CHAPTER FOUR

4. Typical Vapour-Compression System

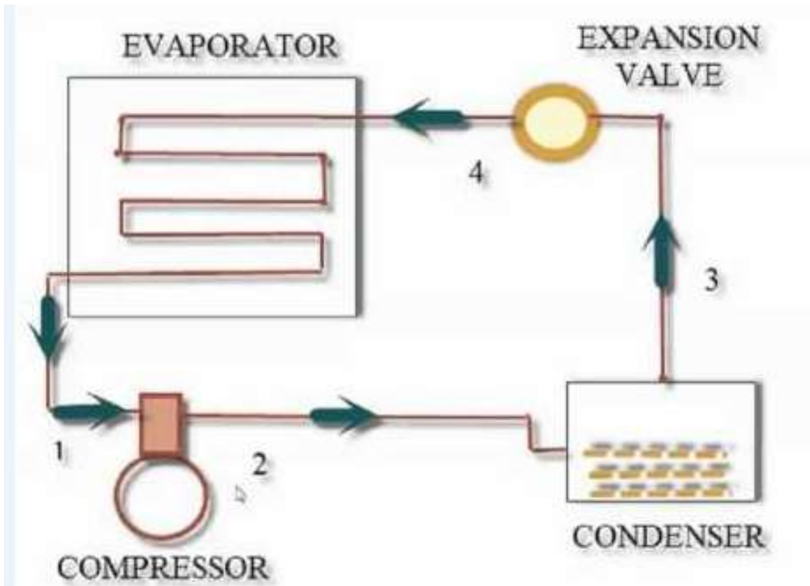

Fig.12.a. Flow diagram of simple vapour compression system

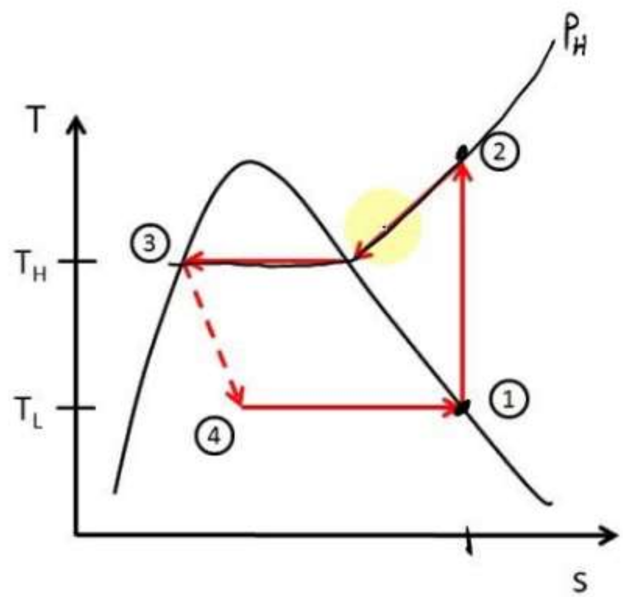

Fig 12.b. T-S diagram for a simple vapour compression system.

In the mechanical refrigerating system shown in Fig12.a; a suitable refrigerant (usually R12) is vaporized. This vapour is compressed and cooled to a liquid state and is reused again. Following the refrigerant cycle, the refrigerant is carried through 3, a liquid line and the liquid is throttled through the expansion devices(s), where the proper amount of refrigerant required at the evaporator is metered and the pressure of the liquid entering the evaporator is reduced, so that the liquid vaporize in the evaporator at the desired low temperature. At the expansion device, about 10%-20% of the refrigerant liquid is flashed into vapour. The mixture of the liquid and vapour is passed into the evaporator through liquid line 4, which provides heat transfer surface through which heat from the refrigerated space (or the cabinet box and its content) can pass into the vaporizing refrigerant; a suction line, conveys the low pressure vapour from the evaporator to the suction inlet, 1 of the compressor. The vapour compressor's function is to remove the vapour from the evaporator and to rise the temperature and pressure to a point such that the vapour can be condensed normally at the condenser. The high temperature and high pressure gas is discharged through discharge line 2, into the condenser whose purpose is to provide heat passes from the hot through which heat passes from the hot refrigerant to the condensing media.

4.1. Standard vapour compression Refrigeration system

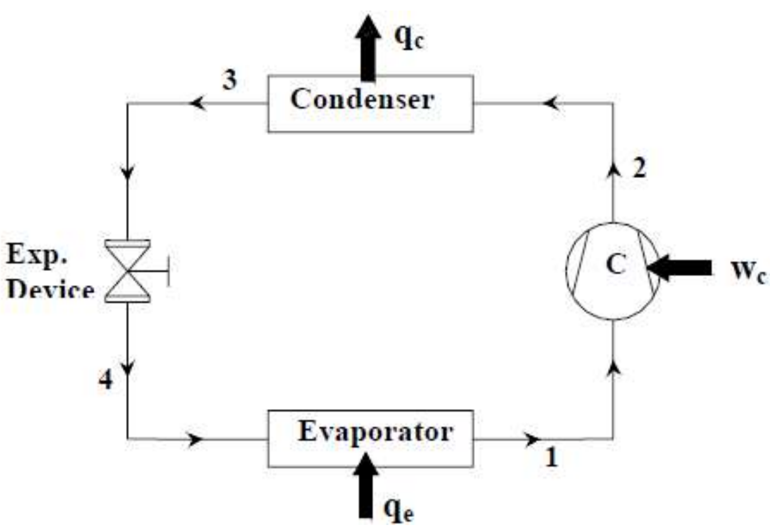

Fig. 13. Schematic diagram of a standard, saturated, single stage (SSS) vapour compression refrigeration system

