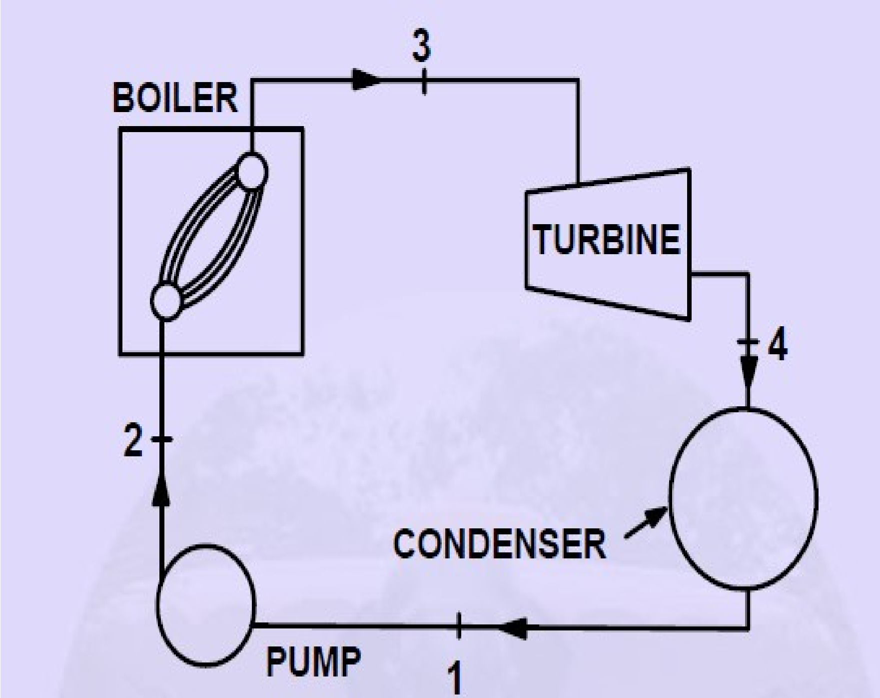
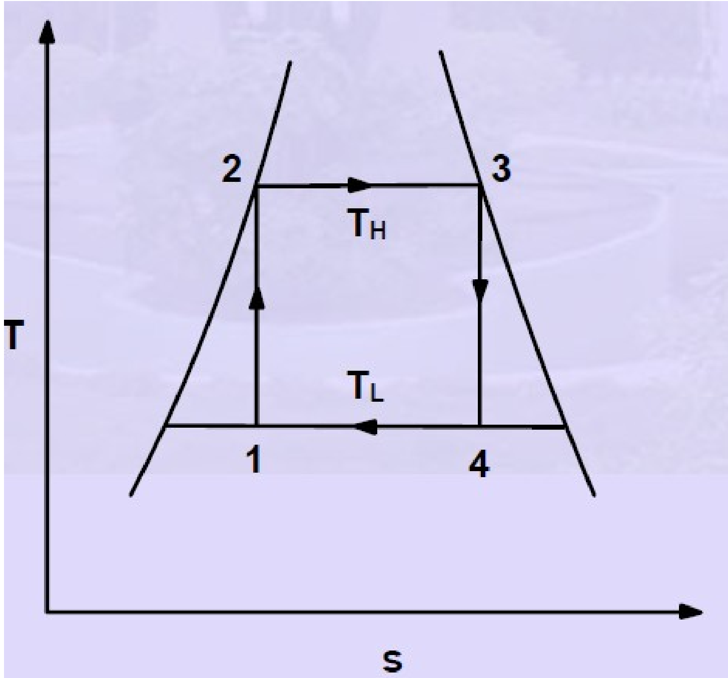
# Vapor Power Cycles




Carnot vapour cycle



- Process 1-2: Reversible adiabatic compression process from P1 to P2.
- Process 2-3: Reversible isothermal heat addition process at constant temperature TH.
- Process 3-4: Reversible adiabatic expansion process from P3 to P4.
- Process 4-1: Reversible isothermal heat rejection process at constant temperature TL.
- Saturated vapor leaves the boiler at state 3, enters the turbine and expands to state 4.
- The fluid then enters the condenser, where it is cooled to state 1 and then it is
- compressed to state 2 in the pump. The efficiency of the cycle is as follows:

$$\eta_{carnot} = \frac{T_H - T_L}{T_H} = \left[1 - \frac{T_L}{T_H}\right]$$

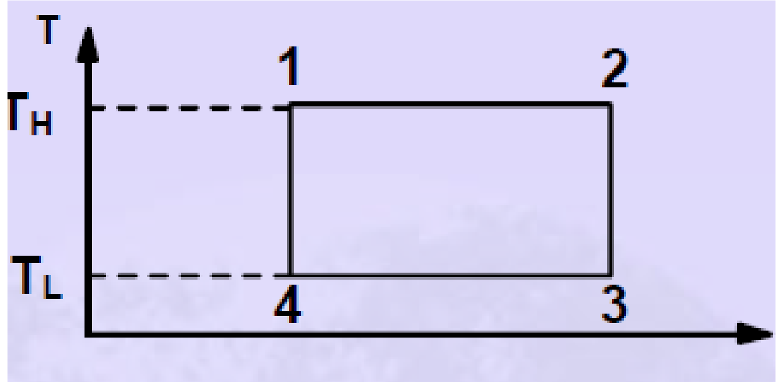
- Practically, it is very difficult to add or reject heat to or from the working fluid at constant temperature. But, it is comparatively easy to add or reject heat to or from the working fluid at constant pressure. Therefore, Carnot cycle is not used as an idealized cycle for steam power plants. However, ideal cycle for steam power plant is Rankine cycle in which heat addition and rejection takes place at constant pressure process

# Carnot Cycle

A Carnot gas cycle operating in a given temperature range is shown in the T-s diagram in Fig. 4.1(a). One way to carry out the processes of this cycle is through the use of steady-state, steady-flow devices as shown in Fig. 4.1(b). The isentropic expansion process 2-3 and the isentropic compression process 4-1 can be simulated quite well by a well-designed turbine and compressor respectively, but the isothermal expansion process 1-2 and the isothermal compression process 3-4 are most difficult to achieve. Because of these difficulties, a steady-flow Carnot gas cycle is not practical.

