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^oC	**22^oC**	**38^oC**
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.*

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

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

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

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.

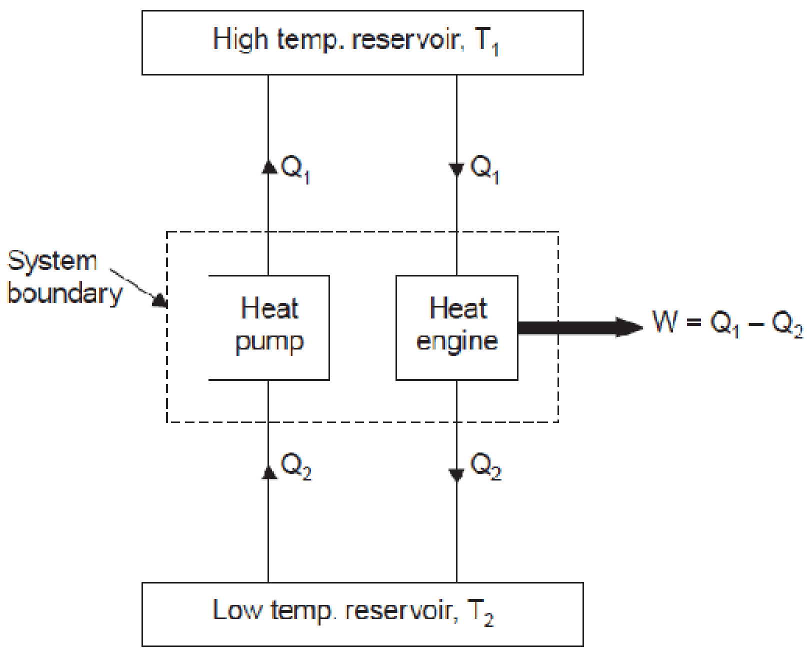


Fig. 1. Equivalence of Clausius statement to Kelvin-Planck statement.

