CHAPTER ONE

1. INTRODUCTION TO REFRIGERATION AND AIR CONDITION

Refrigeration may be defined as the process of reducing and maintaining a temperature of a space or material below that of the surroundings. This is accomplished by removing heat from body being refrigerated and transferred it to another body whose temperature is higher than that of the refrigerated body or space. It is evident that refrigerating and heating are actually opposite ends of the same process. Often, it is the desired result that distinguishes one from the other. Refrigeration is basic to the heating, ventilation and air conditioning industry. One of the most important applications of refrigeration has been the preservation of perishable food products, food processing, packaging, storing and transportation by storing them at low temperatures. The effect of storage temperature on useful storage life of food products is given in Table 1. Refrigeration systems are also used extensively for providing thermal comfort to human beings by means of air conditioning. **Air Conditioning** refers to the treatment of air so as to simultaneously control its temperature, moisture content, cleanliness, odour and circulation, as required by occupants, a process, or products in the space. The subject of refrigeration and air conditioning has evolved out of human need for food and comfort. The purpose of refrigerator is to transfer heat from a cold chamber which is at a lower temperature than that of its surrounding. Elementary refrigerators have been used which utilizes the melting of ice or the sublimation of carbon-dioxide at atmospheric pressure to provide cooling effect.

Table 1. *Effect of storage temperature on useful storage life of food products*

Food Product	**Average useful storage life (days)**		
	0^{o}C	**22^{o}C**	**38^{o}C**
Meat	6-10	1	< 1
Fish	2-7	1	< 1
Poultry	5-18	1	< 1
Dry meats and fish	> 1000	> 350 & < 1000	> 100 & < 350
Fruits	2 - 180	1 – 20	1 – 7
Dry fruits	> 1000	> 350 & < 1000	> 100 & < 350
Leafy vegetables	3 - 20	1 – 7	1 – 3
Root crops	90 - 300	7 – 50	2 – 20
Dry seeds	> 1000	> 350 & <	> 100 & <

		1000	350

1.1 THE LAWS OF THERMODYNAMICS

For this course, the first and the second laws shall be considered.

a. First Law of Thermodynamics

It is observed that when a system is made to undergo a complete cycle then net work is done *on* or *by* the system. Consider a cycle in which net work is done by the system. Since energy cannot be created, this mechanical energy must have been supplied from some source of energy. Now the system has been returned to its initial state : Therefore, its *intrinsic* energy is unchanged, and hence the mechanical energy has not been provided by the system itself. The only other energy involved in the cycle is the heat which was supplied and rejected in various processes. Hence, by the law of conservation of energy, the net work done by the system is equal to the net heat supplied to the system. The First Law of Thermodynamics can, therefore, be stated as follows:

"When a system undergoes a thermodynamic cycle then the net heat supplied to the system from the surroundings is equal to net work done by the system on its surroundings.

or

$$\oint dQ = \oint dW$$

where $\oint$ represents the sum for a complete cycle.

The first law of Thermodynamics *cannot be proved analytically, but experimental evidence has repeatedly confirmed its validity*, and since no phenomenon has been shown to contradict it, the first law is accepted as a *law of nature.* It may be remarked that no restriction was imposed which limited the application of first law to reversible energy transformation. Hence the first law applies to reversible as well as irreversible transformations: For non-cyclic process, a more general formulation of first law of thermodynamics is required. A new concept which involves a term called *internal energy* fulfills this need.

— The First Law of Thermodynamics may also be stated as follows:

"Heat and work are mutually convertible but since energy can neither be created nor destroyed, the total energy associated with an energy conversion remains constant".

Or

— "No machine can produce energy without corresponding expenditure of energy, *i.e.*, it is impossible to construct a perpetual motion machine of first kind".

b. Application of first Law to a process

When a process is executed by a system, the *change in stored energy of the system is numerically equal to the net heat interactions minus the net work interaction during the process.*

$$\therefore E2 - E1 = Q - W$$

$$\therefore \Delta E = Q - W \text{ [or } Q = \Delta E + W]$$

$$\text{Or} \quad \int_1^2 d(Q - W) = \Delta E = E_2 - E_1$$

where E represents the *total internal energy*.

If the electric, magnetic and chemical energies are *absent* and changes in potential and kinetic energy for a *closed system* are neglected, the above equation can be written as

$$\int_1^2 d(Q - W) = \Delta U = U2 - U1$$

$$\therefore \quad Q - W = \Delta U = U_2 - U_1$$

Generally, when heat is added to a system its temperature rises and external work is performed due to increase in volume of the system. *The rise in temperature is an indication of increase of internal energy*. Heat *added* to the system will be considered as *positive* and the heat *removed* or *rejected*, from the system, as *negative.*

c. Statements of second Law of Thermodynamics

The second law of thermodynamics has been enunciated meticulously by Clausius, Kelvin and Planck in slightly different words although both statements are basically identical. Each statement is based on an *irreversible process*. The *first considers transformation of heat between two thermal reservoirs* while the *second considers the transformation of heat into work.*

i. Clausius Statement

"*It is impossible for a self-acting machine working in a cyclic process unaided by any external agency, to convey heat from a body at a lower temperature to a body at a higher temperature*".

In other words, heat of, itself, cannot flow from a colder to a hotter body.

ii. Kelvin-Planck Statement

"*It is impossible to construct an engine, which while operating in a cycle produces no other effect except to extract heat from a single reservoir and do equivalent amount of work*".

Although the Clausius and Kelvin-Planck statements appear to be different, they are really equivalent in the sense that a *violation of either statement implies violation of other*.

iii. Equivalence of Clausius Statement to the Kelvin-Planck Statement

Refer Fig 1. Consider a higher temperature reservoir T_1 and low temperature reservoir T_2. It shows a heat pump which requires no work and transfers an amount of Q_2 from a low temperature to a higher temperature reservoir (in violation of the Clausius statement). Let an amount of heat Q_1 (greater than Q_2) be transferred from high temperature reservoir to heat engine which devolops a net work, $W = Q_1 – Q_2$ and rejects Q_2 to the low temperature reservoir. Since there is no heat interaction with the low temperature, it can be eliminated. The combined system of the heat engine and heat pump acts then like a heat engine exchanging heat with a single reservoir, which is the violation of the Kelvin-Planck statement.

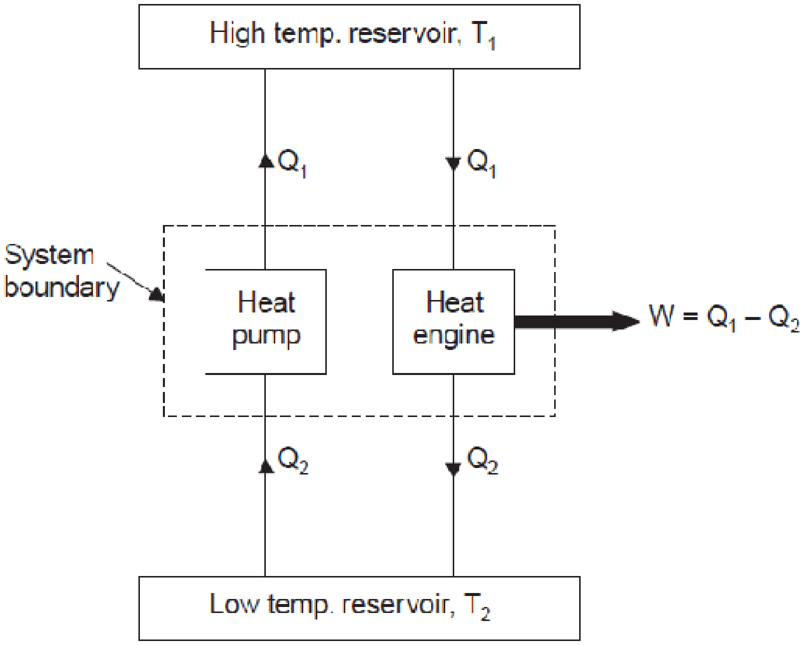


Fig. 1. Equivalence of Clausius statement to Kelvin-Planck statement.

1.2 Carnot cycle

The cycle was first suggested by a French engineer Sadi Carnot in 1824 which works on reversible cycle and is known as *Carnot cycle*. Any fluid may be used to operate the Carnot cycle (Fig 2-4) which is performed in an engine cylinder the head of which is supposed alternatively to be perfect conductor or a perfect insulator of a heat. Heat is caused to flow into the cylinder by the application of high temperature energy source to the cylinder head during expansion, and to flow from the cylinder by the application of a lower temperature energy source to the head during compression.

It can be shown that the second Law of Thermodynamics that no heat engine can be more efficient than a reversible heat engine working between the same temperature limits. Carnot showed that the most efficient possible cycle is one in which all heat rejected is rejected at a lower fixed temperature. The cycle therefore consists of two isothermal processes joined by two adiabatic processes. Since all processes are reversible, then the adiabatic processes in the cycle are also isentropic. The cycle is most conveniently represented on T-S diagram.

a. The diagrams showing the processes in the Carnot cycle systems

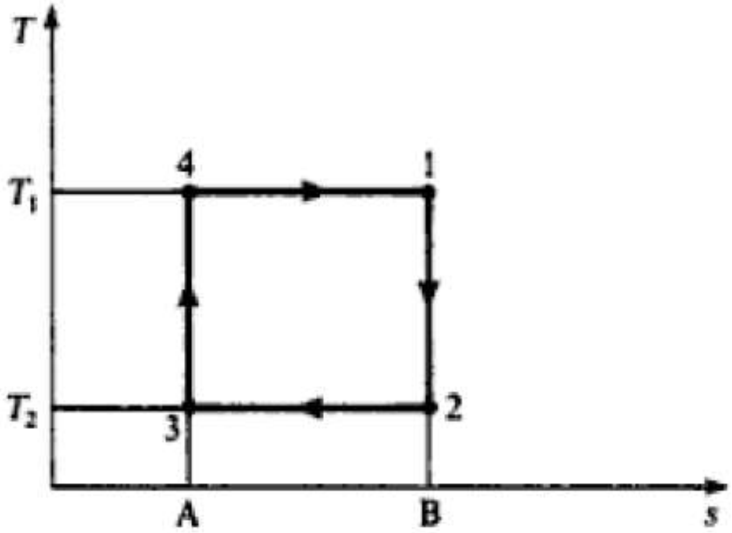


Fig. 2. Carnot cycle on a T-S diagram

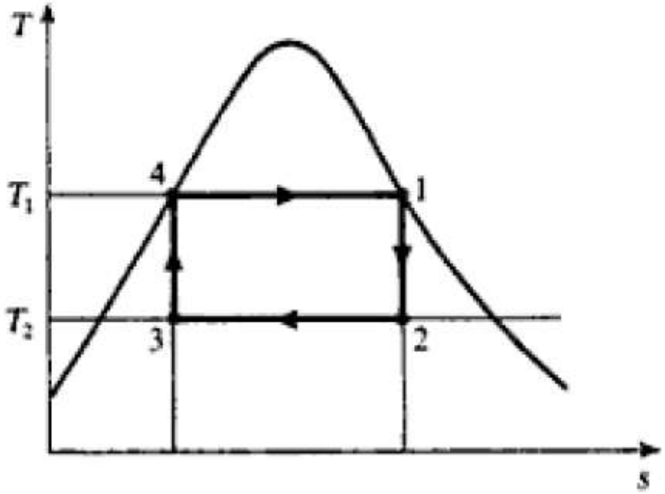


Fig. 3. Carnot cycle for a wet vapour on a T-S diagram

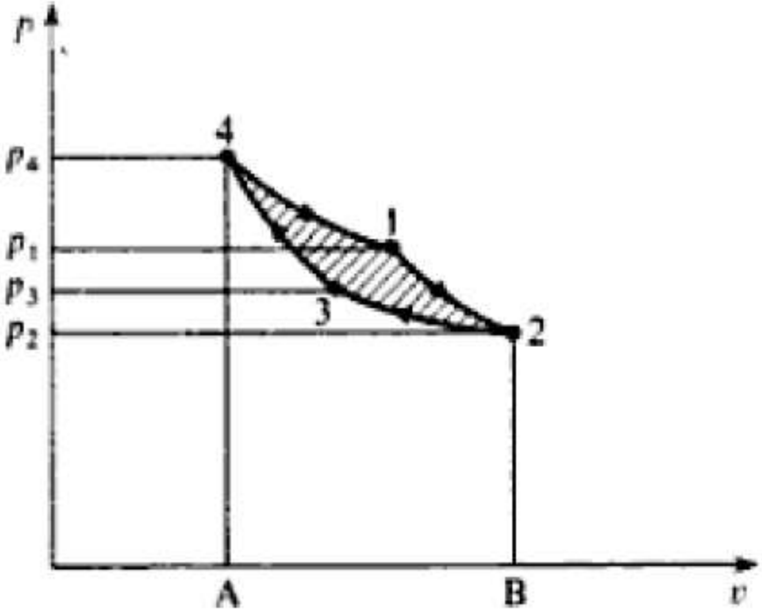


Fig. 4. Carnot cycle on a P-V diagram

b. The ***assumptions*** made for describing the working of the Carnot engine are as follows:

(i) The piston moving in a cylinder does not develop any friction during motion.

