1.0 PRINCIPLE & APPLICATION OF REFRIGERATION

Definition: Refrigeration is defined as the branch of science that deals with the process of reducing and maintaining the temperature of a space or material below the temperature of the surroundings.

- The purpose of refrigerator is to transfer heat from a cold chamber which is at a temperature lower than that of its surroundings.
- The natural flow of heat from the surroundings back to the cold chamber can be resisted by insulating the chamber from the surroundings.

HEAT PUMP

- This energy rejection in the refrigeration system must be carried out at a temperature above that of the surroundings.
- This energy can be used for heating purposes and refrigerating plants designed entirely for this purpose are called *heat pumps*.

Definition Heat pump is the, transferring of energy against the natural temperature gradient from a low – temperature to a higher one. It is analogous to pumping of water from a low level to a higher one against the natural gradient of gravitational force.

REFRIGERATION AND HEAT PUMP

- There is no difference in operation between a refrigerator and a heat pump.
- With the refrigerator the important quantity is the energy removed from cold chamber called the refrigerating effect, and
- With the heat pump it is the energy to be rejected by the refrigerant for heating purposes.
- The machine can be used for both purposes

NEED FOR THERMAL INSULATION

- Heat will 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 surrounding.

- 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.

THE REFRIGERATION LOAD

The rate at which heat must be removed from the refrigerated space or material in order to produce and maintain the desired temperature conditions is called the refrigeration load, the cooling load, or the heat load.

Sources of Cooling Load:

a) The heat transmitted by conduction through the insulated walls.
b) The heat that must be removed from the warm air that enters the space through opening and closing doors.
c) The heat that must be removed from the refrigerated product to reduce the temperature of the product to the storage temperature;
d) The heat given off by people working in the space and by motors, lights and other heat-producing equipment operating in the space.

ICE REFRIGERATOR

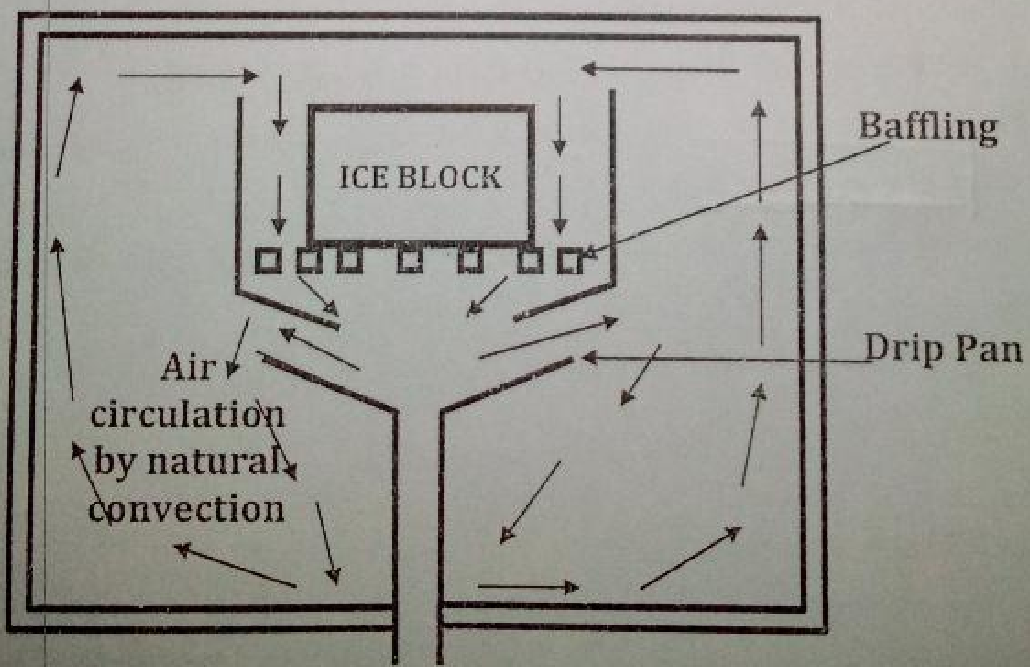

Fig. 1: Ice Refrigerator

Disadvantages of using Ice as a Refrigerant

a) It is not possible to obtain temperature lower than 0 °C.
b) It is necessary to be replenishing the supply of ice frequently; this practice is neither convenient nor economical.
c) More obvious disadvantage of ice is the problem of disposing of the water resulting from the melting of the ice.
d) The difficulty experienced in controlling the rate of refrigeration, which in turn makes it difficult to maintain the desired low temperature level within the refrigerated space.