The Carnot gas cycle could also be achieved in a cylinder-piston apparatus (a reciprocating engine) as shown in Fig. 4.2(b). The Carnot cycle on the p-v diagram is as shown in Fig. 4.2(a), in which processes 1-2 and 3-4 are isothermal while processes 2-3 and 4-1 are isentropic. We know that the Carnot cycle efficiency is given by the expression.

$$\eta_{th} = 1 - \frac{T_L}{T_H} = 1 - \frac{T_4}{T_1} = 1 - \frac{T_3}{T_2}$$




(a)

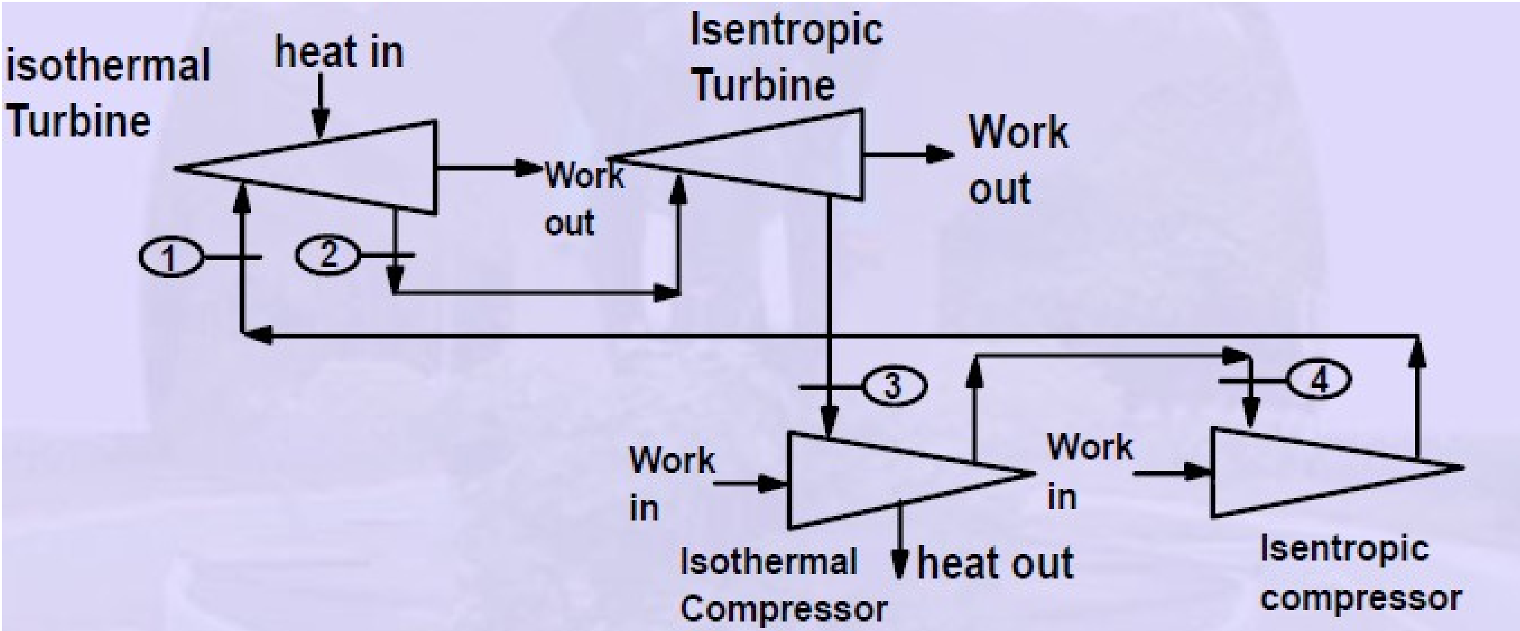



Fig.4.1. Steady flow Carnot engine

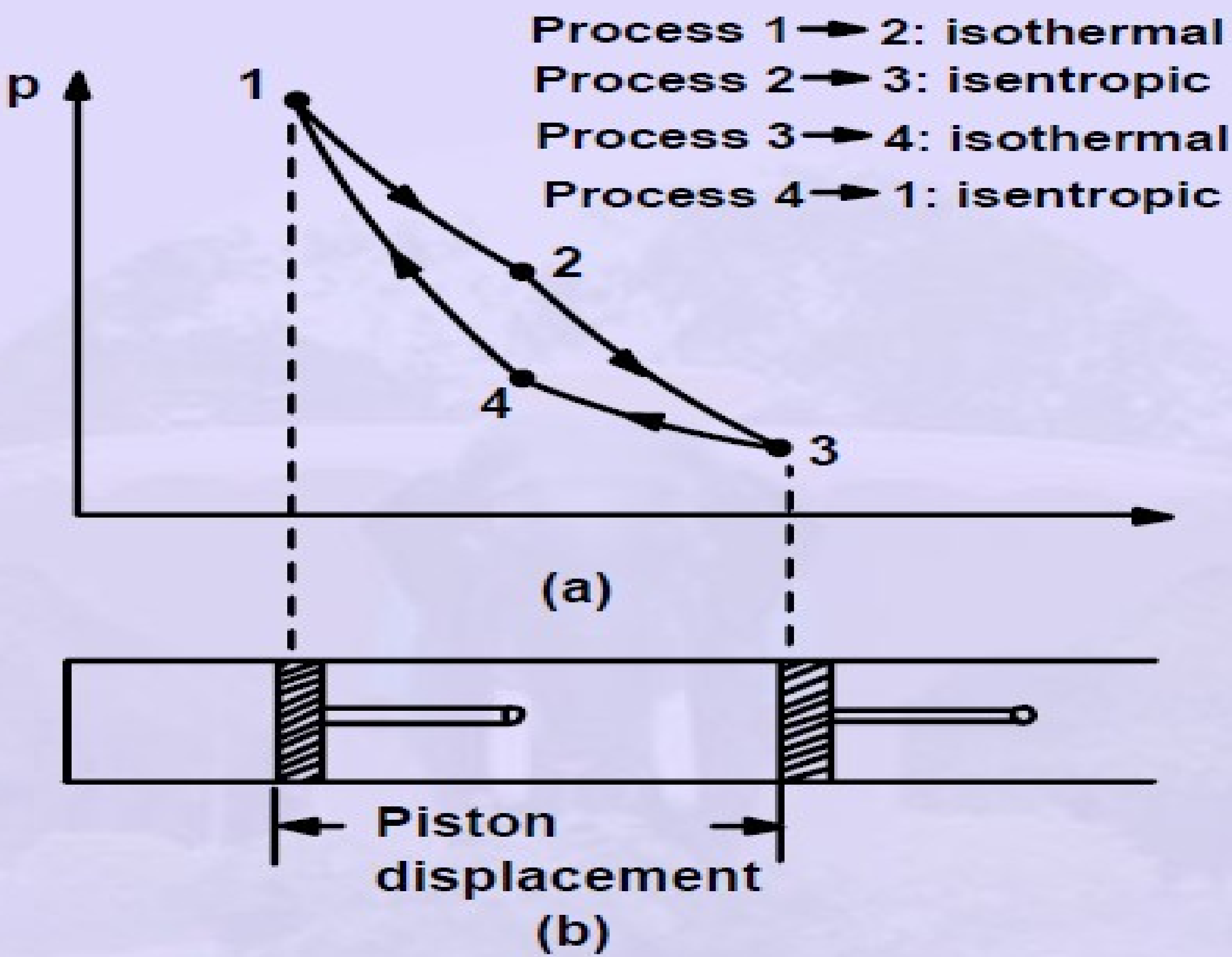



Fig.4.2. Reciprocating Carnot engine

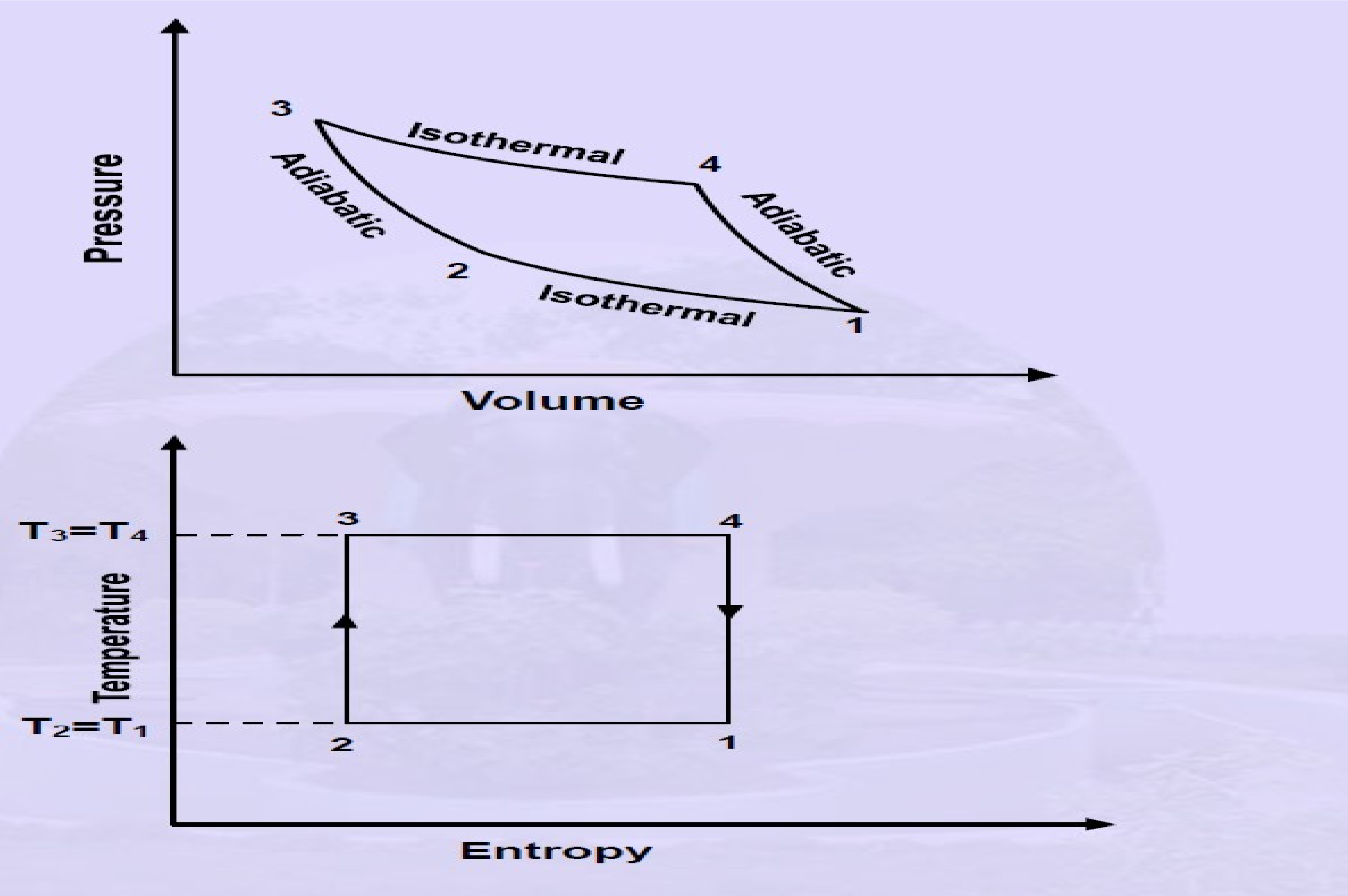



Fig.4.3. Carnot cycle on p-v and T-s diagrams