(ii) The walls of piston and cylinder are considered as perfect insulators of heat.

(iii) The cylinder head is so arranged that it can be a perfect heat conductor or perfect heat insulator.

(iv) The transfer of heat does not affect the temperature of source or sink.

(v) Working medium is a perfect gas and has constant specific heat.

(vi) Compression and expansion are reversible.

c. Following are the *four stages* of Carnot cycle: Hot energy source is applied. Heat Q_1 is taken in whilst the fluid expands isothermally and reversibly at constant high temperature T_1.

Process 1-2 is isentropic expansion from T_1 to T_2

Process 2-3 is isothermal heat rejection.

Process 3-4 is isentropic compression from T_2 to T_1

Process 4-1 is isothermal heat supply.

The cycle is completely independent of the working substance used. The cycle efficiency of a heat engine, is given by the net work output divided by the gross heat supplied.

$$\therefore W = Q_1 - Q_2$$

Also, thermal efficiency, $\eta_{th} = \dfrac{\textit{work done}}{\textit{heat supplied by the source}} = \dfrac{Q_1 - Q_2}{Q_1}$

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

($Q_1 = m\,c_p\,T_1$, $Q_2 = m\,c_p\,T_2$ and m = mass of fluid)

d. The Carnot cycle *cannot be performed in practice* because of the following **reasons**:

1. It is impossible to perform a frictionless process.

2. It is impossible to transfer the heat without temperature potential.

3. Isothermal process can be achieved only if the piston moves very slowly to allow heat transfer so that the temperature remains constant. Adiabatic process can be achieved only if the piston moves as fast as possible so that the heat transfer is negligible due to very short time available. The isothermal and adiabatic processes take place during the same stroke therefore the piston has to move very slowly for part of the stroke and it has to move very fast during remaining stroke. This variation of motion of the piston during the same stroke is not possible.

1.3. CARNOT'S THEOREM

"It states that of all engines operating between a given constant temperature source and a given constant temperature sink, none has a higher efficiency than a reversible engine".

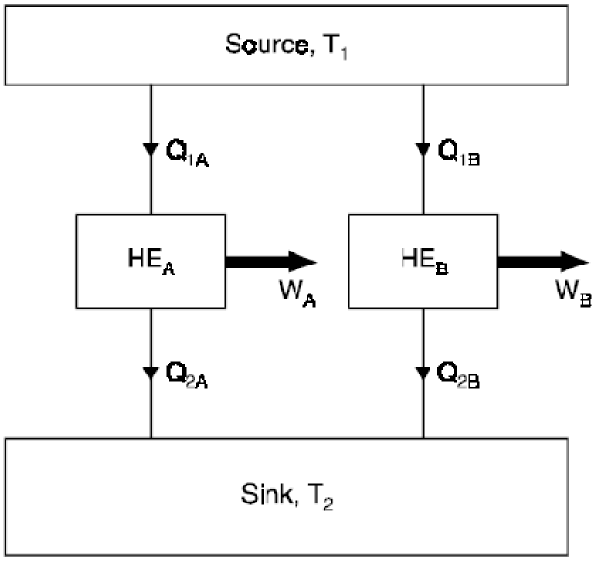


Fig. 5. Two cyclic heat engines HE_A and HE_B operating between the same source and sink.

HE_A and HE_B are the two engines operating between the given source at temperature $T1$ and the given sink at temperature $T2$**.** HE_B is reversible.

CHAPTER TWO

2. The Carnot refrigeration cycle

The first Law of Thermodynamics states: **"When a system undergoes a thermodynamic cycle then the net heat supplied to the system from the surroundings is equal to net work done by the system on its surroundings.** i.e. the sum of the net heat supplied to the system from the surroundings and the net work input to the system from its surroundings is equal to zero. Fig. 6. Shows a reversed heat engine cycle. The effect of the reversed heat engine is to transfer a quantity heat, Q_1, from a cold source at temperature, $T_{1.}$

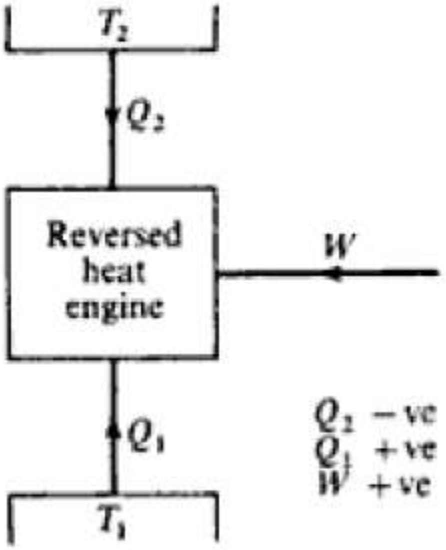


Fig. 6. Reversedheat engine

The reversed heat engine fulfils the requirements of a refrigerator. Appling the first law of Thermodynamics to the system of Fig.6, it gives:

$$\sum \mathrm{d}Q + \sum \mathrm{d}W = 0$$

or $$Q_1 + Q_2 + W = 0$$

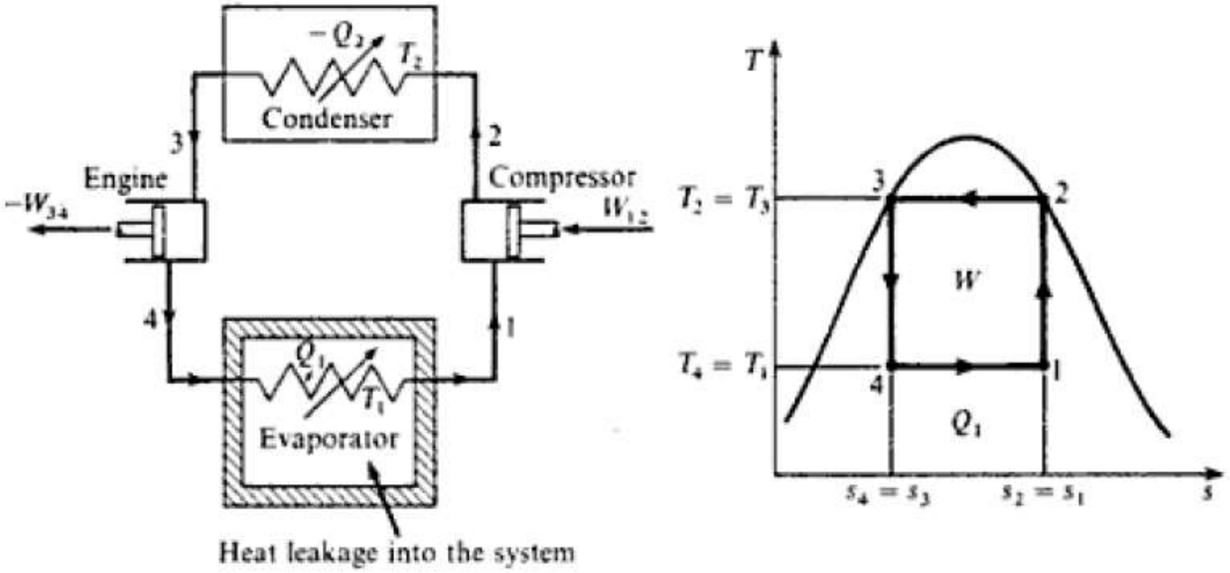
therefore

$$W + Q_1 = -Q_2$$

$$\mathrm{COP}_{\mathrm{ref}} = \frac{Q_1}{\sum W}$$

$$\mathrm{COP}_{\mathrm{hp}} = \frac{-Q_2}{\sum W}$$ (COP_{hp} is sometimes called the performance ratio)

The best COP will be given by a cycle which is a Carnot cycle operating between the given temperature conditions. Such a cycle using a wet vapour as the working substance is shown diagramatically in Fig.7. (a). Wet vapour is used as the example, sine the process of constant-pressure heat supply and the heat rejection are made at constant temperature, a necessary requirement of the Carnot cycle and one which is not fulfilled by using a superheated vapour.



(a) (b)

Fig. 7. Reversed heat engine system operating on the Carnot cycle

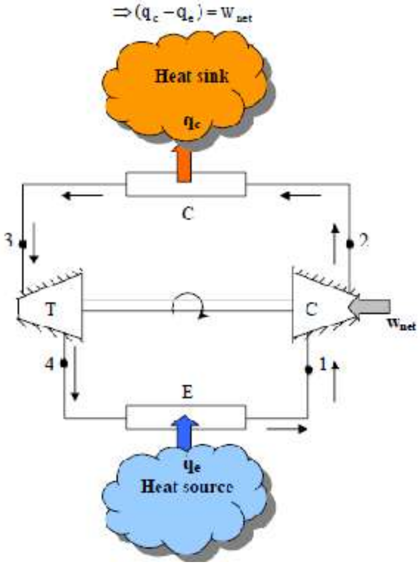


Fig. 7c. Schematic of a Carnot Refrigeration System

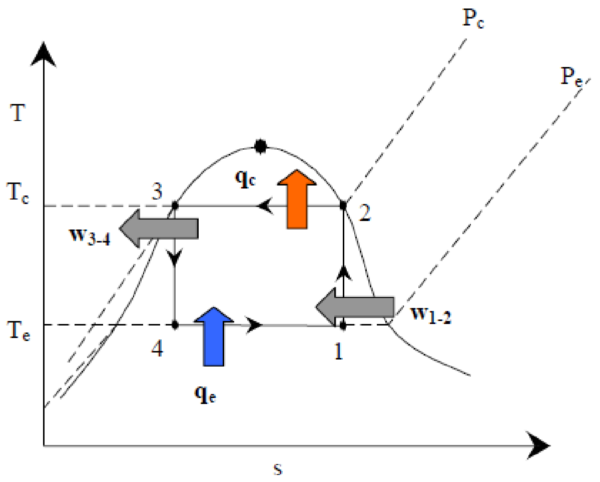


Fig. 7d. Carnot Refrigeration Cycle on T-S diagram

Carnot refrigeration cycle is a completely reversible cycle, hence is used as a model of perfection for a refrigeration cycle operating between a constant temperature heat source and sink. The basic Carnot refrigeration system for pure vapour consists of four components: compressor, condenser, turbine and evaporator. Refrigeration effect ($q_{4-1} = q_e$) is obtained at the evaporator as the refrigerant undergoes the process of vaporization (process 4-1) and extracts the latent heat from the low temperature heat source. The low temperature, low pressure vapour is then compressed isentropically in the compressor to the heat sink temperatureT_C. The refrigerant pressure increases from P_e to P_c during the compression process (process 1-2) and the exit vapour is saturated. Next the high pressure, high temperature saturated refrigerant undergoes the process of condensation in the condenser (process 2-3) as it rejects the heat of condensation ($q_{2-3} = q_C$) to an external heat sink at T_c. The high pressure saturated liquid then flows through the turbine and undergoes isentropic expansion (process 3-4). During this process, the pressure and temperature fall from P_c, T_c to P_e, T_e. Since a saturated liquid is expanded in the turbine, some amount of liquid flashes into vapour and the exit condition lies in the two-phase region. This low temperature and low pressure liquid-vapour mixture then enters the evaporator completing the cycle. The cycle involves two isothermal heat transfer processes (processes 4-1 and 2-3) and two isentropic work transfer processes (processes 1-2 and 3-4). Heat is extracted isothermally at evaporator temperature T_e during process 4-1, heat is rejected isothermally at condenser temperature T_c during process 2-3. Work is supplied to the compressor during the isentropic compression (1-2) of *refrigerant vapour* from evaporator pressure P_e to condenser pressure P_c, and work is produced by the system as *refrigerant liquid* expands isentropically in the turbine from condenser pressure P_c to evaporator pressure P_e. All the processes are both internally as well as externally reversible, i.e., net entropy generation for the system and environment is zero. Applying first and second laws of thermodynamics to the Carnot refrigeration cycle,

$$\oint \delta q = \oint \delta w$$

$$\oint \delta q = q_{4-1} - q_{2-3} = q_e - q_c$$

$$\oint \delta w = w_{3-4} - w_{1-2} = w_T - w_C = -w_{net}$$

now for the reversible, isothermal heat transfer processes 2-3 and 4-1, we can write:

$$q_c = -q_{2-3} = -\int_2^3 T.ds = T_c(s_2 - s_3)$$

$$q_e = q_{4-1} = \int_4^1 T.ds = T_e(s_1 - s_4)$$

where Te and Tc are the evaporator and condenser temperatures, respectively, and,

$$s_1 = s_2 \text{ and } s_3 = s_4$$

the Coefficient of Performance (COP) is given by:

$$COP_{Carnot} = \frac{\text{refrigeration effect}}{\text{net work input}} = \frac{q_e}{w_{net}} = \frac{T_e(s_1 - s_4)}{T_c(s_2 - s_3) - T_e(s_1 - s_4)} = \left(\frac{T_e}{T_c - T_e}\right)$$

thus the COP of Carnot refrigeration cycle is a function of evaporator and condenser temperatures only and is independent of the nature of the working substance. This is the reason why exactly the same expression was obtained for air cycle refrigeration systems operating on Carnot cycle. The Carnot COP sets an upper limit for refrigeration systems operating between two constant temperature thermal reservoirs (heat source and sink). From Carnot's theorems, for the same heat source and sink temperatures, no irreversible cycle can have COP higher than that of Carnot COP.