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

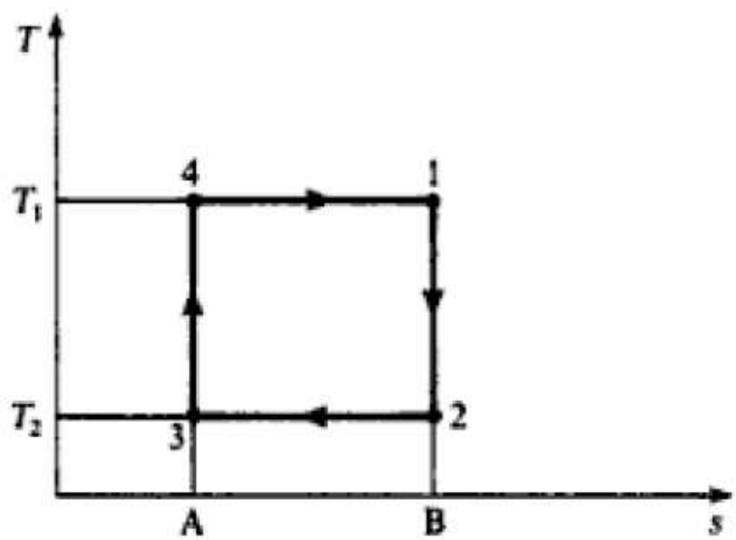


Fig. 2. Carnot cycle on a T-S diagram

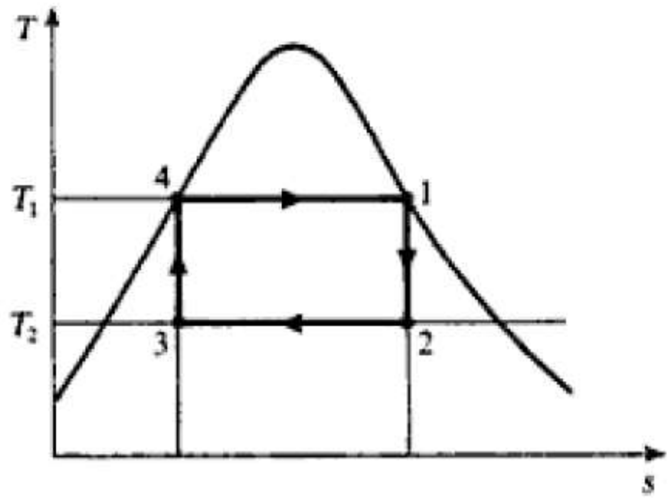


Fig. 3. Carnot cycle for a wet vapour on a T-S diagram

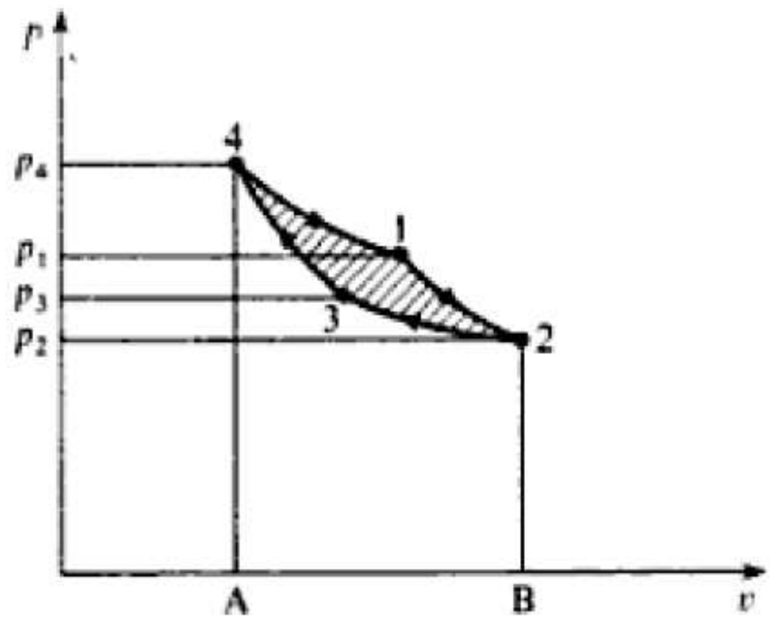


Fig. 4. Carnot cycle on a P-V diagram

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

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

($Q_1 = m\ c_p\ T_1$, $Q_2 = m\ c_p\ T_2$ 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".

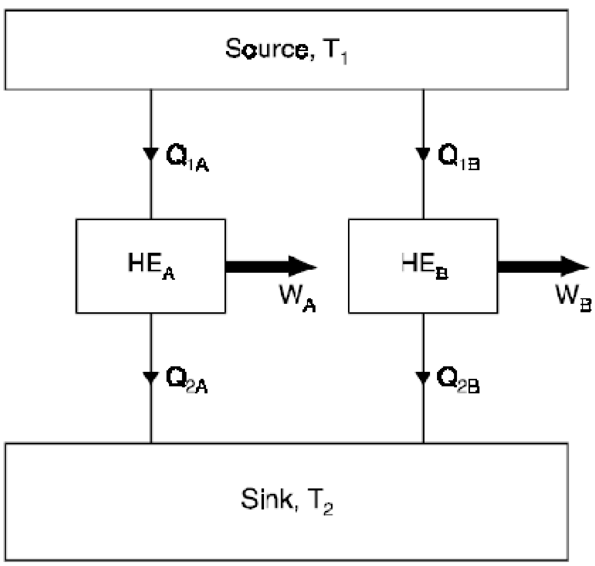


Fig. 5. Two cyclic heat engines HE_A and HE_B operating between the same source and sink.

