4-1\ in\ T-s\ diagram$$

$$q_1 = T_1 dS = T_1(S_1 - S_4)$$

  As $S_1 = S_2\ and\ S_3 = S_4$

$$\therefore q_1 = T_1(S_2 - S_3) - - - - - - - - -(6.2)$$

- **Heat rejected** during condensation process,

$$q_2 = Area\ under\ the\ line\ 2-3\ in\ T-s\ diagram$$

$$q_2 = T_2 dS = T_2(S_2 - S_3) - - - - - - - - -(6.3)$$

- The **net work done** of the cycle,

$$w_{net} = q_1 - q_2$$

  From equation 6.2 and 6.3,

$$\therefore w_{net} = T_1(S_2 - S_3) - T_2(S_2 - S_3)$$

$$\therefore w_{net} = (S_2 - S_3)(T_1 - T_2) - - - - - - - - -(6.4)$$

- From equation 6.1,

  Thermal efficiency,

$$\eta_{Carnot} = \frac{(S_2 - S_3)(T_1 - T_2)}{T_1(S_2 - S_3)}$$

$$\therefore \eta_{Carnot} = \frac{(T_1 - T_2)}{T_1}$$

$$\therefore \eta_{Carnot} = 1 - \frac{T_2}{T_1} - - - - - - - - - (6.5)$$

- Equation 6.5 of Carnot vapor cycle efficiency is similar to the Carnot gas power cycle. It shows that, the efficiency of Carnot cycle is depends upon the limit of temperatures and is independent of the nature of working substance.

Practical Difficulties Associated with Carnot Vapor Power Cycle

I. The cycle is more difficult to operate in practice with superheated steam due to the necessity of supplying the superheat at constant temperature. So maximum possible temperature is limited.

II. In the turbine, the dry and saturated steam expands isentropically. The quality of steam decreases during expansion. The presence of high moisture content in steam will lead to erosion and wear of the turbine blades.

III. It is difficult to control the condensation at state 3, before reaching to saturated liquid state.

IV. It is difficult to compress a wet vapor (water + steam) isentropically, as required by the process 3-4. Because of large specific volume of vapor than liquid, the compressor size and work input will have to be large and this higher compression work will reduce the thermal efficiency of the plant.

- *These practical difficulties limit the use of Carnot cycle as a suitable model for design of steam power plants.*