APPLICATIONS OF REFRIGERATION

Refrigeration applications may be grouped into six general categories:

a) domestic refrigeration
b) commercial refrigeration
c) industrial refrigeration
d) marine & transportation refrigeration
e) comfort air conditioning
f) industrial air conditioning.

DOMESTIC REFRIGERATION

Domestic refrigeration is rather limited in scope, being concerned primarily with household refrigerators and home freezers. However, because the number of units in service is quite large, domestic refrigeration represents a significant portion of the refrigeration industry.

COMMERCIAL REFRIGERATION

Commercial refrigeration is concerned with the designing, installation, and maintenance of refrigerator used by retail stores; restaurants, hotels, and institutions for the storing and dispensing of perishable commodities of all types.

INDUSTRIAL REFRIGERATION.

- Industrial is often confused with commercial refrigeration because the division between these two areas is not clearly defined.
- Industrial refrigeration is larger in size than that of commercial and has the distinguishing feature of requiring an attendant on duty; usually a licensed engineer.
- Typical industrial applications are ice plants, large food-packing plants, breweries, creameries, and industrial plants.

MARINE REFRIGERATION

Marine refrigeration refer to aboard marine vessels and includes, for example, refrigeration for fishing boats and for vessels transporting perishable cargo as well as refrigeration for the ships stores on vessels of all kinds.

TRANSPORTATION REFRIGERATION

Transportation refrigeration is concerned with refrigeration equipment as it is applied to trucks, both long distance transports and local delivery, and to refrigerated railway cars.

PRESERVATION BY REFRIGERATION

- The preservation of perishables by refrigeration involves the use of low temperature as a means of eliminating or retarding the activity of spoilage agents.
- The storage of perishable at low temperatures greatly reduces the activity of both enzymes and micro-organisms and thereby provides a practical means of preserving perishables in their original fresh state for varying periods of time.
- Preservation of food products can be grouped into two general categories:

Preservation of Living Food

- The preservation problem of living food substances is chiefly one of keeping the food substance alive while at the same time retarding natural enzymic activity in order to slow the rate of maturation or ripening.
- Vegetables and fruit are as much alive after harvesting as they are during the growing period due to the utilization of the previously stored food substances.
- This causes the vegetable or fruit to undergo changes, which will eventually result in deterioration and complete decay of the product.
- The primary purpose of placing such products under refrigeration is to slow the living processes by retarding enzymic activity, thereby keeping the product in a preserved condition for a longer period.

Preservation of Non-Living Food

- Non-living food substances, such as meat, poultry, and fish, are much more susceptible to microbial contamination and spoilage than are living food substances, and they usually require more stringent preservation methods.
- The problem of preservation of non-living food substances is one of protecting dead tissue from all the forces of putrefaction and decay both enzymic and microbial.
- The enzymes causing the most trouble are those which catalyze hydrolysis and oxidation and are associated with the breakdown of animal fats.

METHODS OF REFRIGERATION

The methods or types of refrigeration systems are:

- Thermoelectric Refrigeration system
- Magnetic Refrigeration system
- Non cyclic Refrigeration system
  - Refrigeration is accomplished by melting ice
  - It is used for small-scale refrigeration or in portable coolers
- Cyclic Refrigeration system
  - Gas cycle refrigeration system
  - Vapour absorption refrigeration system
  - Vapour compression refrigeration system

(a) Thermoelectric Refrigeration System

The process of extracting heat energy electronically from an insulated chamber in order to bring down the temperature of the chamber below that of the surrounding air is known as thermoelectric. Thermoelectric refrigeration employs a principle called the "PELTIER" effect to extract heat electronically. The application of electrical current is across the junction of two dissimilar metal transfers heat from one of the metals to the other.

(b) Magnetic Refrigeration System

Magnetic refrigeration is a cooling technology based on the magneto caloric effect. This technique can be used to attain extremely low temperatures as well as the ranges used in common refrigerators, depending on the design of the system. The primary vehicle for magnetic refrigeration is the Magneto Caloric Effect (MCE), discovered by Warburg in 1881. Specifically, the magneto caloric effect is the response of a magnetic solid to a changing magnet field which is evident as a change in its temperature.