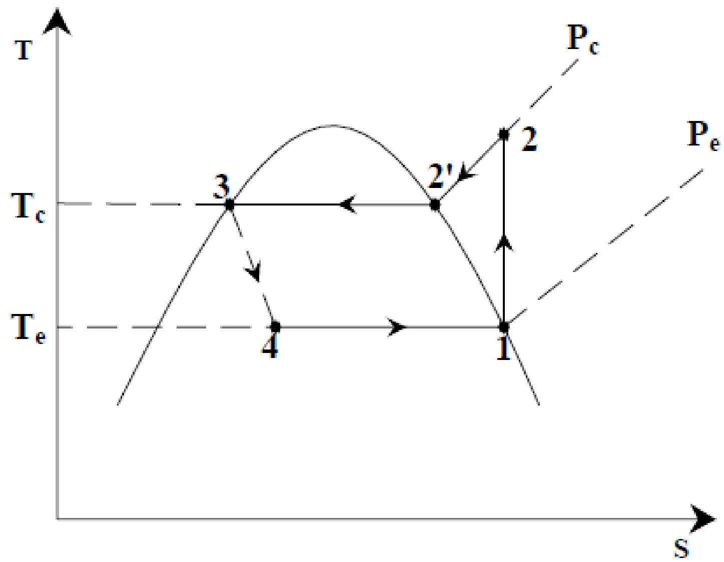

Fig. 14. T-S diagram of a Standard Vapour compression refrigeration system

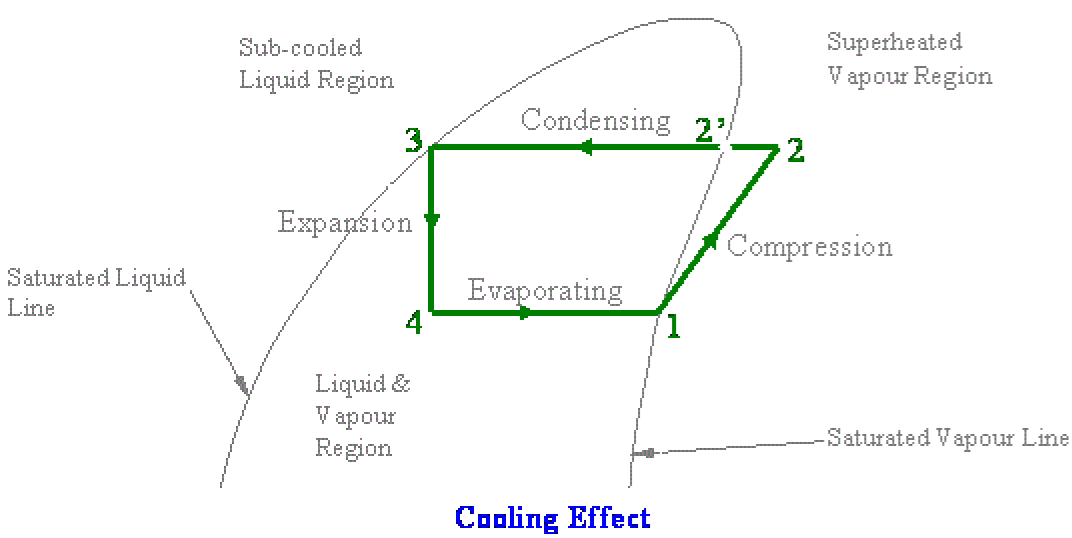

Fig. 15. P-h diagram of Standard Vapour Compression Refrigeration System (VCRS)

Standard Vapour Compression Refrigeration System (VCRS)

Figure 13. Shows the schematic of a standard, saturated, single stage (SSS) vapour compression refrigeration system and the operating cycle on a T s diagram (Fig. 5b) as shown in the figure

,the standard single stage saturated vapour compression refrigeration system consists of the following four processes:

Process 1-2: Isentropic compression of saturated vapour in compressor

Process 2-3: Isobaric heat rejection in condenser

Process 3-4: Isenthalpic expansion of saturated liquid in expansion device

Process 4-1: Isobaric heat extraction in the evaporator

By comparing with Carnot cycle, it can be seen that the standard vapour compression refrigeration cycle introduces two irreversibilities: 1) Irreversibility due to non-isothermal heat rejection (process 2-3) and 2) Irreversibility due to isenthalpic throttling (process 3-4). As a result, one would expect the theoretical COP of standard cycle to be smaller than that of a Carnot system for the same heat source and sink temperatures. Due to these irreversibilities, the cooling effect reduces and work input increases, thus reducing the system COP. This can be explained easily with the help of the cycle diagrams on T s charts. Figure 16 shows comparison between Carnot and standard VCRS in terms of refrigeration effect