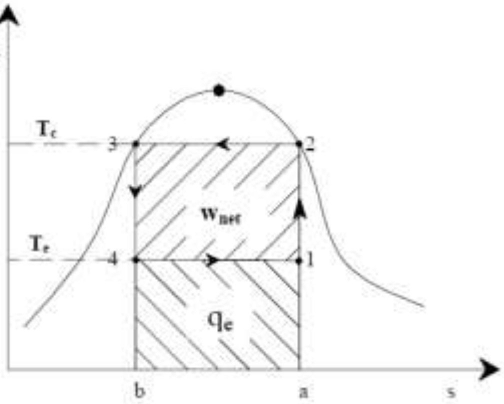


Fig. 8. Carnot Refrigeration cycle represented in T-S plane

It can be seen from the above expression that the COP of a Carnot refrigeration system increases as the evaporator temperature increases and condenser temperature decreases. This can be explained very easily with the help of the T-s diagram (Fig.8). As shown in the figure, COP is the ratio of area a-1-4-b to the area 1-2-3-4. For a fixed condenser temperature T_c, as the evaporator temperature T_e increases, area a-1-4-b (q_e) increases and area 1-2-3-4 (w_{net}) decreases as a result, COP increases rapidly. Similarly for a fixed evaporator temperature T_e, as the condensing temperature T_c increases, the net-work input (area 1-2-3-4) increases, even though cooling output remains constant, as a result the COP falls. Figure 10.3 shows the variation of Carnot COP with evaporator temperature for different condenser temperatures. It can be seen that the COP increases sharply with evaporator temperatures, particularly at high condensing temperatures. COP reduces as the condenser temperature increases, but the effect becomes marginal at low evaporator temperatures. It will be shown later that actual vapour compression refrigeration systems also behave in a manner similar to that of Carnot refrigeration systems as far as the performance trends are concerned.

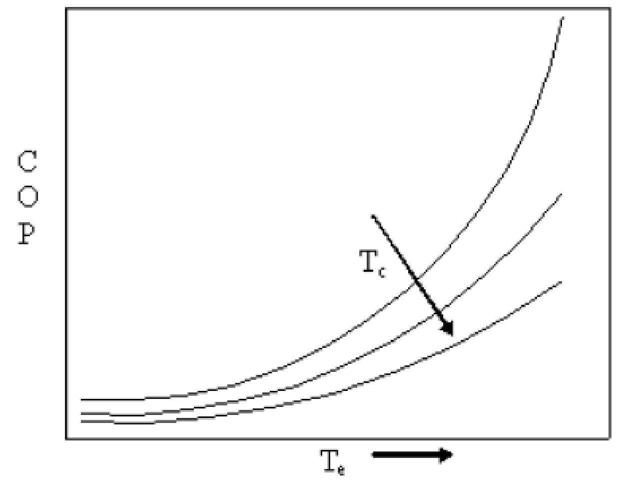


Fig. 9. Effects of evaporator and condenser temperatures on Carnot COP

2.1. Practical difficulties with Carnot refrigeration system:

It is difficult to build and operate a Carnot refrigeration system due to the following practical difficulties:

i. During process 1-2, a mixture consisting of liquid and vapour have to be compressed isentropically in the compressor. Such a compression is known as *wet compression* due to the presence of liquid. In practice, wet compression is very difficult especially with reciprocating compressors. This problem is particularly severe in case of high speed reciprocating compressors, which get damaged due to the presence of liquid droplets in the vapour. Even though some types of compressors can tolerate the presence of liquid in vapour, since reciprocating compressors are most widely is refrigeration, traditionally *dry compression* (compression of vapour only) is preferred to wet compression.

ii. The second practical difficulty with Carnot cycle is that using a turbine and extracting work from the system during the isentropic expansion of liquid refrigerant is not economically feasible, particularly in case of small capacity systems. This is due to the fact that the specific work output (per kilogram of refrigerant) from the turbine is given by: vapour/gas, the work output from the turbine in case of the liquid will be small. In addition, if one considers the inefficiencies of the turbine, then the net output will be further reduced. As a result using a turbine for extracting the work from the high pressure liquid is not economically justified in most of the cases1.

One way of achieving dry compression in Carnot refrigeration cycle is to have two compressors – one isentropic and one isothermal as shown in Fig.10.

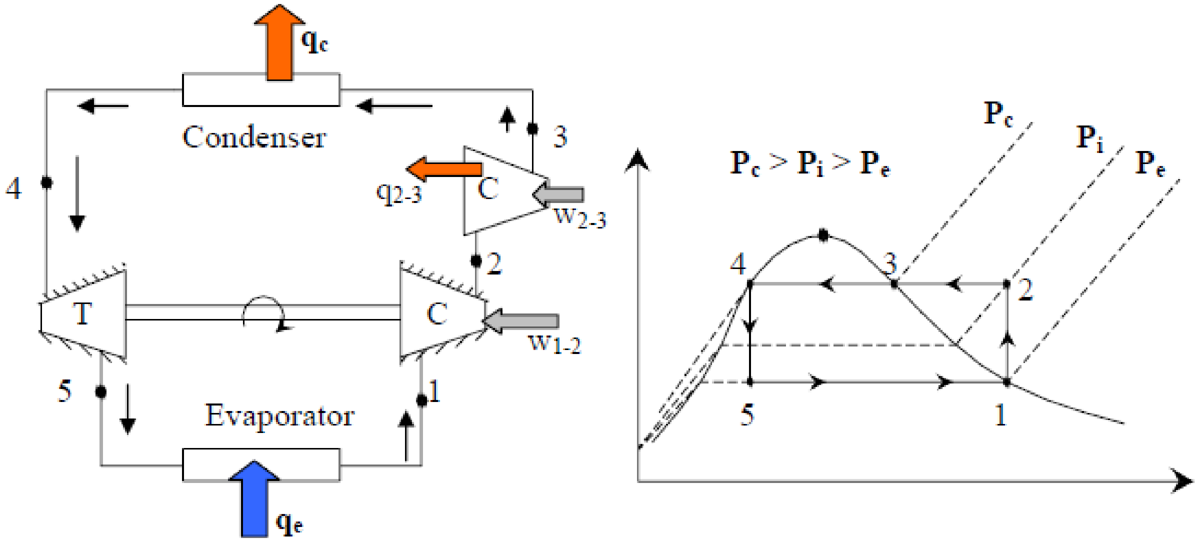
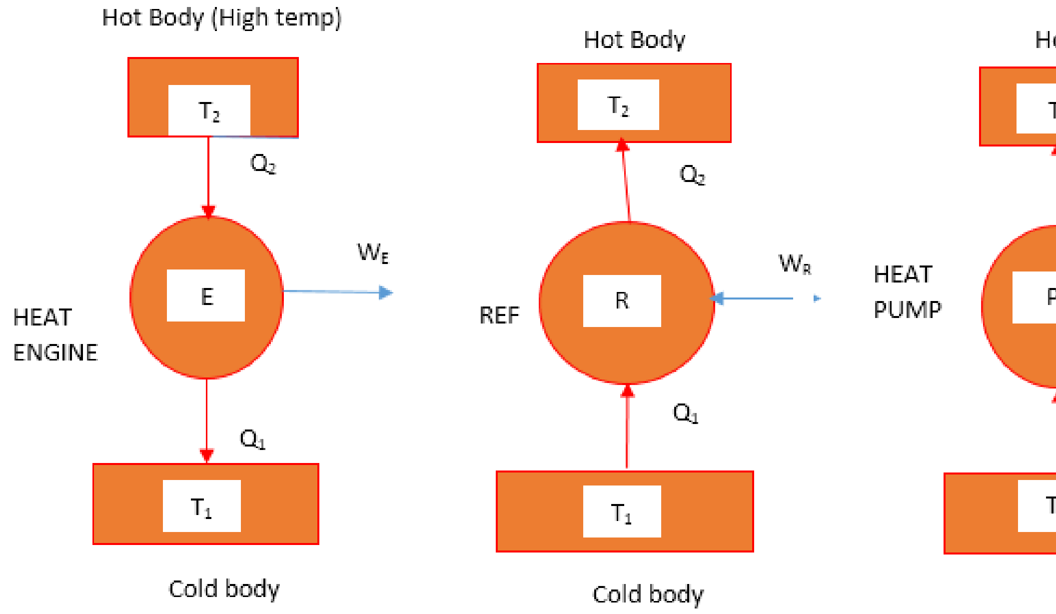


Fig.10. Carnot refrigeration cycle is to have two compressors – one isentropic and one isothermal

As shown in Fig.4, the Carnot refrigeration system with dry compression consists of one isentropic compression process (1-2) from evaporator pressure P_e to an intermediate pressure P_i and temperature T_c, followed by an isothermal compression process (2-3) from the intermediate pressure P_i to the condenser pressure P_c. Though with this modification the problem of wet compression can be avoided, still this modified system is not practical due to the difficulty in achieving true isothermal compression using high- speed compressors. In addition, use of two compressors in place of one is not economically justified. From the above discussion, it is clear that from practical considerations, the Carnot refrigeration system need to be modified. Dry compression with a single compressor is possible if the isothermal heat rejection process is replaced by isobaric heat rejection process. Similarly, the isentropic expansion process can be replaced by an isenthalpic throttling process. A refrigeration system, which incorporates these two changes is known as Evans-Perkins or reverse Rankine cycle. This is the theoretical cycle on which the actual vapour compression refrigeration systems are based.

2.2 DIFFERENCE BETWEEN A HEAT ENGINE, REFRIGERATION AND HEAT PUMP



(a) (b) (c)

Fig. 11. (a) Heat engine, (b) Refrigerator, and (c) Heat pump cycles.

(a). Heat Engine

In the heat engine, Q_2 is the heat supplied to the engine and the heat is converted to useful work, W_E. Q_1 is the heat rejected to useful engine. The net work done by the heat engine is given by $W_E = Q_2 - Q_1$. The performance of the heat engine, expressed by its efficiency is the coefficient performance of the engine, i.e.

$$(C.O.P)_E = \frac{Workdone}{Heat\ Supplied} = \frac{W_E}{Q_2} = \frac{Q_2 - Q_1}{Q_2}$$

Expressing this in terms of temperatures, $(\mathrm{C.O.P})_E = \frac{T_2 - T_1}{T_2} = 1 - \frac{T_1}{T_2}$

(b). Refrigeration

Refrigeration as shown in (b) is a reversed heat engine which cools or maintains the temperature of a body (T_1) lower than the atmospheric temperature (T_a). This is done by extracting the heat, (Q_1) from a cold body and delivery it to a hot body (Q_2).

To achieve this, work (W_R) is required to be done by the surrounding on the system. According to First law of Thermodynamics, $W_R = Q_2 - Q_1$. The performance of a refrigerator, $(C.O.P)_R$ is expressed as the ratio of heat taken from the cold body (Q_1) (the refrigerating effect) to the amount of work required to be done on the system, W_R. i.e.

$(C.O.P)_R = \frac{Q_1}{W_R} = \frac{Q_1}{Q_2 - Q_1}$

Expressing this in terms of temperatures,

$$(C.O.P)_E = \frac{T_2 - T_1}{T_2}$$

(c). Heat Pump

Heat pump and refrigerator is same, in cycle. The main difference between the two is in their operating temperatures. A refrigerator works between the cold body temperature (T_1) and the atmospheric temperature (Ta); whereas the heat pump operates between the hot body temperature (T_2) and the atmospheric temperature, (Ta). Nevertheless a refrigerator used for cooling in summer can be used as a heat pump for heating in winter.