(c) Gas Cycle Refrigeration System

When the working fluid is a gas that is compressed and expanded but does not change phase, the refrigeration cycle is called a gas cycle. Air is most often used as working fluid in gas cycle. As there is no condensation and evaporation intended in a gas cycle, components corresponding to the condenser and evaporator in a vapour compression cycle are the hot and cold gas to gas heat exchangers in gas cycles. The gas cycle is less efficient than the vapour compression cycle because the gas cycle works on the reverse Brayton cycle instead of the reverse Rankine cycle. As such the working fluid does not receive and reject heat at constant temperature. In the gas cycle, the refrigeration effects are equal to the product of the specific heat of gas and the rise in temperature of the gas. Therefore, for the same cooling load, a gas refrigeration cycle will require a large mass flow rate and the system would be bulky.

(d) Vapour Absorption Refrigeration Cycle

In the early years of the twentieth century the vapour absorption cycle using water-ammonia pair as working fluids was popular and widely used. In this system, ammonia is used as refrigerant and water is used as absorbent. Also, in vapour absorption cycle using lithium bromide-water pair as working fluids, pure water is used as refrigerant and lithium bromide solution is used as absorbent. Heat for the vapour absorption refrigeration system can be provided by waste heat extracted from process, diesel generator set etc. Absorption system requires electricity to run pumps only. In the lithium bromide- water cycle, the refrigerant (water) evaporates at around 4°C under the high vacuum condition of 750 mmHg in the evaporator. When the refrigerant (water) evaporates, the latent heat of vaporization is taken from incoming chilled water. This latent heat of vaporization transferred to the refrigerant (water) will cool the chilled water which runs through the heat exchanger tubes in the evaporator. In order to keep evaporating the refrigerant vapour must be discharged from the evaporator and refrigerant (water) must be supplied. The heat generated in the absorption process is lead out of system by cooling water continually. The absorption also maintains the vacuum inside the evaporator. As lithium bromide solution is diluted the effect to absorb the refrigerant vapour reduces in order to keep absorption process.

(e) Vapour Compression Refrigeration Cycle

Vapour compression refrigeration system is one of the many refrigeration methods available for use. It uses can be traced back to professor Williams Cullen of Glasgow University in 1748 that produced refrigeration by creating partial vacuum over ethyl ether. In 1834, Jacob Perkins proposed a hand operates compressor machine working on ether. Among all refrigeration systems, vapour compression refrigeration system is the most commonly used in household refrigerators as well as in much large commercial and industrial refrigeration systems. This system belongs to the general class of vapour cycles, wherein the working fluid (refrigerant) undergoes phase change at least during one cycle. In a vapour compression refrigeration system, refrigeration is obtained as the refrigerant evaporates at low temperatures. The input to the system is in the form of mechanical energy required to run the compressor. Hence this system is also called the mechanical refrigeration system. Vapour compression refrigeration system is available to suit almost all applications with the refrigeration capacities ranging from few Watts to few megawatts. A wide variety of refrigerants can be used in this system to suit different applications, capacities etc.

2.0 VAPOUR COMPRESSION REFRIGERATION

The vapour compression cycle is the most widely used refrigeration cycle in practice. A vapour compression refrigeration system is made of four components: compressor, condenser, expansion device and evaporator (Fig. 2). A vapour is compressed (in compressor), then condensed to a liquid (in condenser), and the pressure is dropped (in expansion device) so that the fluid can evaporate at a low pressure (in evaporator). These components are connected by pipelines in which a refrigerant with suitable thermodynamic properties circulates (Fig. 3).