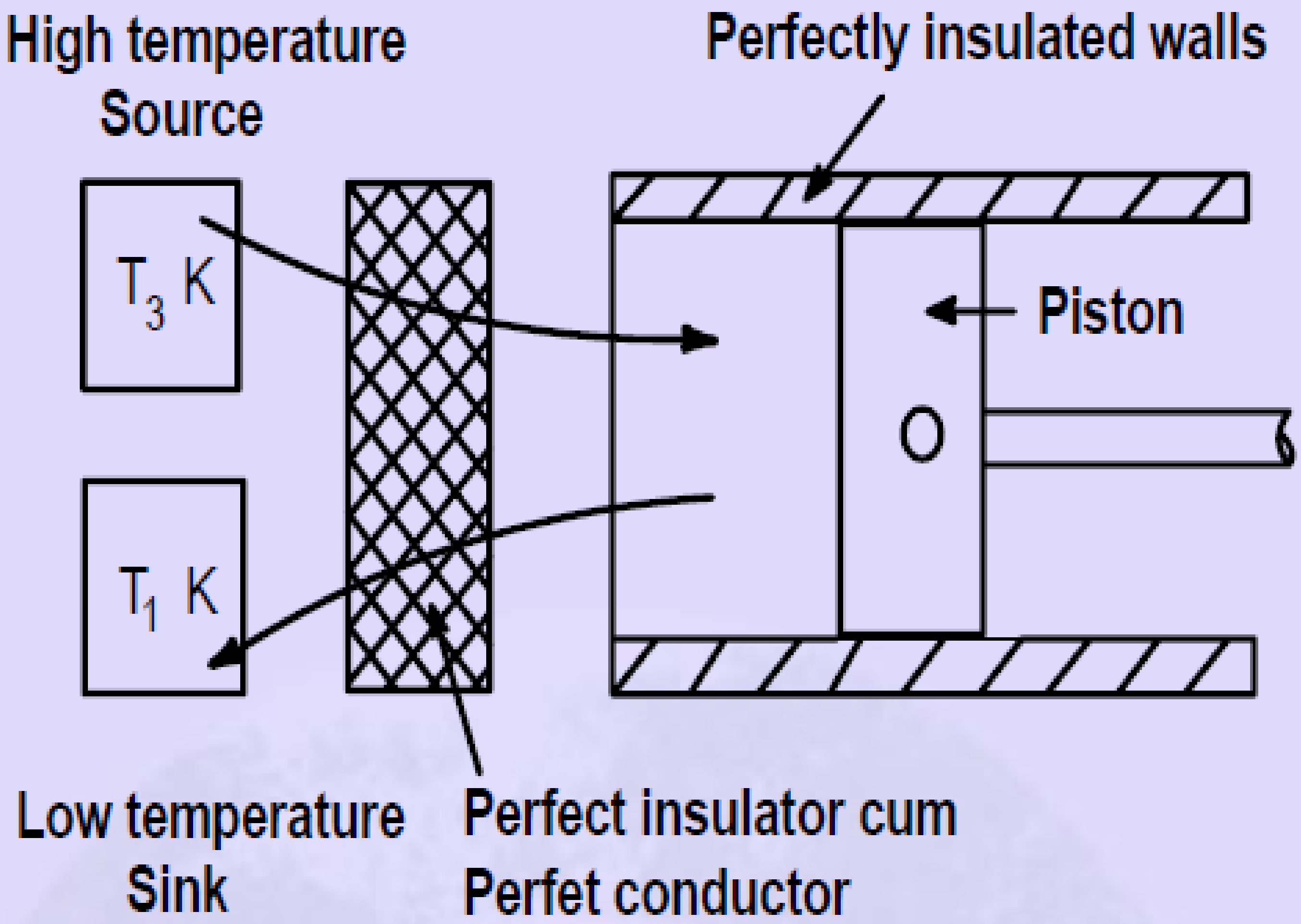



Fig.4.4. Working of Carnot engine

Since the working fluid is an ideal gas with constant specific heats, we have, for the isentropic process,

$$\frac{T_1}{T_4} = \left(\frac{V_4}{V_1}\right)^{\gamma-1} \quad ; \quad \frac{T_2}{T_3} = \left(\frac{V_3}{V_3}\right)^{\gamma-1}$$