Similarly as discussed for refrigerator,

$$W_P = Q_2 - Q_1$$

The $(C.O.P)_P$ or the energy performance ratio (E.P.R) of a heat pump,

$$(C.O.P)_P \ or \ E.P.R = \frac{Q_2}{W_P} = \frac{Q_2}{Q_2 - Q_1}$$

Expressing this in terms of temperatures,

$$E.P.R = \frac{Q_2}{Q_2 - Q_1} = \frac{T_2}{T_2 - T_1}$$

$$\frac{T_2}{T_2 - T_1} - 1 = \frac{T_2 - (T_2 - T_1)}{T_2 - T_1}$$

$$= \frac{T_1}{T_2 - T_1} = (C.O.P)_R$$

$$\therefore (C.O.P)_R + 1 \rightarrow \frac{Q_1}{Q_2 - Q_1} + 1 = \frac{Q_1 + Q_2 - Q_1}{Q_2 - Q_1} = \frac{Q_2}{Q_2 - Q_1}$$

Also, $(C.O.P)_R + 1 = \frac{T_1}{T_2 - T_1} + 1$

$$= \frac{T_1 + T_2 - T_1}{T_2 - T_1} = \frac{T_2}{T_2 - T_1}$$

$$\rightarrow (C.O.P)_R + 1 = (C.O.P)_P$$

$$\text{Also, } \frac{Q_1}{Q_2 - Q_1} + 1 = \frac{Q_2}{Q_2 - Q_1}$$

$$But, \ (C.O.P)_E = \frac{W_E}{Q_2} = \frac{T_2 - T_1}{T_2}$$

$$\text{And, } \frac{1}{(C.O.P)_P} = \frac{\frac{1}{T_2}}{T_2 - T_1} = \frac{T_2 - T_1}{T_2}$$

$$\therefore (C.O.P)_E = \frac{1}{(C.O.P)_P}$$

d. Temperature Limitations for Reversed Carnot cycle

We know that $(C.O.P)_R = \frac{T_1}{T_2 - T_1}$

T_1= Lower temperature, T_2= Higher temperature

The C.O.P of the reversed Carnot cycle may be improved by:

1. Decreasing the higher temperature
2. Increasing the lower temperature, i.e. the temperature of the cold body, T_1

This does not show that the temperatures T_1 and T_2 could be varied at will due to certain functional limitations. It should be kept in mind that the higher temperature (T_2) is the temperature of cooling water or the air available for rejection of heat and the lower temperature (T_1) is the temperature to be maintained in the refrigerator. The heat transfer will take place in the right direction only when the higher temperature is more than the temperature of cooling water or air to which heat is to be rejected. Thus if the temperature of cooling water or air i.e. T_2 available for heat rejection is low, then the C.O.P of the Carnot refrigerator will be high. T_2 is less during winter (cold), than during summer (hot), therefore, C.O.P in winter (cold sensor) will be higher than C.O.P in summer (hot or dry season). This implies Carnot refrigerators work efficiently in winter than in summer. Also if the lower temperature fixed by the refrigeration application is high, the C.O.P of Carnot refrigerator will be high. Thus a Carnot refrigerator used for making ice at 0^0C (273K) will have less C.O.P than a Carnot refrigerator used for air-conditioned plant in summer at 20^0C when the atmospheric temperature is 40^0C. The Carnot C.O.P for refrigerator is less than Carnot C.O.P for a domestic air-conditioner.

2.2.1. Refrigeration and Refrigeration Systems

Refrigeration is the cooling effect of the process of extracting heat from a lower temperature heat source, a substance or cooling medium, and transferring it to a higher temperature heat sink, probably atmospheric air and surface water, to maintain the temperature of the heat source below that of the surroundings. A *refrigeration system* is a combination of components, equipment, and piping, connected in a sequential order to produce the refrigeration effect. Refrigeration systems that provide cooling for air-conditioning are classified mainly into the following categories:

i. **Vapor compression systems:** In these systems, a compressor(s) compresses the refrigerant to a higher pressure and temperature from an evaporated vapor at low pressure and temperature. The compressed refrigerant is condensed into liquid form by releasing the latent heat of condensation to the condenser water. Liquid refrigerant is then throttled to a low-pressure, low-temperature vapor, producing the refrigeration effect during evaporation. Vapor compression is often called *mechanical refrigeration*, that is, refrigeration by mechanical compression.

ii. **Absorption systems:** In an absorption system, the refrigeration effect is produced by means of thermal energy input. After liquid refrigerant produces refrigeration during evaporation at very low pressure, the vapor is absorbed by an aqueous absorbent. The solution is heated by a direct fired gas furnace or waste heat, and the refrigerant is again vaporized and then condensed into liquid form. The liquid refrigerant is throttled to a very low pressure and is ready to produce the refrigeration effect again.

iii. **Gas expansion systems:** In an air or other gas expansion system, air or gas is compressed to a high pressure by compressors. It is then cooled by surface water or atmospheric air and expanded to a low pressure. Because the temperature of air or gas decreases during expansion, a refrigeration effect is produced.

iv. **Steam jet refrigeration system:** If water is sprayed into a chamber where a low pressure is maintained, part of the water will evaporate. The enthalpy of evaporation will cool the remaining water to its saturation temperature at the pressure in the chamber. Obviously lower temperature will require lower pressure. Water freezes at 0 ° C hence temperature lower than 4$_o$C cannot be obtained with water. In this system, high velocity steam is used to entrain the evaporating water vapour. High-pressure motive steam passes through either convergent or convergent divergent nozzle where it acquires either sonic or supersonic velocity and low pressure of the order of 0.009 kPa corresponding to an evaporator temperature of 4 ° C. The high momentum of motive steam entrains or carries along with it the water vapour evaporating from the flash chamber. Because of its high velocity it moves the vapours against the pressure gradient up to the condenser where the pressure is 5.6-7.4 kPa corresponding to condenser temperature of 35-45 ^{o}C. The motive vapour and the evaporated vapour both are condensed and recycled. This system is known as steam jet refrigeration system.

v. **Thermoelectric refrigeration system:** Thermoelectric refrigeration is a means of removing heat from one area and putting it in another area using electrical energy rather than refrigerant as the heat "carrier". Thermoelectric refrigeration requires none of the conventional equipment necessary in a vapour compression system. There is no compressor, evaporator, condenser or refrigerant. There are no moving parts, the unit is silent, compact and requires little service. Thermoelectric cooling units, when used for refrigeration are called modules. The module consists of cold and hot junctions. The cold side of the module, removes heat from the refrigerating chamber and releases the heat at the hot junction through the flow of electric current.

2.2.2. Application of refrigeration in food processing, preservation and distribution.

i. Storage of Raw Fruits and Vegetables

It has been established that some bacteria are responsible for degradation of food, and that enzymatic processing cause ripening of the fruits and vegetables. Bacteria and the rate of enzymatic processes are reduced at very low temperature thereby helps to reduce the spoilage rate and thus improve on the shelf life of the food. It can be seen that the storage temperature affects the useful storage life significantly. In general the storage life of most of the food products depends upon water activity, which essentially depends upon the presence of water in liquid form in the food product and its temperature. Hence, it is possible to preserve various food products for much longer periods under frozen conditions. In case of fruits and vegetables, the use of refrigeration starts right after harvesting to remove the post-harvest heat, transport in refrigerated transport to the cold storage or the processing plant. A part of it may be stored in cold storage to maintain its sensory qualities and a part may be distributed to retail shops, where again refrigeration is used for short time storage. Refrigeration helps in retaining the sensory, nutritional and eating qualities of the food. The excess crop of fruits and vegetables can be stored for use during peak demands and off-season; and transported to remote locations by refrigerated transport. In general, the shelf life of most of the fruits and vegetables increases by storage at temperatures between 0 to 10 ^{o}C. Table 6 shows the typical storage conditions for some fruits and vegetables as recommended by ASHRAE. Nuts, dried fruits and pulses that are prone to bacterial deterioration can also be stored for long periods by this method. The above mentioned fruits and vegetables can be stored in raw state. Some highly perishable items require initial processing before storage. The fast and busy modern day life demands ready-to-eat frozen or refrigerated food packages to eliminate the preparation and cooking time.

Table 2. Recommended storage conditions for fruits and vegetables

Fruit & Vegitables	Storage Temperature, °C	Relative Humidity, %	Maximum, recommended storage time	Storage time in cold Storages for vegetables In tropical countries
Apples	0 – 4	90 – 95	2 - 6 months	
Beetroot	0	95 – 99	4 – 6 months	
Cabbage	0	95 – 99	5 – 6 months	2 months
Carrots	0	98 – 100	5 – 9 months	2 months
Cauliflower	0	95	3 – 4 weeks	1 week
Cucumber	10 - 13	90 – 95	10 – 14 days	
Eggplant	8 - 12	90 – 95	7 days	
Lettuce	0	95 – 100	2 – 3 weeks	
Melons	7 - 10	90 - 95	2 weeks	
Mushrooms	0 - 4	95	2 - 5	1 day
Onions	0	65 - 70	6 – 8 months	
Oranges	0 - 4	85 - 90	3 – 4 months	
Peas, Green	0	95 - 98	1 – 2 weeks	
Pears	0	90 - 95	2 – 5 months	
Potatoes	4 - 16	90 - 95	2 – 8 months	
Pumpkin	10 - 13	70 – 75	6 – 8 months	
Spinach	0	95	1 – 2 weeks	1 week
Tomatoes	13 - 21	85 - 90	1 – 2 weeks	1 week

ii. Fish

Icing of fish according to ASHRAE Handbook on Applications, started way back in 1938. In India, iced fish is still transported by rail and road, and retail stores store it for short periods by this method. Freezing of fish aboard the ship right after catch results in better quality than freezing it after the ship docks. In some ships, it is frozen along with seawater since it takes months before the ships return to dock. Long-term preservation of fish requires cleaning, processing and freezing.

iii. Meat and poultry

These items also require refrigeration right after slaughter during processing, packaging. Short-term storage is done at 0 ^{o}C. Long-term storage requires freezing and storage at -25 ^{o}C.

iv. **Dairy Products**

The important dairy products are milk, butter, buttermilk and ice cream. To maintain good quality, the milk is cooled in bulk milk coolers immediately after being taken from cow. Bulk milk cooler is a large refrigerated tank that cools it between 10 to 15 ^{o}C. Then it is transported to dairy farms, where it is pasteurized. Pasteurization involves heating it to 73 ^{o}C and holding it at this temperature for 20 seconds. Thereafter, it is cooled to 3 to 4 ^{o}C. The dairies have to have a very large cooling capacity, since a large quantity of milk has to be immediately cooled after arrival. During the lean period, the refrigeration plants of dairies are used to produce ice that is used during peak periods to provide cooling by melting. This reduces the required peak capacity of the refrigeration plant. Ice cream manufacture requires pasteurization, thorough mixing, emulsification and stabilization and subsequently cooling to 4 to 5 ^{o}C. Then it is cooled to temperature of about – 5 ^{o}C in a freezer where it stiffens but still remains in liquid state. It is packaged and hardened at –30 to –25 ^{o}C until it becomes solid; and then it is stored at same temperature. Buttermilk, curd and cottage cheese are stored at 4 to 10 ^{o}C for increase of shelf life. Use of refrigeration during manufacture of these items also increases their shelf life. There are many varieties of cheese available these days. Adding cheese starter like lactic acid and several substances to the milk makes all of these. The whey is separated and solid part is cured for a long time at about 10 ^{O}C to make good quality cheese.

v. **Beverages**

Production of beer, wine and concentrated fruit juices require refrigeration. The taste of many drinks can be improved by serving them cold or by adding ice to them. This has been one of the favourite past time of aristocracy in all the countries. Natural or man-made ice for this purpose has been made available since a very long time. Fruit juice concentrates have been very popular because of low cost, good taste and nutritional qualities. Juices can be preserved for a longer period of time than the fruits. Also, fruit juice concentrates when frozen can be more easily shipped and transported by road. Orange and other citrus juices, apple juice, grape juice and pineapple juice are very popular. To preserve the taste and flavor of juice, the water is driven out of it by boiling it at low temperature under reduced pressure. The concentrate is frozen and transported at $–20^{o}$C. Brewing and wine making requires fermentation reaction at controlled temperature, for example lager-type of beer requires 8 to12^{o}C while wine requires $27\text{-}30^{o}$C. Fermentation is an exothermic process; hence heat has to be rejected at controlled temperature.

vi. **Candy**

Use of chocolate in candy or its coating with chocolate requires setting at $5\text{-}10^{o}$C otherwise it becomes sticky. Further, it is recommended that it be stored at low temperature for best taste.

vii. **Processing and distribution of frozen food**

Many vegetables, meat, fish and poultry are frozen to sustain the taste, which nearly duplicates that of the fresh product. Freezing retains the sensory qualities of colour, texture and taste apart from nutritional qualities. The refrigeration systems for frozen food applications are very liberally designed, since the food items are frozen in shortest period of time. The sharp freezing with temperature often below $–30^{o}$C, is done so that the ice crystals formed during freezing do not get sufficient time to grow and remain small and do not pierce the cell boundaries and damage them. Ready-to-eat frozen foods, packed dinners and bakery items are also frozen by this method and stored at temperatures of –25 to $-20\ ^{o}$C for distribution to retail stores during peak demands or off-season demands.

Vegetables in this list are beans, corn, peas, carrots, cauliflower and many others. Most of these are blanched before freezing. There are various processes of freezing. *Blast freezers* give a blast of high velocity air at $–\ 30^{o}$C on the food container. In *contact freezing*, the food is placed between metal plates and metal surfaces that are cooled to -30^{o}C or lower. *Immersion freezing* involves immersion of food in low temperature brine. *Individual quick freezing* (IQF) is done by chilled air at very high velocities like 5-10 m/s that keeps the small vegetable particles or shrimp pieces floating in air without clumping, so that maximum area is available for heat transfer to individual particles. The frozen particles can be easily packaged and transported. The refrigeration capacities in all the freezers are very large since freezing of large quantities is done in a very short time. Liquid nitrogen and carbon dioxide are also used for freezing.