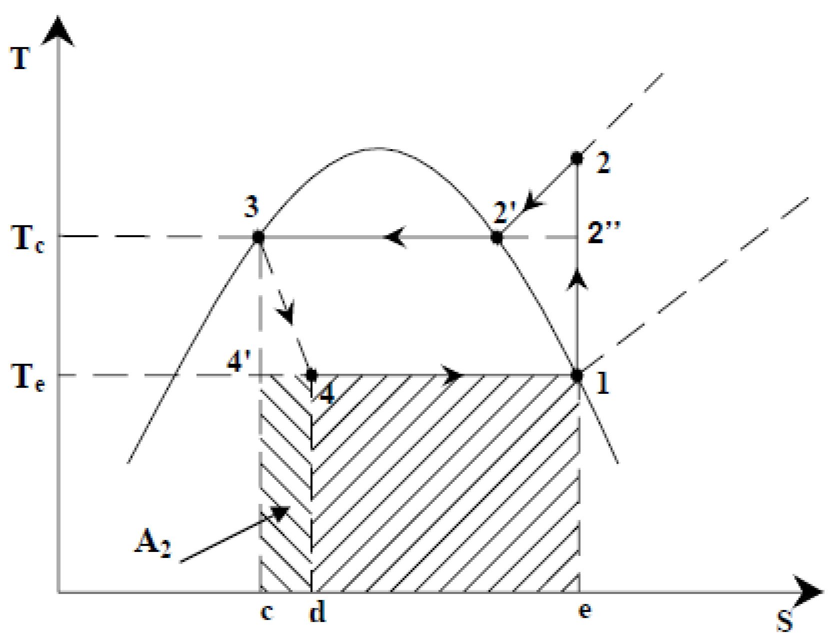

Fig. 16. Comparison between Carnot and standard VCRS

The heat extraction (evaporation) process is reversible for both the Carnot cycle and VCRS cycle. Hence the refrigeration effect is given by:

For Carnot refrigeration cycle (1-2''-3-4'):

$$q_{e,Carnot} = q_{4'-1} = \int_{4'}^{1} T.ds = T_e(s_1 - s_{4'}) = \text{area } e-1-4'-c-e$$

For VCRS cycle (1-2-3-4):

$$q_{e,VCRS} = q_{4-1} = \int_{4}^{1} T.ds = T_e(s_1 - s_4) = \text{area } e-1-4-d-e$$

thus there is a reduction in refrigeration effect when the isentropic expansion process of Carnot cycle is replaced by isenthalpic throttling process of VCRS cycle, this reduction is equal to the area d-4-4'-c-d (area A_2) and is known as *throttling loss*. The throttling loss is equal to the enthalpy difference between state points 3 and 4', i.e.

$$q_{e,Carnot} - q_{VCRS} = \text{area } d-4-4'-c-d = (h_3 - h_{4'}) = (h_4 - h_{4'}) = \text{area } A_2$$

It is easy to show that the loss in refrigeration effect increases as the evaporator temperature decreases and/or condenser temperature increases. A practical consequence of this is a requirement of higher refrigerant mass flow rate.

The heat rejection in case of VCRS cycle also increases when compared to Carnot cycle.

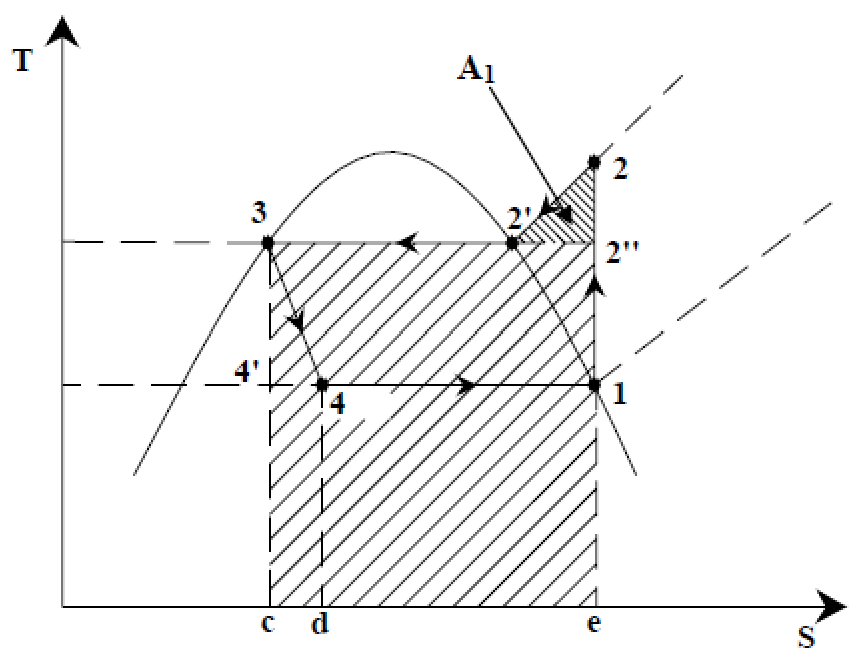

Fig. 17. Comparative evaluation of heat rejection rate of VCRS and Carnot cycle

The heat rejection in case of Carnot cycle (1-2''-3-4') is given by:

$$q_{c,Carnot} = -q_{2''-3} = -\int_{2''}^{3} T.ds = T_c(s_{2''} - s_3) = \text{area } e-2''-3-c-e$$