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, $T_{1.}$

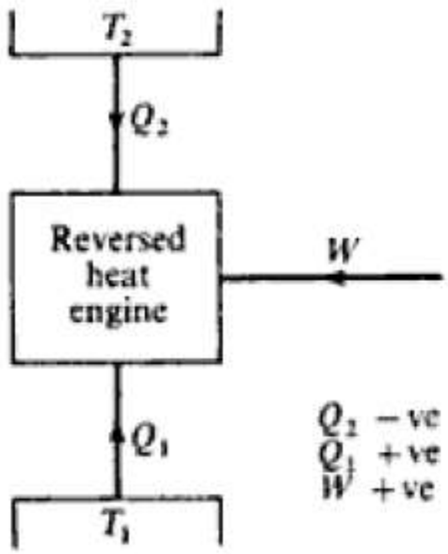


Fig. 6. Reversedheat engine

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

$$\sum dQ + \sum dW = 0$$

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

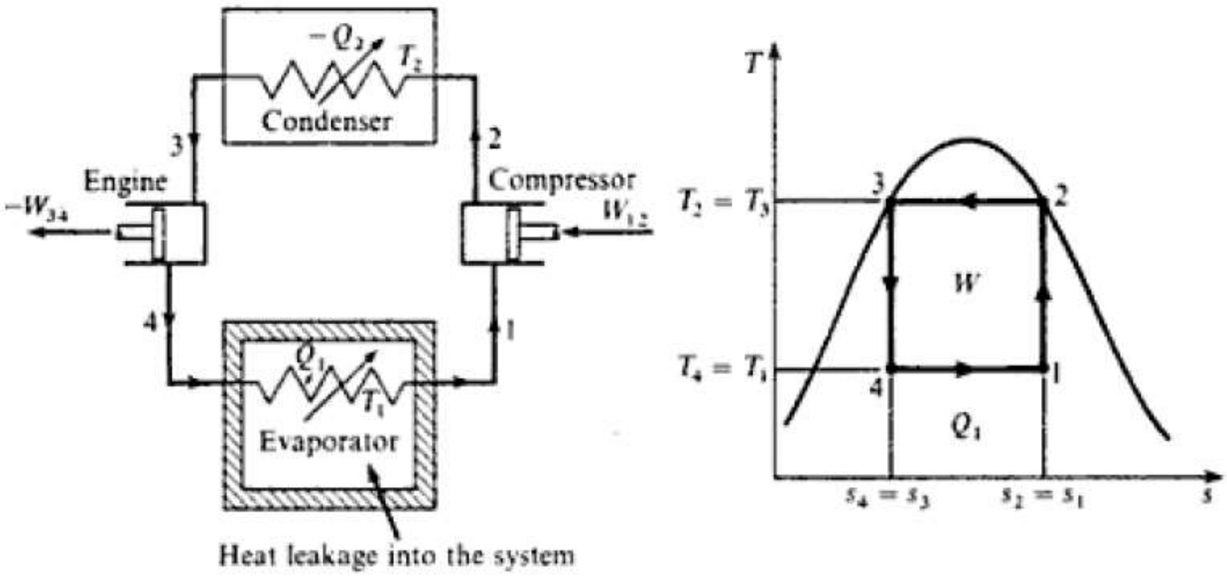
therefore

$$W + Q_1 = -Q_2$$

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

$$\text{COP}_{hp} = \frac{-Q_2}{\sum W}$$ (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

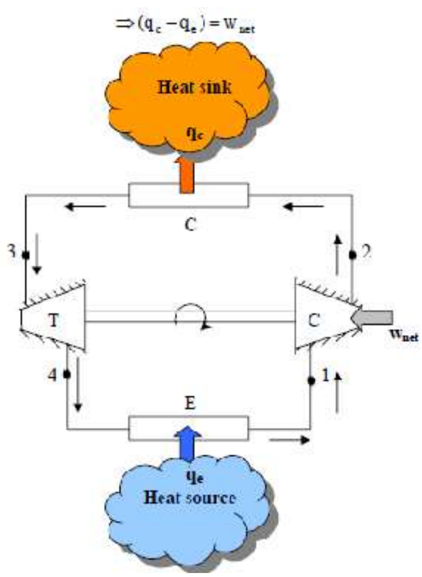


Fig. 7c. Schematic of a Carnot Refrigeration System

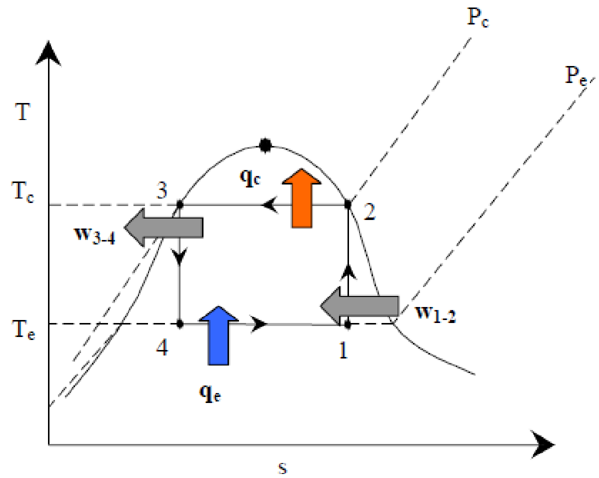


Fig. 7d. Carnot Refrigeration Cycle on T-S diagram

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 temperature T_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.