2.2. Applications of refrigeration in chemical and process industries

The industries like petroleum refineries, petrochemical plants and paper pulp industries etc. require very large cooling capacities. The requirement of each industry-process wise and equipment-wise is different hence refrigeration system has to be customized and optimized for individual application. The main applications of refrigeration in chemical and process industries involve the following categories.

i. **. Separation of gases:** In petrochemical plant, temperatures as low as -150^{o}C with refrigeration capacities as high as 10,000 Tons of Refrigeration (TR) are used for separation of gases by fractional distillation. Some gases condense readily at lower temperatures from the mixtures of hydrocarbon. Propane is used as refrigerant in many of these plants.

ii. **Condensation of Gases:** some gases that are produced synthetically, are condensed to liquid state by cooling, so that these can be easily stored and transported in liquid state. For example, in synthetic ammonia plant, ammonia is condensed at –10 to 10^{o}C before filling in the cylinders, storage and shipment. This low temperature requires refrigeration.

iii. **Dehumidification of Air:** Low humidity air is required in many pharmaceutical industries. It is also required for air liquefaction plants. This is also required to prevent static electricity and prevents short circuits in places where high voltages are used. The air is cooled below its dew point temperature, so that some water vapour condenses out and the air gets dehumidified.

iv. **Solidification of Solute:** One of the processes of separation of a substance or pollutant or impurity from liquid mixture is by its solidification at low temperature. Lubricating oil is dewaxed in petroleum industry by cooling it below -25^{o}C. Wax solidifies at about -25^{o}C.

v. **Storage as liquid at low pressure:** Liquid occupies less space than gases. Most of the refrigerants are stored at high pressure. This pressure is usually their saturation pressure at atmospheric temperature. For some gases, saturation pressure at room temperature is very high hence these are stored at relatively low pressure and low temperature. For example natural gas is stored at 0.7 bar gauge pressure and -130^{o}C. Heat gain by the cylinder walls leads to boiling of some gas, which is compressed, cooled and expanded back to 0.7 bar gauge.

vi. **Removal of Heat of Reaction:** In many chemical reactions, efficiency is better if the reaction occurs below room temperature. This requires refrigeration. If these reactions are exothermic in nature, then more refrigeration capacities are required. Production of viscose rayon, cellular acetate and synthetic rubber are some of the examples. Fermentation is also one of the examples of this.

vii. **Cooling for preservation:** Many compounds decompose at room temperature or these evaporate at a very fast rate. Certain drugs, explosives and natural rubber can be stored for long periods at lower temperatures.

viii. **Recovery of Solvents:** In many chemical processes solvents are used, which usually evaporate after reaction. These can be recovered by condensation at low temperature by refrigeration system. Some of the examples are acetone in film manufacture and carbon tetrachloride in textile production.

2.2.3. Special applications of refrigeration

In this category we consider applications other than chemical uses. These are in manufacturing processes, applications in medicine, construction units etc.

i. **Cold Treatment of Metals:** The dimensions of precision parts and gauge blocks can be stabilized by soaking the product at temperature around – 90^{o}C. The hardness and wear resistance of carburized steel can be increased by this process. Keeping the cutting tool at $–100^{o}$C for 15 minutes can also increase the life of cutting tool. In deep drawing process the ductility of metal increases at low temperature. Mercury patterns frozen by refrigeration can be used for precision casting.

ii. **Medical:** Blood plasma and antibiotics are manufactured by freeze-drying process where water is made to sublime at low pressure and low temperature. This does not affect the tissues of blood. Centrifuges refrigerated at $–10^{o}$C, are used in the manufacture of drugs. Localized refrigeration by liquid nitrogen can be used as anesthesia also.

iii. **Ice Skating Rinks:** Due to the advent of artificial refrigeration, sports like ice hockey and skating do not have to depend upon freezing weather. These can be played in indoor stadium where water is frozen into ice on the floor. Refrigerant or brine carrying pipes are embedded below the floor, which cools and freezes the water to ice over the floor.

iv. ***Construction:*** Setting of concrete is an exothermic process. If the heat of setting is not removed the concrete will expand and produce cracks in the structure. Concrete may be cooled by cooling sand, gravel and water before mixing them or by passing chilled water through the pipes embedded in the concrete. Another application is to freeze the wet soil by refrigeration to facilitate its excavation.

v. **Desalination of Water:** In some countries fresh water is scarce and seawater is desalinated to obtain fresh water. Solar energy is used in some cases for desalination. An alternative is to freeze the seawater. The ice thus formed will be relatively free of salt. The ice can be separated and thawed to obtain fresh water.

vi. **Ice Manufacture:** This was the classical application of refrigeration. Ice was manufactured in plants by dipping water containers in chilled brine and it used to take about 36 hours to freeze all the water in cans into ice. The ice thus formed was stored in ice warehouses. Now that small freezers and icemakers are available. Hotels and restaurants make their own ice, in a hygienic manner. Household refrigerators also have the facility to make ice in small quantities. The use of ice warehouses is dwindling because of this reason. Coastal areas still have ice plants where it is used for transport of iced fish. Refrigeration systems are also required in remote and rural areas for a wide variety of applications such as storage of milk, vegetables, fruits, food grains etc., and also for storage of vaccines etc. in health centers. One typical problem with many of the rural and remote areas is the continuous availability of electricity.

2.3. Need for Thermal Insulation

Since heat always migrate from a region of high temperature to a region of lower temperature, there is always a continuous flow of heat into the refrigerated region from the warmer surroundings. To limit the flow of heat into the refrigerated region to some practical minimum, it is usually necessary to isolate the region from its surroundings with a good heat-insulating material.

CHAPTER THREE

(a). The refrigerating Agent

This is the substance employed as the heat absorber or cooling agent, and is called the refrigerant.

All cooling processes may be classified as either sensible or latent according to the effect the absorbed heat has upon the refrigerant.When the absorbed heat causes an increase in the temperature of the refrigerant, then it is sensible cooling process; whereas when the absorbed heat causes a change in the physical state of the refrigerant (either melting or vaporizing), then it is latent cooling process.

Some useful terms

(b). The terms that are frequently used in Refrigeration and Air conditional operations.

i. Sensible Heat: This is heat addition to or removed from a substance which causes a change in temperature in the substance.

ii. Specific Heat Capacity: This is the amount of heat added or released to change the temperature of 1kg of the substance by 1'c. Different substance require different amounts of heat per unit mass to cause there change in temperature.

iii. Latent Heat: "This is heat, which brings about a change of state with no change in temperature.

iv. All pure substances are to change their state i.e. from solid to liquid, from liquid to gas and vice-versa.

v. Saturation Temperature: The temperature at which a fluid will change from liquid phase to vapour phase or, conversely, from the vapour phase to the liquid phase.

vi. Liquid at this temperature is called a saturated liquid, while a vapour at this temperature is called a saturated vapour. For a given pressure, the saturation temperature is the maximum temperature the liquid can have and the minimum temperature that vapour can have.

vii. Superheated Vapour: This is a vapour at any temperature above the saturation temperature corresponding to its pressure.

viii. Sub cooled Liquid: If after condensation, the resulting liquid is cooled so that its temperature is reduced below the saturation temperature, it is sub cooled.

ix. Critical Temperature: The temperature of a gas may be raised to a point such that it cannot become saturated regardless of the amount of pressure applied. The critical temperature of any gas is the highest temperature that the gas can have and still be condensable by the application of pressure.

x. Critical Pressure: Critical pressure is the lowest pressure at which a substance can exist in the liquid state at its critical temperature; that is, it is the saturation pressure at the critical temperature.

xi. Condensation: Condensation of vapour may be accomplished in several ways:
    i. By extracting heat from vapour;
    ii. By increasing the pressure of the vapour.
    iii. By some combination of these two methods.

b. **Refrigerant**: It is the working medium used in refrigeration systems is called the refrigerant. It is the heat carrying medium, which during the refrigerating cycle (i.e. compression, condensation, expansion and evaporation) it absorbs heat from a low temperature system and discard the absorbed heat to a higher temperature system. The natural ice, the mixture of ice and salt were the first refrigerants, later ether, NH_3, SO_2, methyl chloride and CO_2 came into use as refrigerants, in compression cycle refrigeration machines, most of the early refrigerants have been discarded for safety reasons, and lack of thermal or chemical stability. In the present days refrigerants such as halo-carbon and hydro-carbon compounds are used for air conditioning and refrigeration applications. The suitability of a particular refrigerant for a certain application is determined by its cost, thermodynamic, physical, chemical and other various practical factors and properties. There is no single refrigerant that is suitable for all applications, hence no refrigerant. A certain refrigerant may be preferred for a particular application because of its advantages for that purposes, nevertheless it still has some disadvantages when viewed with a different perspective. Therefore when choosing a refrigerant for an application the one that has greater advantages and less disadvantages will be preferred.

c. Desirable properties of a Refrigerant

We have earlier stated that no refrigerant is an ideal refrigerant; nevertheless we accept the refrigerant with the following properties to be ideal:

- Low boiling point, high latent heat of vaporisation, low specific heat of liquid low specific volume of vapour, non-corrosive to metal, non-flammable and non-explosive, non-toxic, low cost, easy to be liquefied at moderate pressure and temperature, easy to locate leaks by odour or suitable indicators, and mixes well with oil.
- The standard comparison of refrigerants, as used in the refrigeration industry, is based on an evaporating temperature 0f -15^{0}c and a condensing temperature of +30^{0}c

Classification of the desirable properties or characteristics of Refrigerant:
(i) Thermodynamics (ii) Physical and chemical, (iii) safety groups.

i. Thermodynamic characteristics:

(a) High latent enthalpy of vaporization: this ensures a large refrigerating effect per unit mass of the refrigerant circulated in a small capacity system, too low of a flow rate may actually lead to problems.
(b) Low freezing temperatures: otherwise large amounts of power will be required for compression.
(c) Positive evaporating pressure: pressure in the evaporator should be above atmospheric pressure to prevent air from leaking into the system.
(d) Relatively low condensing pressure: to prevent expensive piping and equipment.

ii. Physical and chemical characteristics:

(a) High dielectric strength of vapour: this permits the use of hermetically sealed compressors where vapour may come in contact with motor windings.

(b) Good heat transfer characteristics: Thermo physical properties are required that high heat transfer coefficient can be obtained. This includes properties such as density, heat, viscosity, and thermal conductivity.

(c) Satisfactory oil solubility: a system must be designed with oil solubility characteristics in mind, so that if oil is dissolved in the refrigerant or vice versa, it will not affect lubrication and heat transfer characteristics and also will not lead to oil logging in the evaporator.

(d) Low water solubility: this characteristic is essential because water in a refrigerant can lead to corrosion or freeze up in the expansion devices.

(e) Inertness and stability: the refrigerant must not react with materials it will contact and its own chemical make-up must not change with time.

iii. Safety:

(a) Non-flammability: refrigerant should not burn or aid combustion when mixed with air.

(b) Non-toxicity: it should not be toxic to humans either directly or indirectly through foodstuffs.

(c) Non-irritability: of the refrigerant means it should not cause irritation to human eyes, nose, lungs or skin.

In addition to the classes of characteristics stated above, it should be relatively low in cost and be easy to detect leaks when arise.

d. Designation System for Refrigerant (Assigning number to each refrigerant)

The ASHRAE designation system has been used in assigning a number to each refrigerant. In this system the halo-carbons and hydrocarbons are designated as follows:

(1) The first digit on the right is the number of fluorine (F) atoms in a molecule.

(2) The second digit from the right is one more than the number of hydrogen (H) atoms in a molecule.

(3) The third digit from the right is one less than the number of carbon (C) atoms, but when the digit is zero, the number is omitted.

Inorganic refrigerants are designated by adding 700 to the molecular weight of the compound. For example water (H2O) has molecular weight of 18 and its ASHRAE designation as a refrigerant is 718. The ASHRAE number designation for dichlorotetra-fluoroethane (CCIF2CCIF2) can be determined as follows: there are four fluorine atoms, and two carbon atoms per molecule. Thus the ASHRAE designation is:

C	H	F	
(2-1)	(0+1)	(4)	= 114

Thus the refrigerant number of $CCIF_2CCIF_2$ is R-114,

Also, for monochloropenta-fluoroetthane ($CCIF_2CF_3$)

C	H	F	
(2-1)	(0+1)	(5)	= 115

Thus the refrigeration number of $CCIF_2CF_3$ is R-115.

The general chemical formula for the refrigerant (methane or ethane base) is: $C_m H_n Cl_p F_q$.

Table 3. The commonly used halocarbon refrigerants

S/N		Refrigerant number	Chemical name	
1.		R-11	Trichloromonofluoromethane	CCL3F
2.		R-12	Dichlorodifluoromethane	CCL2F2
3.		R-13	Monochlorotrifluoromethane	CCLF3
4.		R-14	Carbontetrafluoride	CF4
5.		R-21	Dichloromonofluoromethane	CHCL2F
6.		R-22	Monochlorodifluoromethane	CHCLF2
7.		R-30	Methylene chloride	CH2CL2

8.		R-40	Methyl chloride	CH3CL
9.		R-100	Ethyl choride	C2H5CL
10.		R-113	Trichlorotrifluoroethane	CCL2FCCLF2
11.		R-114	Dichlorotetrafluoroethane	CCLF2CCLF2
12.		R-115	Monochloropentafluoroethane	CCLF2CF3

Amongst the halo-carbon refrigerants discussed above, only R-11, R-12, and R-22 are the most important and are extensively used nowadays.