In case of VCRS cycle, the heat rejection rate is given by:

$$q_{c,VCRS} = -q_{2-3} = -\int_{2}^{3} T.ds = \text{ area } e-2-3-c-e$$

Hence the increase in heat rejection rate of VCRS compared to Carnot cycle is equal to the area 2''-2-2' (area A_1). This region is known as *superheat horn*, and is due to the replacement of isothermal heat rejection process of Carnot cycle by isobaric heat rejection in case of VCRS. Since the heat rejection increases and refrigeration effect reduces when the Carnot cycle is modified to standard VCRS cycle, the net work input to the VCRS increases compared to Carnot cycle. The net work input in case of Carnot and VCRS cycles are given by:

$$w_{net,Carnot} = (q_c - q_e)_{Carnot} = \text{area } 1-2''-3-4'-1$$

$$w_{net,VCRS} = (q_c - q_e)_{VCRS} = \text{area } 1-2-3-4'-c-d-4-1$$

As shown in Fig. below the increase in net work input in VCRS cycle is given by

$$w_{net,VCRS} - w_{net,Carnot} = \text{ area } 2''-2-2' + \text{area } c-4'-4-d-c = \text{area } A_1 + \text{area } A_2$$

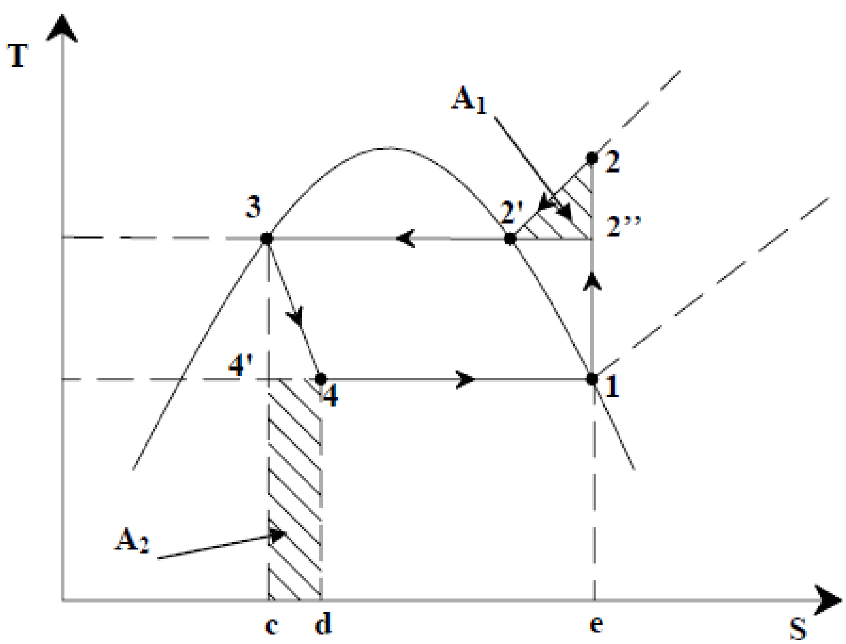

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Figure 18. Illustrating the increase in network input in VCRS cycle.

4.2. Theoretical vapour compression cycle with wet vapour after compression.

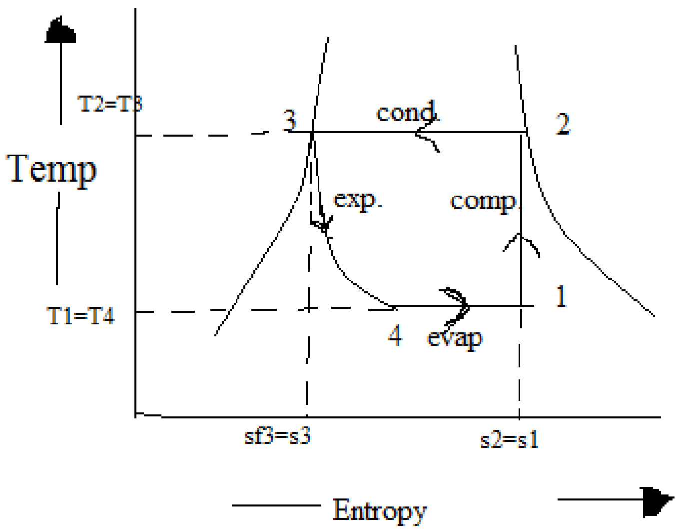

Fig. 11. T-S diagram for Wet Vapour Compression Cycle

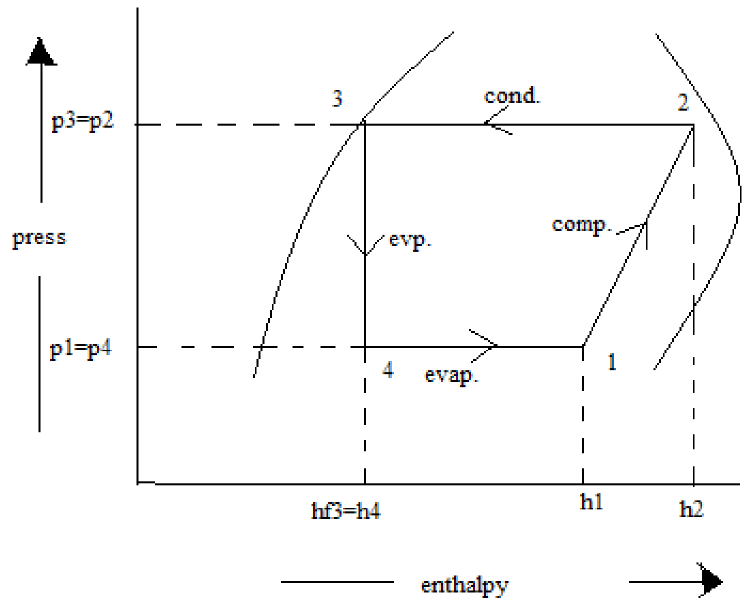

Fig. 12. P-h diagram for Wet Vapour Compression Cycle

In this cycle, enthalpy at state 2 is found with the help of dryness fraction at this point (2). The dryness fraction at points 1 and 2 may be obtained by equating entropies at state 1 and 2.