Now, $T_1 = T_2$ and $T_4 = T_3$, therefore

$$\frac{v_4}{v_1} = \frac{v_3}{v_2} = r = \text{compression or expansion ratio}$$

- Therefore, Carnot cycle efficiency may be written as,

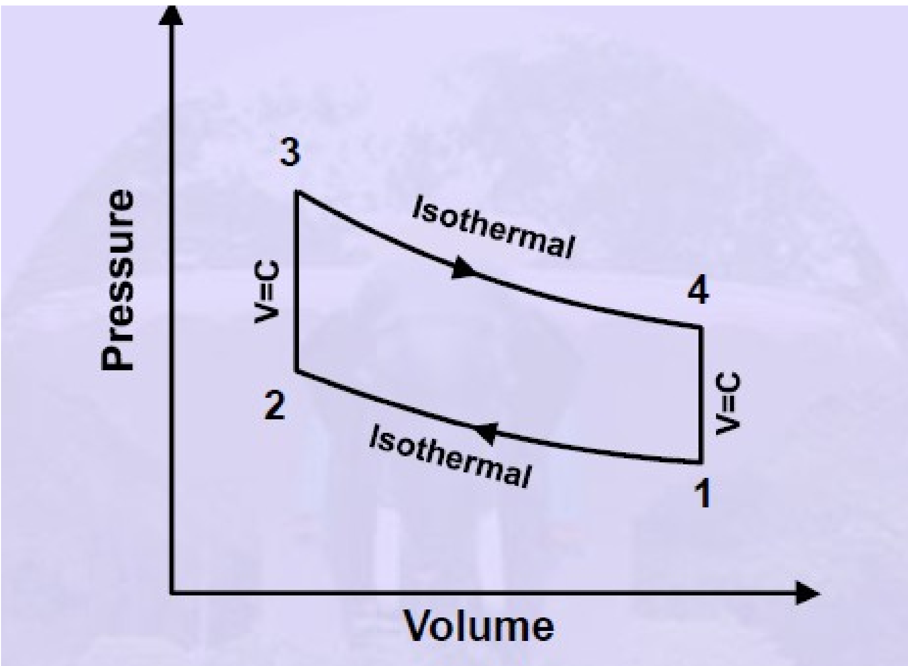
$$\eta_{th} = 1 - \frac{1}{r_p^{\frac{\gamma - 1}{\gamma}}}$$

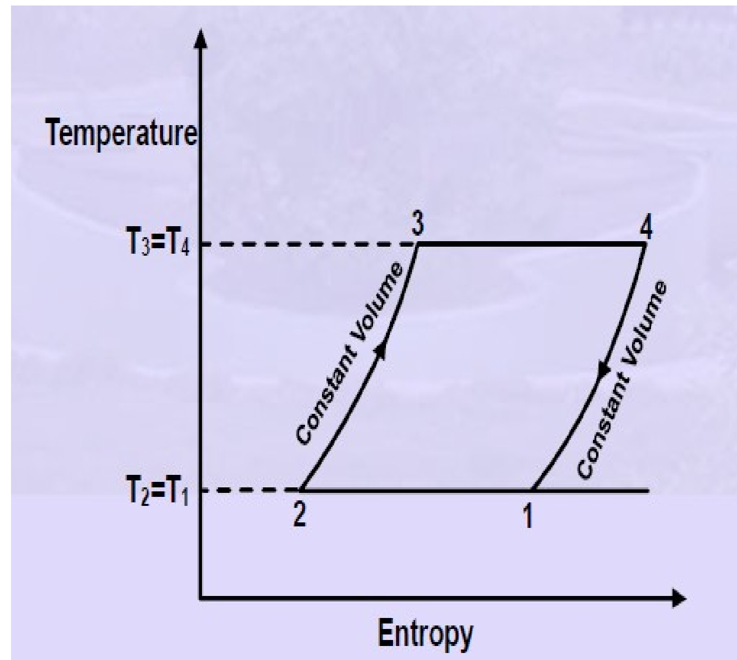
- From the above equation, it can be observed that, the Carnot cycle efficiency can be increased by increasing the pressure ratio. This means that Carnot cycle should be operated at high peak pressure to obtain large efficiency.

# Stirling Cycle (Regenerative Cycle) :

- The Carnot cycle has a low mean effective pressure because of its very low work output. Hence, one of the modified forms of the cycle to produce higher mean effective pressure whilst theoretically achieving full Carnot cycle efficiency is the Stirling cycle. It consists of two isothermal and two constant volume processes. The heat rejection and addition take place at constant temperature. The p-v and T-s diagrams for the Stirling cycle are shown in Fig.4.2.

# The p-v and T-s diagrams for the Stirling cycle



# Stirling Cycle Processes:

*a) The air is compressed isothermally from state 1 to 2 (TL to TH).*

*b) The air at state-2 is passed into the regenerator from the top at a temperature T1. The air passing through the regenerator matrix gets heated from TL to TH.*

*c) The air at state-3 expands isothermally in the cylinder until it reaches state-4.*

*d) The air coming out of the engine at temperature TH (condition 4) enters into regenerator from the bottom and gets cooled while passing through the regenerator matrix at constant volume and it comes out at a temperature TL, at condition 1 and the cycle is repeated.*

*e) It can be shown that the heat absorbed by the air from the regenerator matrix during the process 2-3 is equal to the heat given by the air to the regenerator matrix during the process 4-1, then the exchange of heat with external source will be only during the isothermal processes.*

- Now we can write, Net work done = W

  = Qs - QR

- Heat supplied = QS

  = heat supplied during the isothermal process 3-4.