Classification of refrigerants: they are broadly divided into (1) primary and (2) secondary refrigerants. Primary refrigerants directly take part in refrigeration system while secondary are first cooled by the primary refrigerants before used for cooling purposes. Primary refrigerants are classified into: (1) halo-carbon, (2) azeotrope (3) inorganic and hydro-carbon refrigerants.

e. **Azeotrope refrigerants:** this refers to a suitable mixture of refrigerants whose vapour and liquid phases retain identical compositions over a wide range of temperatures. However, the mixtures have properties that differ from either of their components.

Table 4. Azeotropic refrigerants, chemical formula and refrigerant numbers

Refrigerant number	Azoetropic mixing refrigerants	Chemical formula
R-500	73.8% R-12 and 26.2% R-152	CCL2F2/CH3CHF2
R-502	48.8% R-22 and 51.2% R-115	CHCLF2/CCLF2CF3
R-503	40.1% R-23 and 59.9% R-13	CHF3/CCLF3
R-504	48.2% R-32 and 51.8% R-115	CH2F2/CCLF2CF3

f. **Inorganic refrigerants**: these refrigerants were exclusively used before the advent of halocarbon refrigerants, and are still used due to their inherent thermodynamic and physical properties.

Table 5. Inorganic refrigerants their chemical names and refrigerant number.

Refrigerants number	Chemical name	Chemical formula

R-17	Ammonia	NH3
R-729	Air	_
R-744	Carbon dioxide	CO2
R-764	Sulphur dioxide	SO2
R-118	Water	H2O

g. **Hydrocarbon refrigerants:** most of these refrigerants are used in industrial and commercial installations. They possess satisfactory thermodynamic properties but are highly flammable and explosive.

Table. 6. Hydrocarbon their chemical names and refrigerant numbers

Refrigerant number	Chemical name	Chemical formula
R-170	Ethane	C2H6
R-290	Propane	C3H3
R-600	Butane	C4H10
R-600a	Isobutene	C4H10
R-1120	Trichloroethylene	C2H4CL3
R-1130	Dichloroethylene	C2H4CL2
R-1150	Ethylene	C2H4
R-1270	propylene	C3H6

Secondary refrigerants-brines: brines are secondary refrigerants and are generally used when temperature are required to be maintained below the freezing point of water i.e. 0°C, then water is commonly used as a secondary refrigerant.

Brine is a solution of salt in water. When salt is mixed in water, it lowers the freezing temperature of the solution (and increases the boiling temperature) because the salt dissolved in water takes off the latent heat from the solution and cools it below the freezing point of water.

The mass of the salt in solution, expressed as the percentage of the mass of the solution is known as concentration of the solution. As the concentration of the solution increases, its freezing point decreases. But when the concentration of the solution is increased beyond a point, the freezing point increases instead of decreasing. The point at which the freezing temperature is minimum, is known as entectic temperature, and at this point the concentration is known as entectic concentration. The brines commonly used are $CaCl_2$, NaCl, glycols such as ethylene glycol, propylene glycol e.t.c.

CHAPTER FOUR

4. Typical Vapour-Compression System

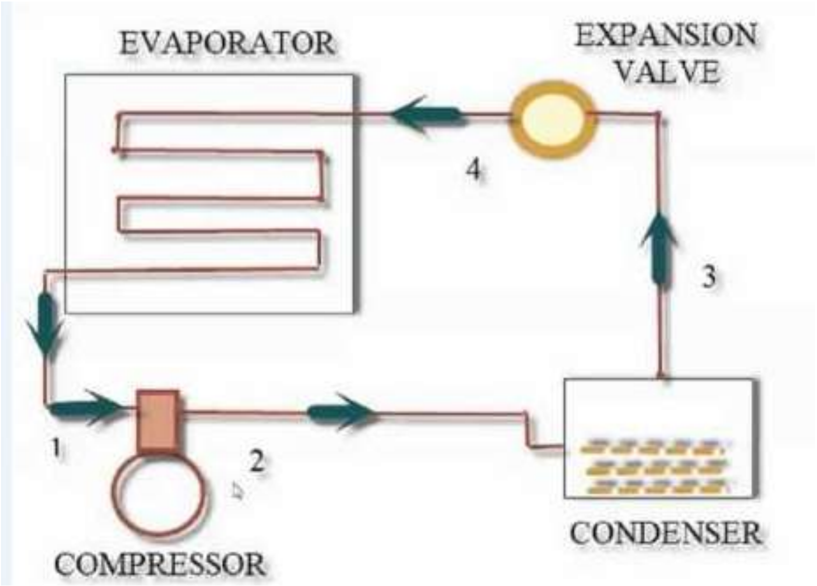


Fig.12.a. Flow diagram of simple vapour compression system

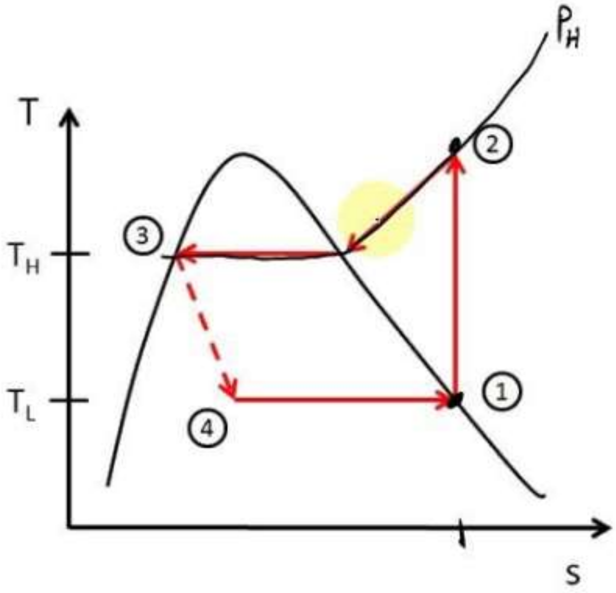


Fig 12.b. T-S diagram for a simple vapour compression system.

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

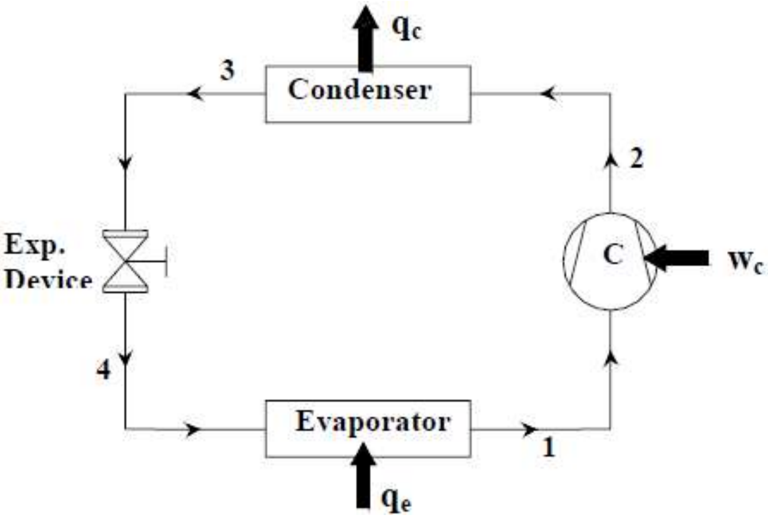


Fig. 13. Schematic diagram of a standard, saturated, single stage (SSS) vapour compression refrigeration system

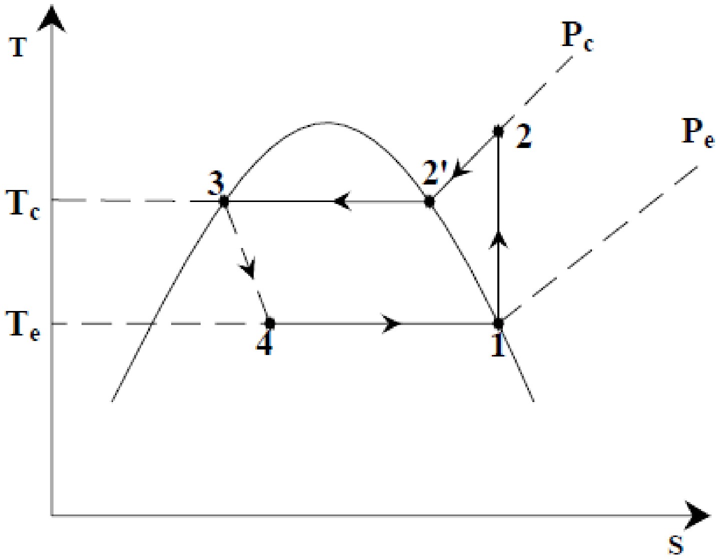


Fig. 14. T-S diagram of a Standard Vapour compression refrigeration system

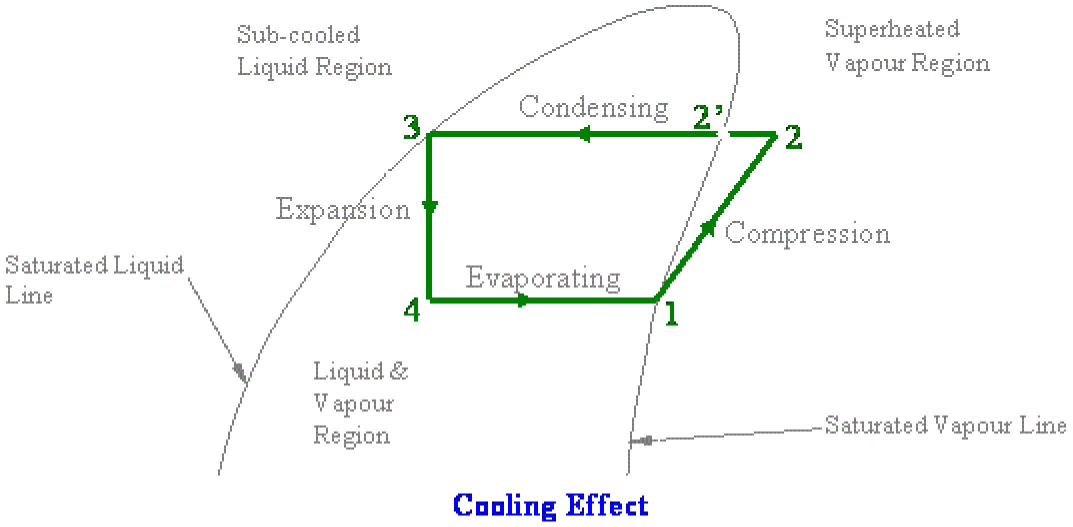


Fig. 15. P-h diagram of Standard Vapour Compression Refrigeration System (VCRS)

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

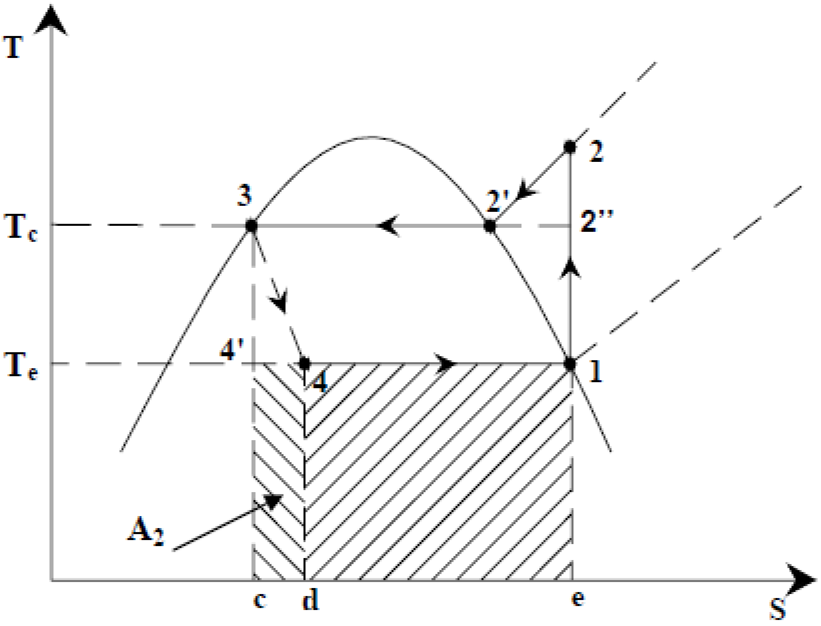


Fig. 16. Comparison between Carnot and standard VCRS

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.