$$\text{C.O.P} = \frac{refrigerating\ effect}{work\ done} = \frac{h1-hf3}{h2-h1}$$

2.4. Theoretical vapour compression cycle with superheated vapour after compression.

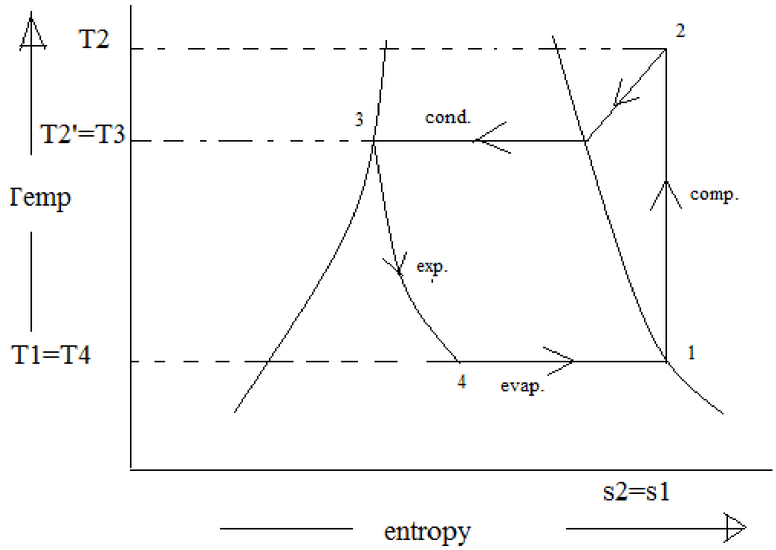

Fig.13 T-S diagram for Dry Vapour Compression Cycle

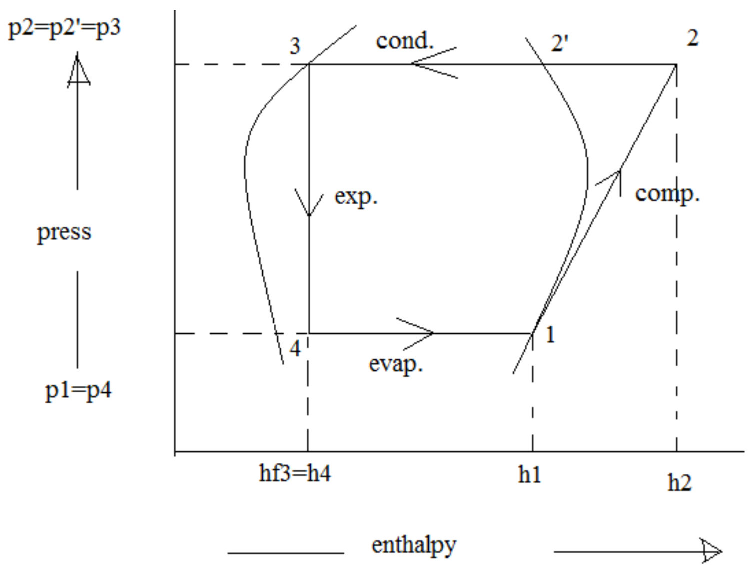

Fig. 14. P-h diagram for Dry Vapour Compresion Cycle

In this cycle, the enthalpy at point 2 is four with the help of degree and superheat. The degree of superheat may be found by equating the entropies at point (1 & 2).

$$\text{C.O.P} = \frac{\text{refrigerating effect}}{\text{work done}} = \frac{h1 - hf3}{h2 - h1}$$

4.3. Theoretical vapour compression cycle with superheated vapour before compression

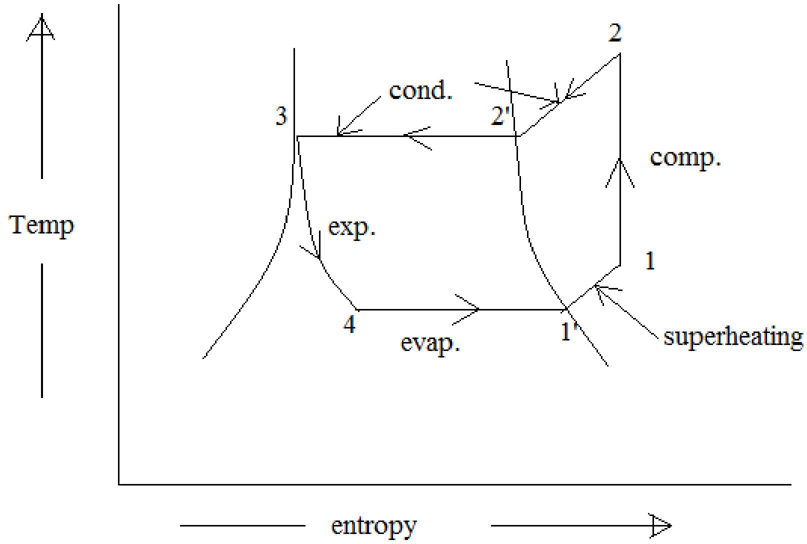

Fig. 15. T-S diagram for Vapour Compression cycle with superheated vapour before compression