$$= P_3V_3 \ln\left(\frac{V_4}{V_3}\right) \; ; \; r = \frac{v_4}{v_3} = CR$$

$$= mRT_H \ln(r)$$

Heat rejected = QR = Heat rejected during the isothermal compression process, 1-2.

$$= P_1V_1 \ln\left(\frac{v_1}{v_2}\right)$$

$$= mR\,T_L \ln(r)$$

$$W_{net} = m\,R \ln(r)\;[T_H - T_L]$$

Now,

$$\eta_{th} = \frac{W_{net}}{Q_s} = \frac{m\,R\,\ln(r)(T_H - T_L)}{m\,R\,\ln(r)\,T_H} \quad \frac{T_H - T_L}{T_H}$$

and

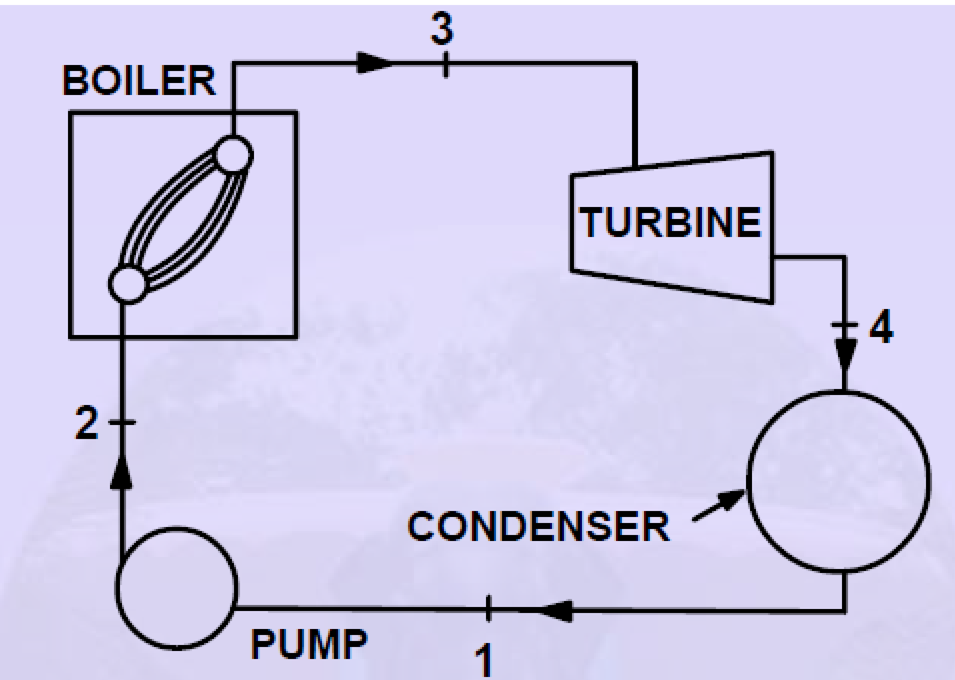
$$\eta_{th} = 1 - \frac{T_L}{T_H}$$

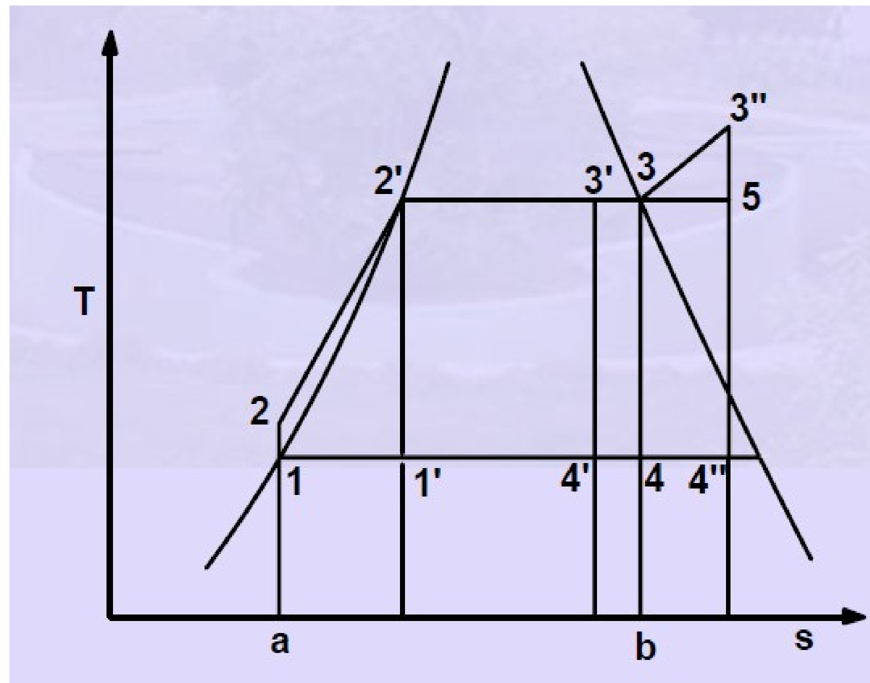
- Thus the efficiency of Stirling cycle is equal to that of Carnot cycle efficiency when both are working with the same temperature limits. It is not possible to obtain 100% efficient regenerator and hence there will be always 10 to 20 % loss of heat in the regenerator, which decreases the cycle efficiency. Considering regenerator efficiency, the efficiency of the cycle can be written as,

$$\eta_{th} = \frac{R \ln(r)(T_H - T_L)}{R\, T_H \ln(r) + (1 - \eta_R)\, C_V (T_H - T_L)}$$