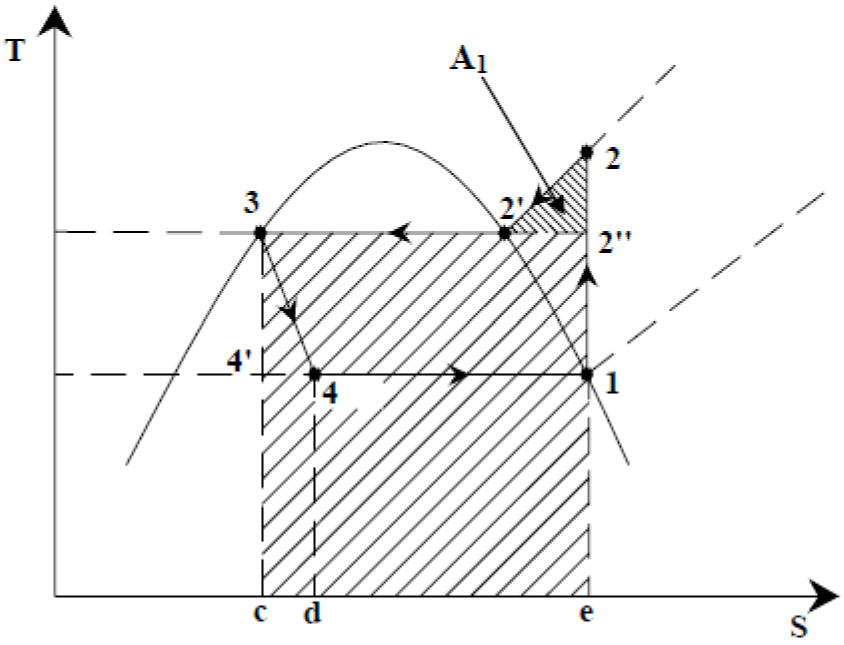


Fig. 17. Comparative evaluation of heat rejection rate of VCRS and Carnot cycle

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

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

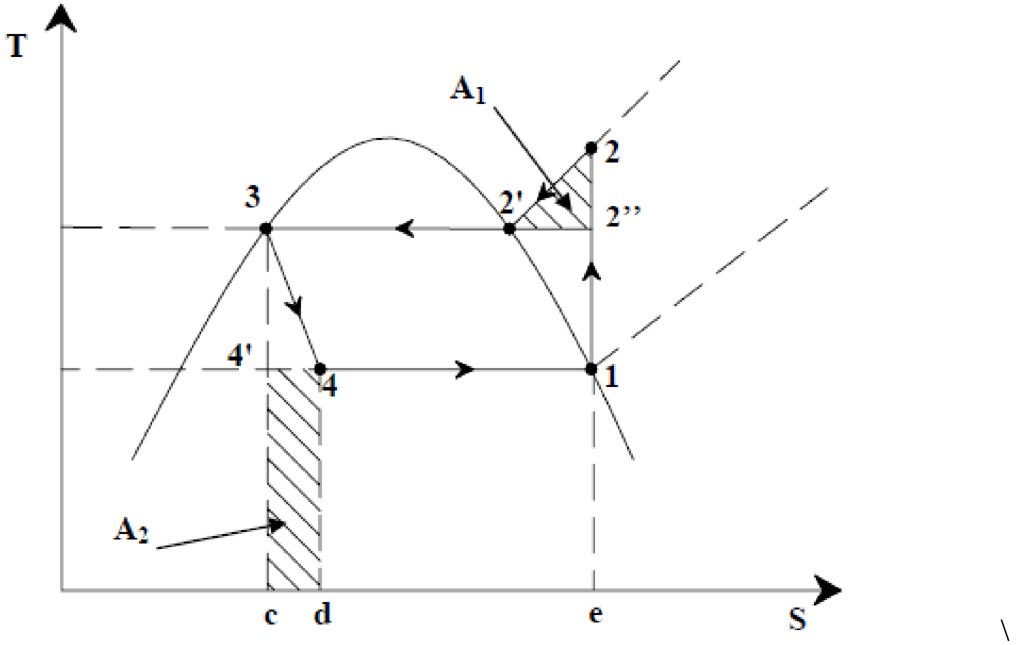


Figure 18. Illustrating the increase in network input in VCRS cycle.

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

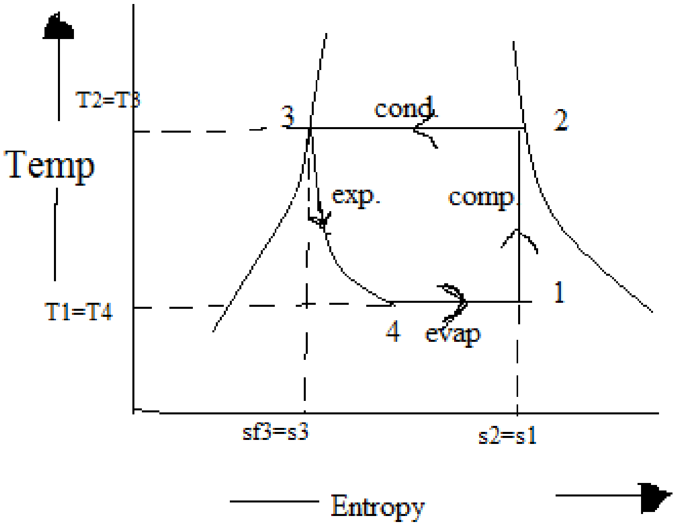


Fig. 11. T-S diagram for Wet Vapour Compression Cycle

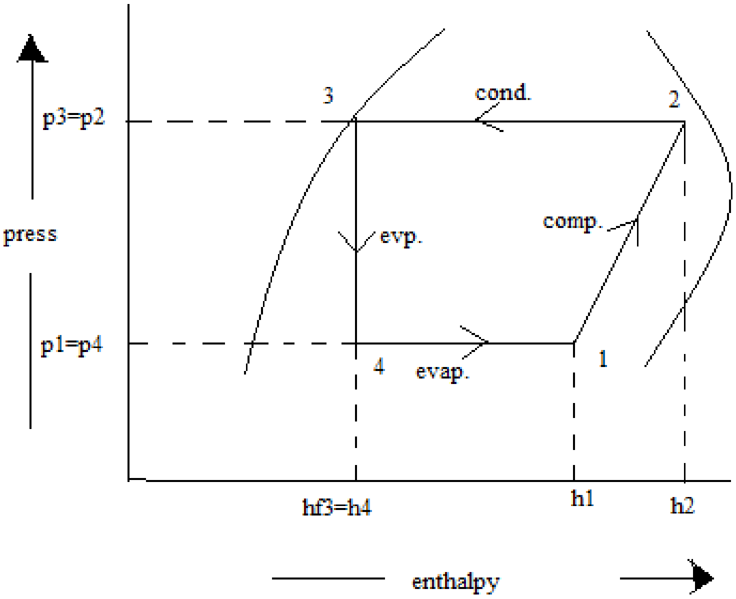


Fig. 12. P-h diagram for Wet Vapour Compression Cycle

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.

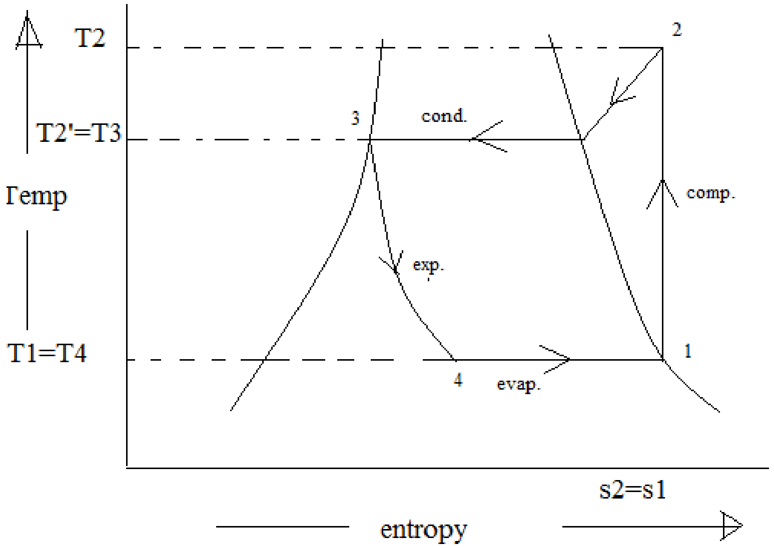


Fig.13 T-S diagram for Dry Vapour Compression Cycle

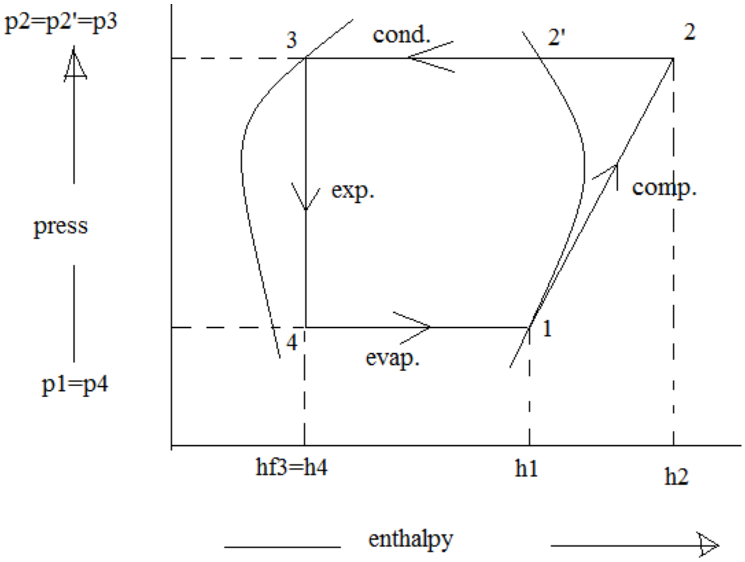


Fig. 14. P-h diagram for Dry Vapour Compresion Cycle

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

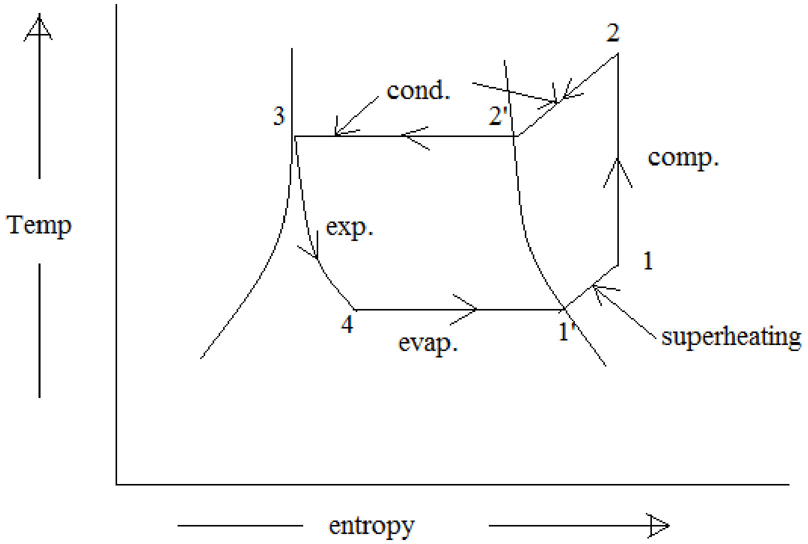


Fig. 15. T-S diagram for Vapour Compression cycle with superheated vapour before compression

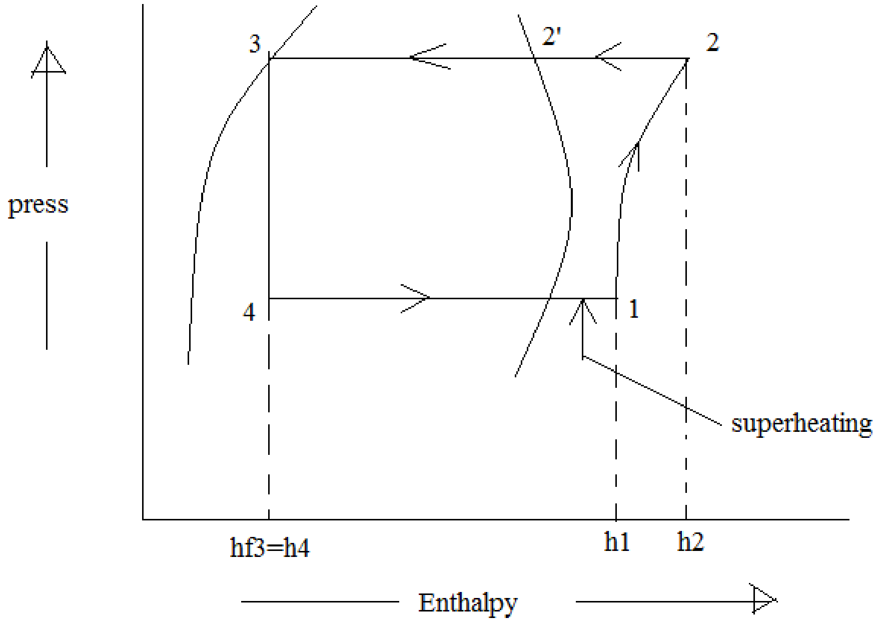


Fig. 16. P-h diagram for Vapour Compression cycle with superheated vapour before compression

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

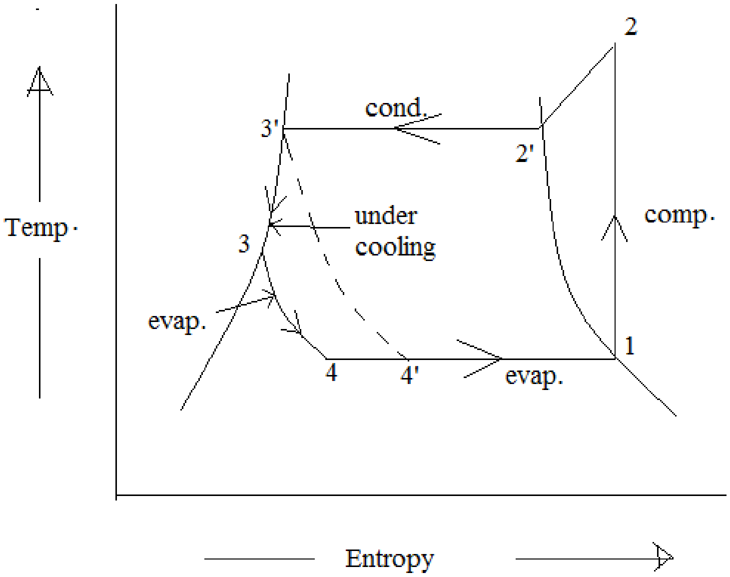


Fig. 17. T-S diagram for Vapour Compression cycle with undercooling refrigerant.