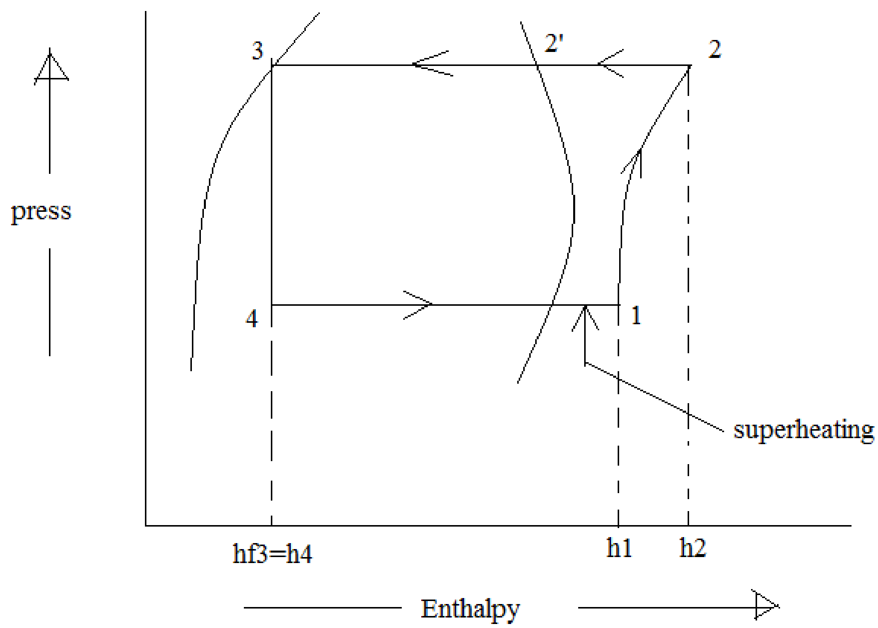

Fig. 16. P-h diagram for Vapour Compression cycle with superheated vapour before compression

In this cycle, the evaporation starts at state 4 and continues up to the point 1.

$$\text{C.O.P} = \frac{\text{Refrigerant effect}}{\text{workdone}} = \frac{h1-hf3}{h2-h1}$$

4.4. Theoretical vapour compression cycle with undercooling or sub cooling of refrigerant

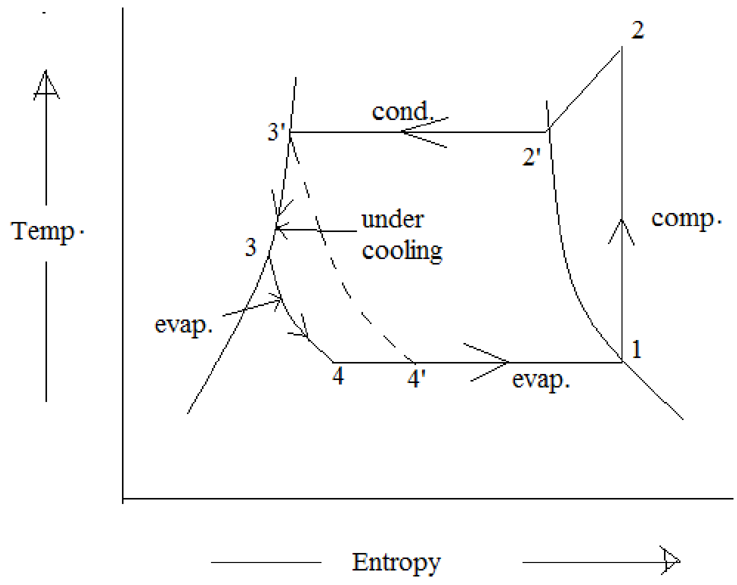

Fig. 17. T-S diagram for Vapour Compression cycle with undercooling refrigerant.

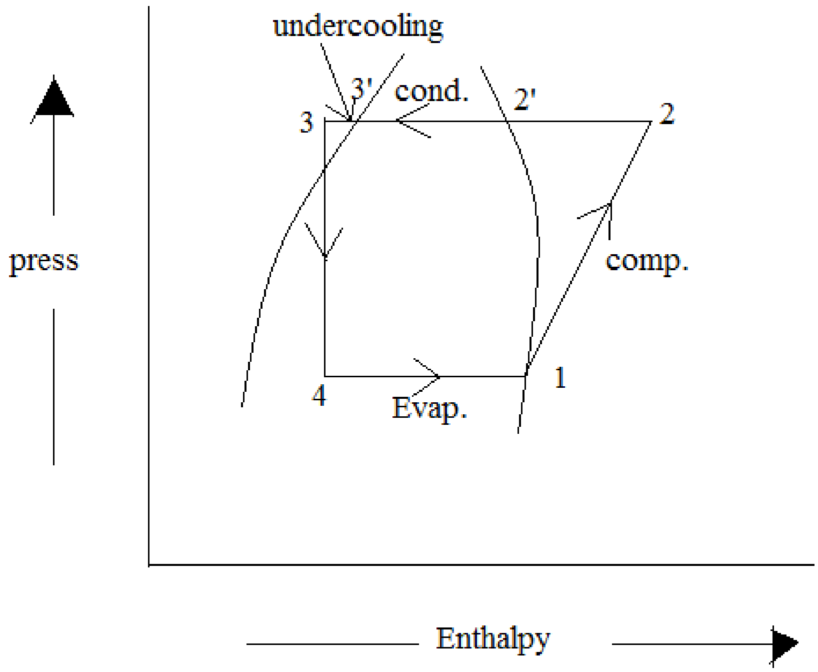

Fig. 18. P-h diagram for Vapour Compression cycle with undercooling refrigerant.