# Rankine Cycle:

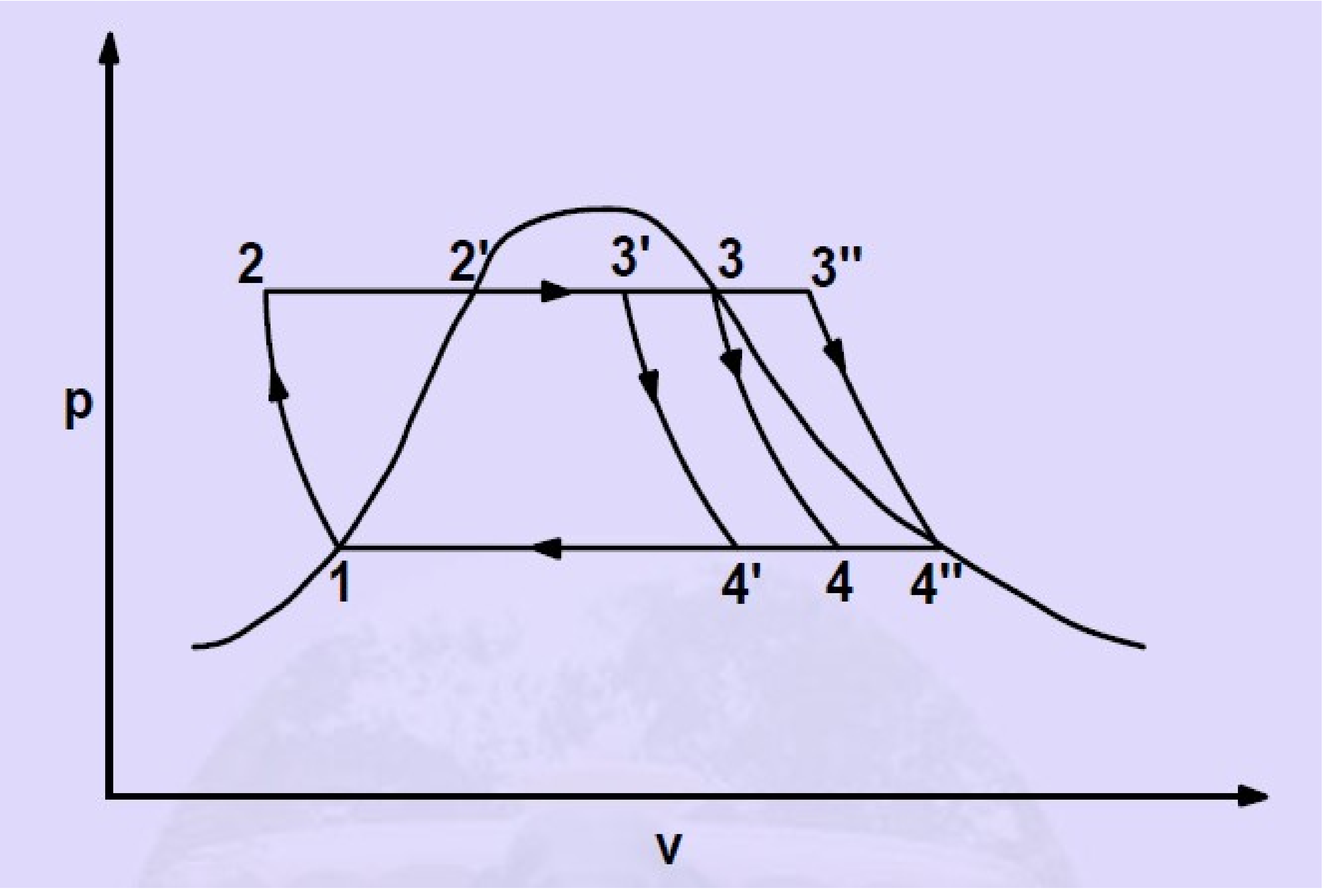
- Rankine cycle is the idealized cycle for steam power plants. This cycle is shown on p-v, T-v, h-s, diagram in the above figures. It consists of following processes:



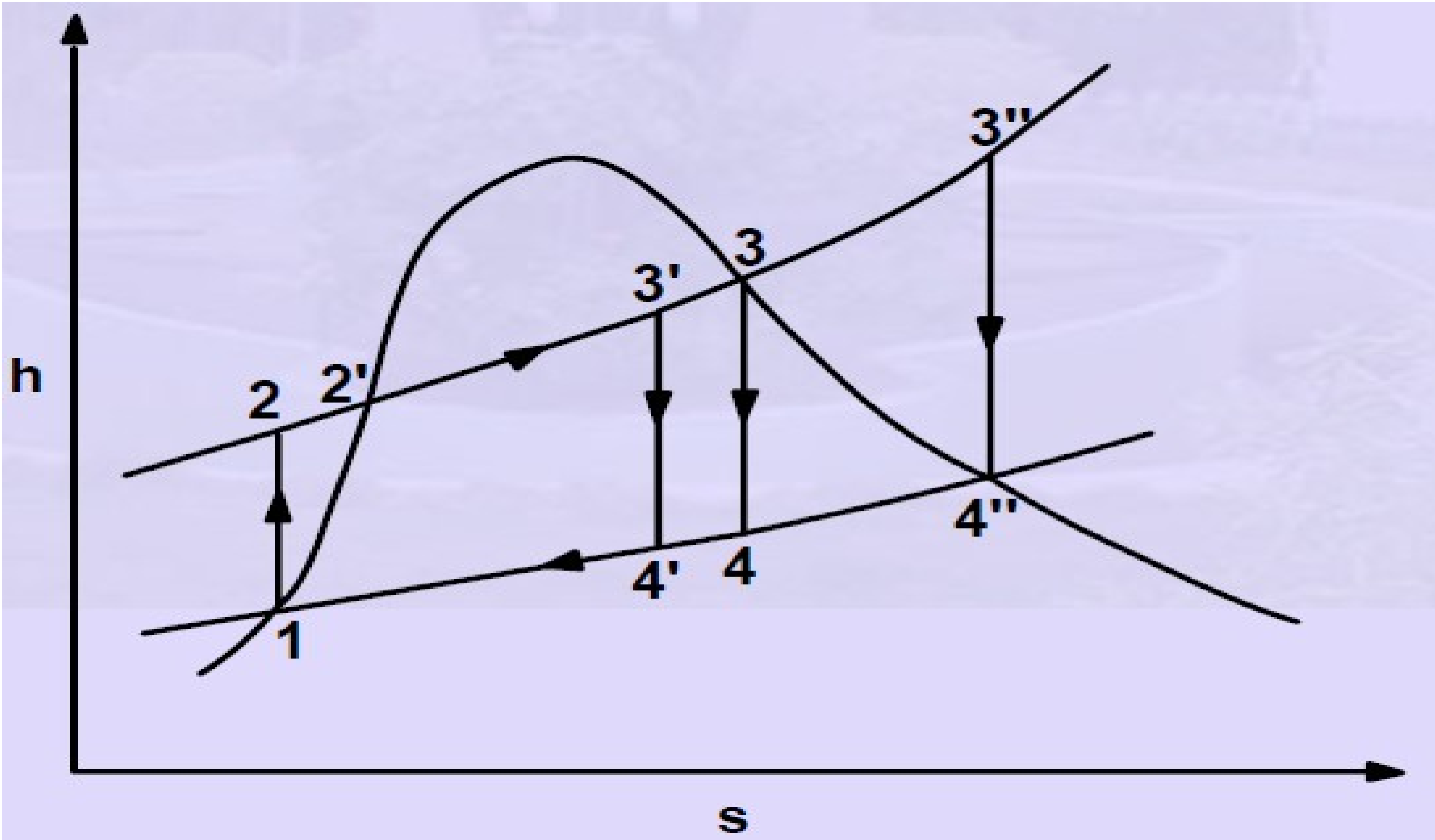




**Rankine vapour power cycle**

**T-s diagram Rankine power cycle**




**p-v diagram Rankine power cycle**




**h-s diagram Rankine power cycle**

- Process 1-2: Water from the condenser at low pressure is pumped into the boiler at high pressure. This process is reversible adiabatic.
- Process 2-3: Water is converted into steam at constant pressure by the addition of heat in the boiler.
- Process 3-4: Reversible adiabatic expansion of steam in the steam turbine.
- Process 4-1: Constant pressure heat rejection in the condenser to convert condensate into water.
- The steam leaving the boiler may be dry and saturated, wet or superheated. The corresponding T-s diagrams are 1-2-3-4-1; 1-2-3’-4’-1 or 1-2-3”-4”-1.

# Thermal Efficiency of Rankine Cycle:

- Consider one kg of working fluid, and applying first law to flow system to various processes with the assumption of neglecting changes in potential and kinetic energy,
- we can write,

$$\delta q - \delta w = dh$$

For process 2-3, $\delta w = 0$ (heat addition process), we can write,

$$(\delta q)_{boiler} = (dh)_{boiler} = (h_3 - h_2)$$

For process 3-4; $\delta q = 0$ (adiabatic process)

$$(\delta w)_{turbine} = -(dh)_{turbine} = (h_3 - h_4)$$

Similarly,

$$(\delta q)_{cond} = (h_1 - h_4)$$

$$(\delta w)_{pump} = (h_1 - h_2)$$

$$(\delta w)_{net} = (\delta w)_{turbine} + (\delta w)_{pump} = (h_3 - h_4) + (h_1 - h_2) = (h_3 - h_4) - (h_2 - h_1)$$

Now, Thermal efficiency

$$\eta_{th} = \frac{\text{Net work}}{\text{heat supplied}} = \frac{(\delta w)_{net}}{(\delta q)_{boiler}}$$

$$\eta_{rankine} = \eta_{th} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)} = \frac{\text{area } 122'341}{\text{area } a22'3ba}$$

The pump work ( )pump δw is negligible, because specific volume of water is very small. Therefore,

$$\eta_{rankine} = \frac{h_3 - h_4}{h_3 - h_2} = \frac{\text{area } 12'341}{\text{area } a12'3ba} \text{ (Neglecting pump work)}$$

- Note that the rankine cycle has a lower efficiency compared to corresponding Carnot cycle 2’-3-4-1’ with the same maximum and minimum temperatures. The reason is that the average temperature at which heat is added in the rankine cycle lies between T2
- and T’ 2 and is thus less than the constant temperature T’2 at which heat is added to the Carnot cycle.

# Reasons for Considering Rankine Cycle as an Ideal Cycle For Steam Power Plants:

1) It is very difficult to build a pump that will handle a mixture of liquid and vapor at state 1’ (refer T-s diagram) and deliver saturated liquid at state 2’. It is much easier to completely condense the vapor and handle only liquid in the pump.
2) In the rankine cycle, the vapor may be superheated at constant pressure from 3 to 3” without difficulty. In a Carnot cycle using superheated steam, the superheating will have to be done at constant temperature along path 3-5. During this process, the pressure has to be dropped. This means that heat is transferred to the vapor as it undergoes expansion doing work. This is difficult to achieve in practice.