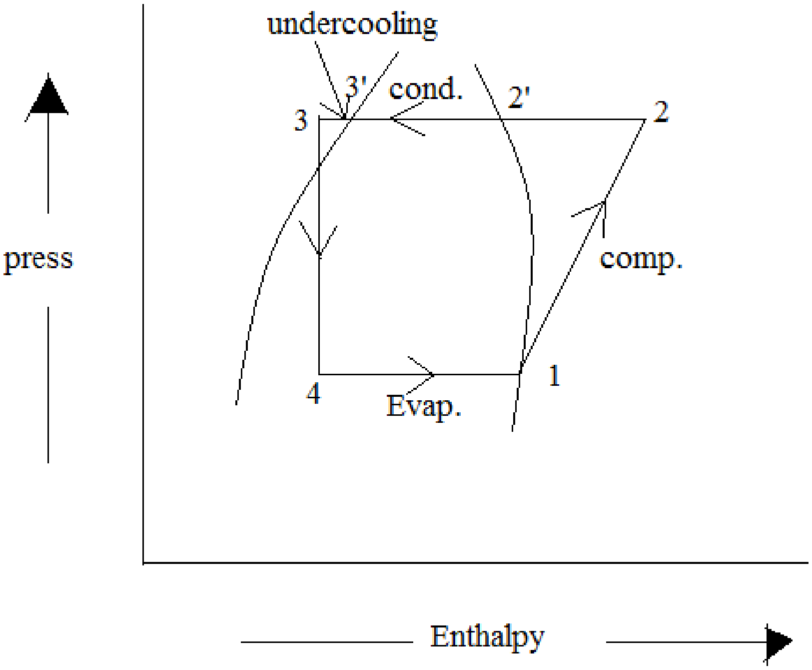


Fig. 18. P-h diagram for Vapour Compression cycle with undercooling refrigerant.

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, $W = h2\text{-}h1$

But $hf3 = hf3'\text{-}cp*\text{degree of undercooling}$

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

4.5. Actual vapour compression cycle

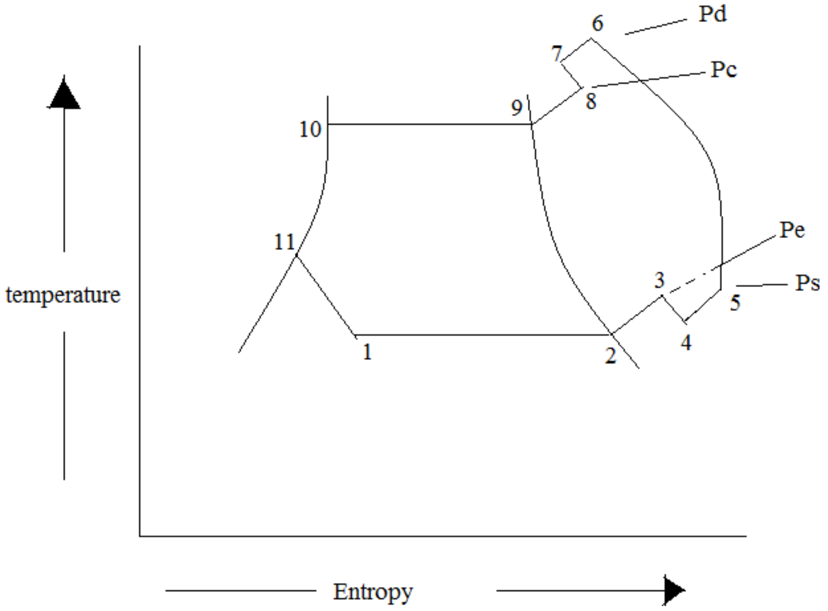


Fig. 19. T-S diagram for actual Vapour Compression cycle.

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

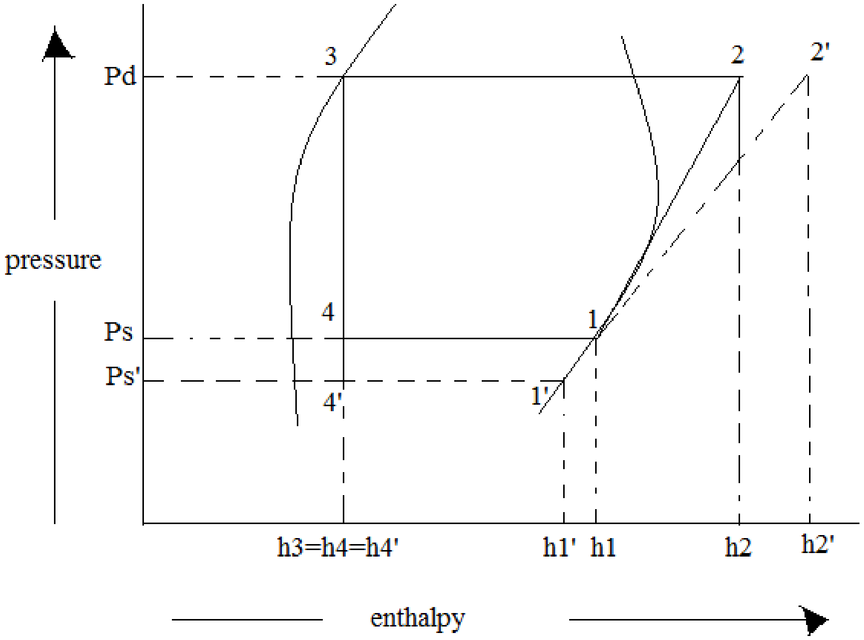


Fig.20. P-h diagram showing effect of suction pressure

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

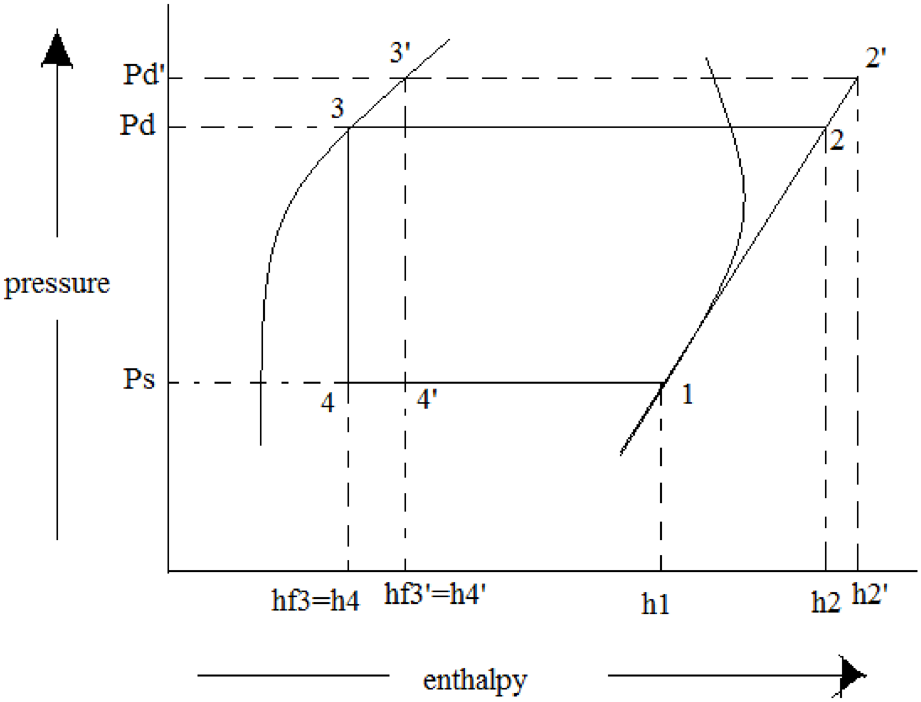


Fig.20. P-h diagram showing effect of discharge pressure

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

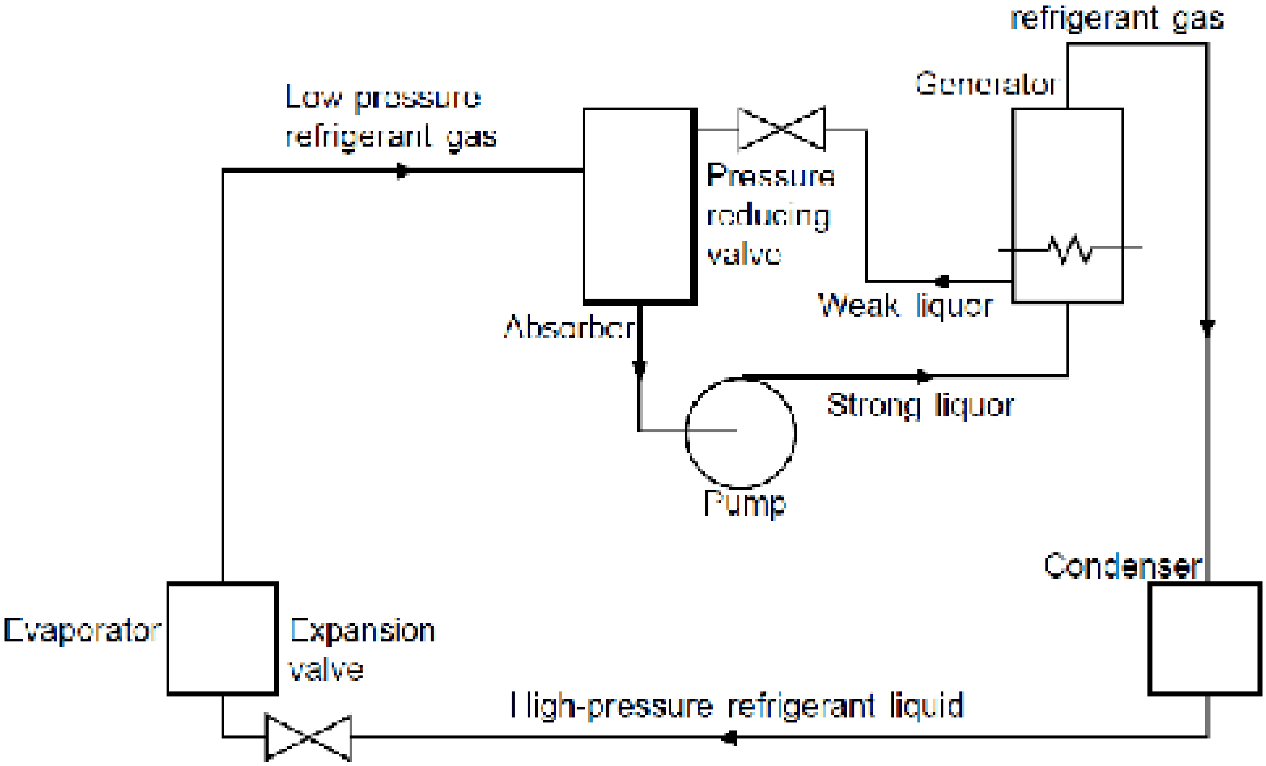
(ii) Increases the work required for compression from (h2-h1) to (h2'-h1).

CHAPTER FIVE

Vapour Absorption Cycle

Vapour can be withdrawn from an evaporator by absorption (Figure2.11) into a liquid. Two combinations are in use, the absorption of ammonia gas into water and the absorption of water vapour into lithium bromide. The latter is non-toxic and so may be used for air-conditioning.

The use of water as the refrigerant in this combination restricts it to systems above its freezing point. Refrigerant vapour from the evaporator is drawn into the absorber by the liquid absorbant, which is sprayed into the chamber. The resulting solution (or liquor) is then pumped up to condenser pressure and the vapour is driven off in the generator by direct heating. The high-pressure refrigerant gas given off can then be condensed in the usual way and passed back through the expansion valve into the evaporator. Weak liquor from the generator is passed through another pressure reducing valve to the absorber. Overall thermal efficiency is improved by a heat exchanger between the two liquor paths and a suction-to liquid heat exchanger for the refrigerant. Power to the liquor pump will usually be electric, but the heat energy to the generator may be any form of low-grade energy such as oil, gas, hot water or steam. The overall energy used is greater than with the compression cycle, so the COP (coefficient of performance) is lower.


refrigerant gas
Generator
Low pressure refrigerant gas
Pressure reducing valve
Weak liquor
Absorber
Strong liquor
Pump
Condenser
Evaporator
Expansion valve
High-pressure refrigerant liquid