After condensation in process 2'-3', the refrigerant is cooled below the saturation temperature (T3') before expansion by throttling; such a process is called **undercooling** or **sub cooling** of the refrigerant and is generally done along the liquid line. The ultimate effect of undercooling is increase the value of coefficient of performance under the same set of conditions.

The process of undercooling is done by circulating more quantity of cooling water through the condenser; it is also achieved by employing a heat exchanger. In actual practice the refrigerant is superheated after compression and undercooled before throttling. The refrigerating effect is a little bit increased by adopting both the superheating and undercooling process as compared with a cycle without them.

In this case, the refrigerating effect or heat absorbed or extracted.

$$Re = h1\text{-}h4$$

$$= h1\text{-}hf3$$

And work done, W = h2-h1

But hf3 = hf3'-cp*degree of undercooling

$$\text{C.O.P} = \frac{\text{refrigerating effect}}{\text{work done}} = \frac{\text{h1} - \text{hf3}}{\text{h2} - \text{h1}}$$

4.5. Actual vapour compression cycle

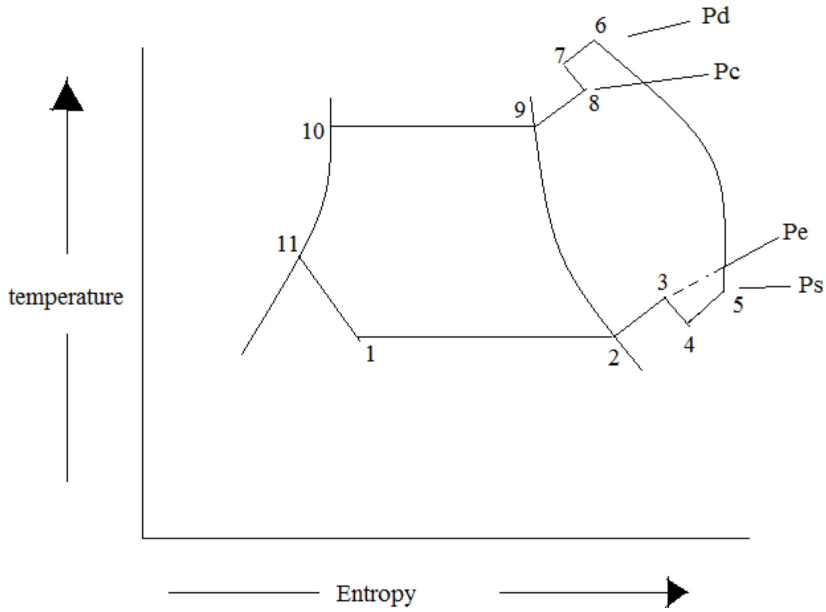

Fig. 19. T-S diagram for actual Vapour Compression cycle.

The actual vapour compression cycle is different from the theoretical vapour compression cycle in many ways. The main deviations between the theoretical and actual cycle are:

(1) Vapour refrigerant leaving the evaporator is in superheated state.

(2) The compression of refrigerant is neither isentropic nor polytropic.

(3) The liquid refrigerant before entering the expansion valve is sub cooled in the condenser.

(4) The pressure drops in the evaporator and condenser.

4.6. The processes in actual compression cycle

(a) Process 1-2-3: this shows the flow of refrigerant in the evaporator; point 1' is the entry of refrigerant into the evaporator and point '3' represents the exit of refrigerant from evaporator in a superheated state. Point '3' also represents the entry of refrigerant into the compressor in a superheated condition.

The superheating in point '2' to point '3' may be due to:

(i) Automatic control of expansion value so that the refrigerant leaves the evaporator as the superheated vapour.

(ii) Picking up a large amount of heat from the evaporator through pipes located within the cooled space.

(iii) Picking up of heat from the suction pipe (i.e. the pipe connecting the evaporator delivery and the compressor suction valve).In the first and second case of superheating the vapour refrigerant, the compressor work is increased, as well as the refrigerant effect. The C.O.P of the actual cycle at the same suction pressure may be greater, less or unchanged.

(b) Process 3-4-5-6-7-8: this represents the flow of refrigerant through the compressor. When the refrigerant enters the compressor through the suction valve at point '3', the pressure falls to point '4', due to frictional resistance to flow; thus the actual suction pressure (Ps) is lower than the evaporating pressure (Pe). During suction, prior to compression, the temperature of the cold refrigerant vapour rises to point '5' when it comes in contact with the compressor cylinder walls.The actual compression of the refrigerant is in process 5-6 which is neither isentropic nor polytropic. This is due to the heat transfer between the cylinder walls and the vapour refrigerant. There is a cooling effect at discharge as given by 6-7. These heating and cooling effects take place at constant pressure, due to the frictional resistance of flow, there is a pressure drop. I.e. the actual discharge pressure (Pd) is more than the condenser pressure (Pc).

(c) Process 8-9-10-11: this represents the flow of refrigerant through the condenser.

Process 8-9 represents the cooling of superheated vapour refrigerant to the dry saturated state. Process 9-10 shows the removal of latent heat which changes the dry saturated refrigerant into liquid refrigerant. Process 10-11 represents the sub-cooling of liquid refrigerant in the condenser before passing through expansion valve. sThis is desirable as it increases the refrigerating effect per kg of the refrigerant flow. It also reduces the volume of refrigerating partially evaporated from the liquid refrigerant while passing through the expansion valve. The increase in refrigerating effect can be obtained by large quantities of circulating cooling water which should be at a temperature much lower than the condensing temperatures.