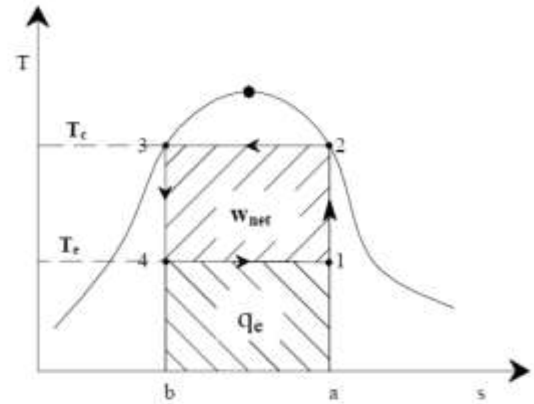


Fig. 8. Carnot Refrigeration cycle represented in T-S plane

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.

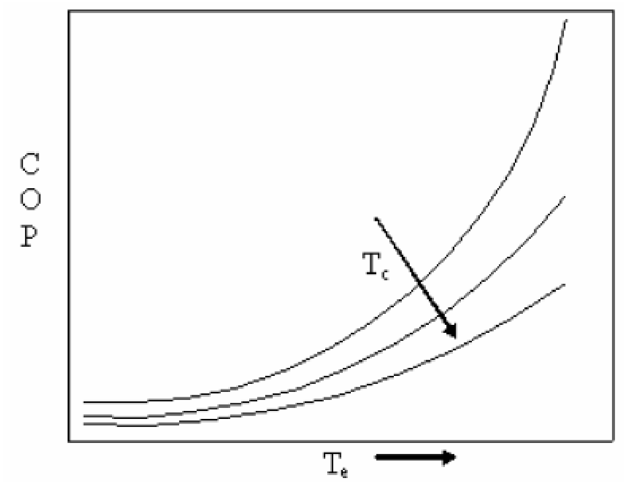


Fig. 9. Effects of evaporator and condenser temperatures on Carnot COP

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.

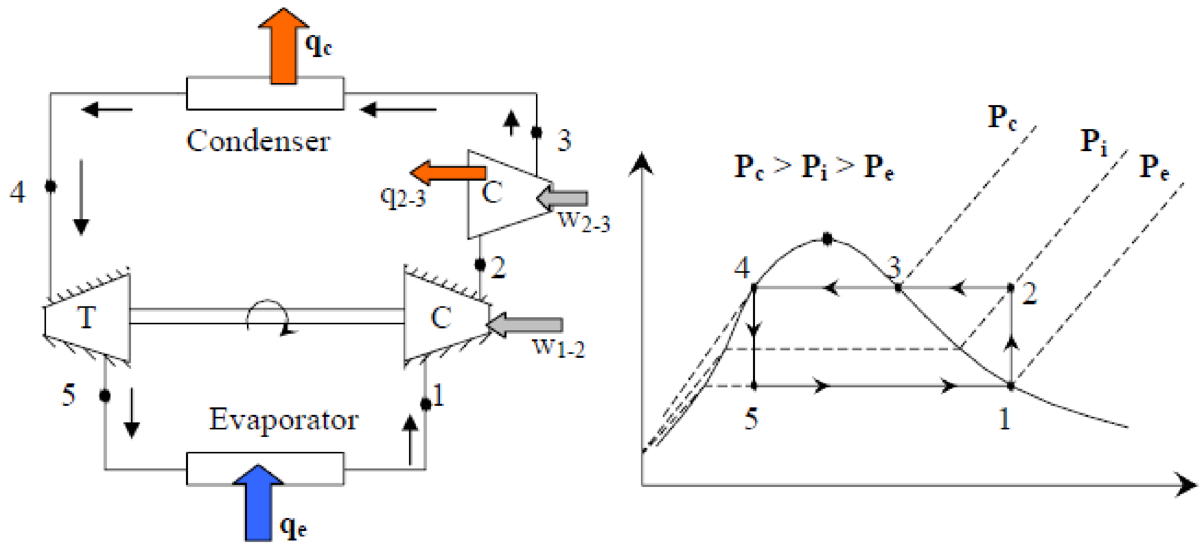


Fig.10. Carnot refrigeration cycle is to have two compressors – one isentropic and one isothermal

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.