(d) Process 11-1: this process represents the expansion of sub-cooled liquid refrigerant by throttling from the condenser pressure to the evaporator pressure.

4.7. Effect of suction pressure

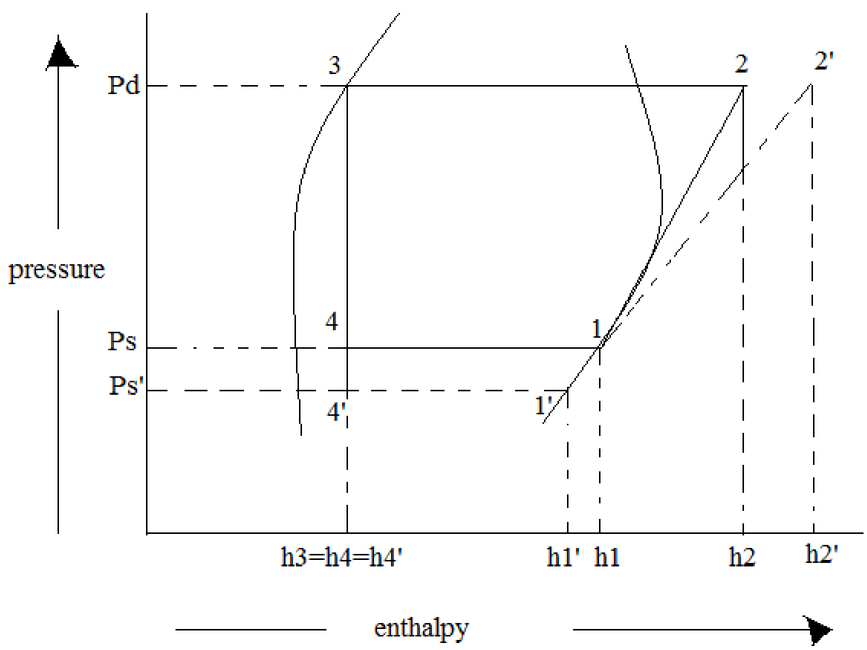

Fig.20. P-h diagram showing effect of suction pressure

We have discussed previously that in actual practice, the suction pressure (or evaporator pressure) decreases due to frictional resistance of flow of the refrigerant.

Let us consider a theoretical vapour compression cycle 1’-2’-3-4’ when the suction pressure decreases from Ps to Ps’ as shown on p-h diagram.

The decrease in suction pressure:

(i) Decrease the refrigerating effect from (h1-h4) to (h1-h4’), and

(ii) Increases the work required for compression from (h2-h1) to (h2’-h1).

4.8. Effect of discharge pressure

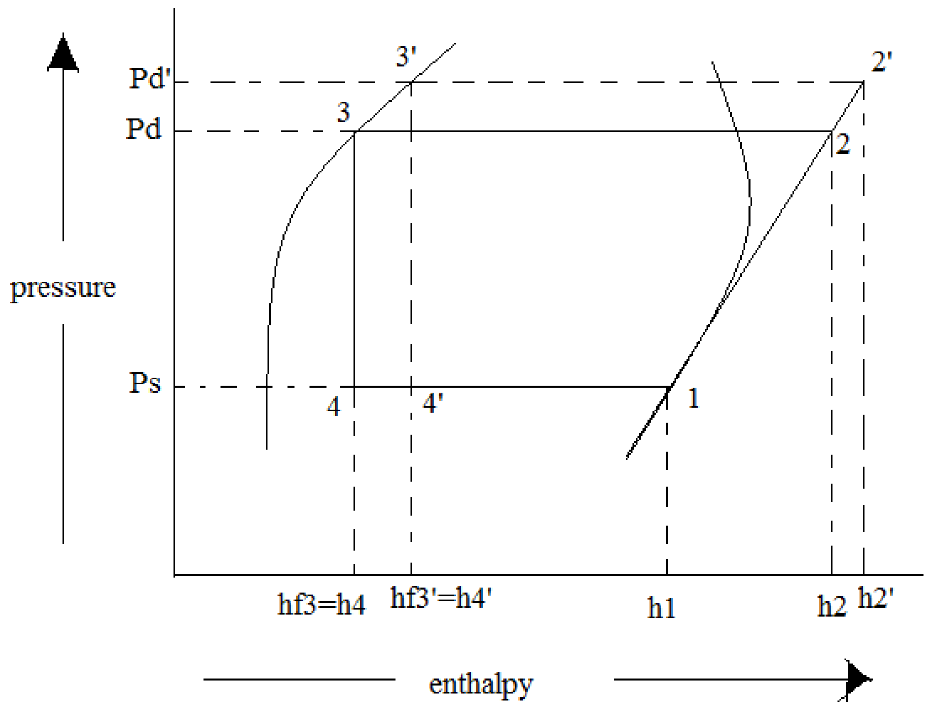

Fig.20. P-h diagram showing effect of discharge pressure

We have discussed previously that in actual practice, the discharge pressure (or condenser pressure) increases due to frictional resistance of flow of the refrigerant.

In the process 1-2’-3’-4’ when the discharge pressure increases from Pd to Pd’ as shown on the p-h diagram, it may be noted that the increase in discharge pressure:

(i) Decrease the refrigerating effect from (h1-h4) to (h1-h4’) and

(ii) Increases the work required for compression from (h2-h1) to (h2’-h1).