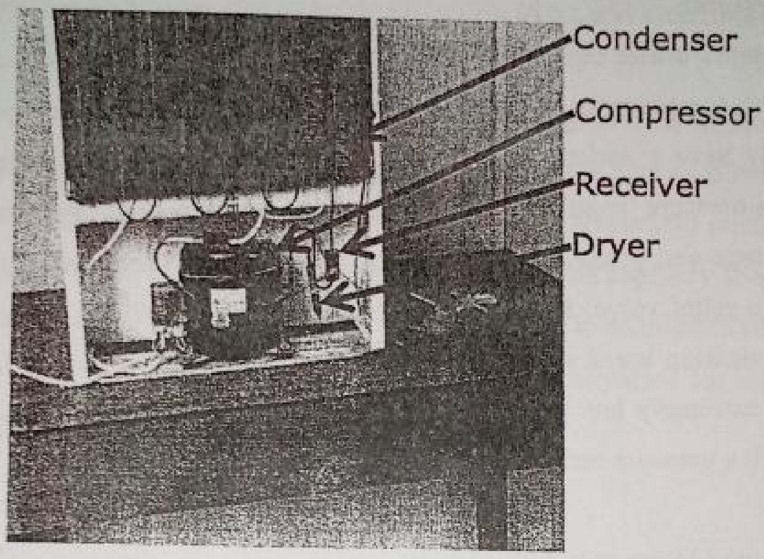

Fig. 2: Domestic Refrigerator

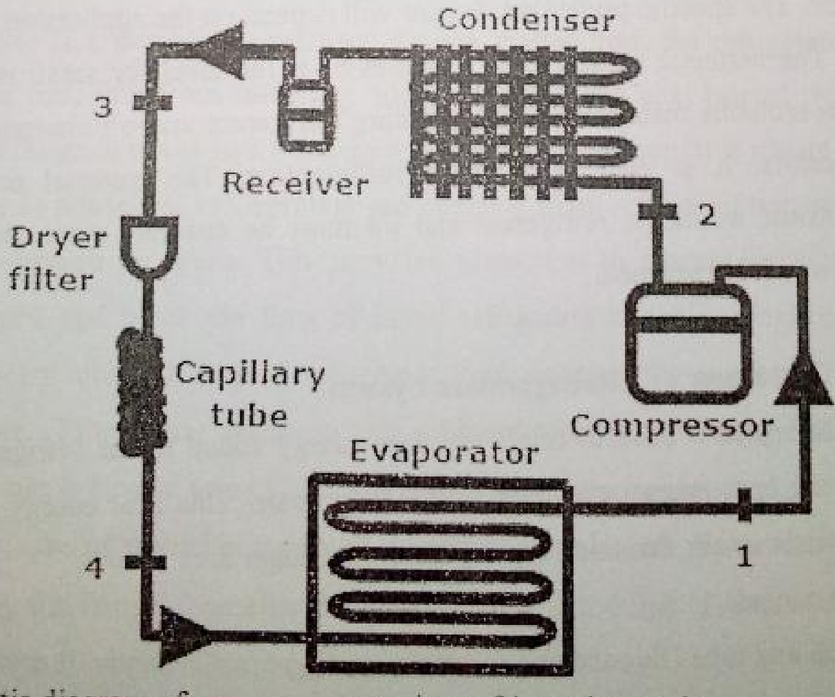

Fig. 3: Schematic diagram of vapour compression refrigeration cycle

Compressor of a Vapour Compression Refrigeration System

Both positive displacement and centrifugal compressors are used in refrigeration applications.

Positive displacement compressors:

In the positive displacement compressors, the pressure of the vapour entering the compressor is increased by decreasing the volume of the compression chamber. Reciprocating, rotary, scroll, and screw compressors are examples of positive displacement compressors.

Centrifugal compressors:

Centrifugal compressors utilize centrifugal forces to increase the pressure of the refrigerant vapour. Refrigeration compressors can be used alone or in parallel and series combinations. Compressors usually have a variety of protection devices for handling adverse conditions. These include high-pressure controls, high-temperature controls, low-pressure protection, time delay, low voltage and phase loss, and suction line strainer. These can include a high-pressure cut off or a relief valve. High-temperature devices are designed to protect against overheating and lubrication break down. Low-pressure protection is provided to protect the compressor against extremely low pressures, which may cause insufficient lubricant return, freeze-up, or too high a pressure ratio.

Time delays are required to prevent damage to the compressor motor from rapid start up after a shutdown. A suction line strainer is used to remove dirt and other particles that may be in the refrigerant line. The specific protection devices will depend on the application and size of the compressor. The hermetic reciprocating compressor is the ideal for small refrigeration systems, where continuous maintenance (replenishing refrigerant and oil charge) cannot be guaranteed. Therefore, it is used in domestic refrigerators. The material compatibility between the electrical windings, refrigerant and oil must be ensured, since the complete system is kept in wedded steel shell.

Evaporator and Condenser of a Refrigeration System

The refrigerant condenser is used to reject the heat energy added to the refrigerant during compression and the heat energy absorbed in the evaporator. This heat energy is typically rejected to either water or air. Common types of heat exchanger are:

- Air cooled
- Shell and tube (flooded and direct expansion)
- Plate heat exchangers

Refrigerant Control Device of Refrigeration Systems

One of the four major components in a vapour compression refrigeration system is the refrigerant control device. The functions are to adjust the quantity of refrigerant flow into the evaporator according to the evaporator load and to create a pressure drop from the high side to the low side of the system in order to permit the refrigerant to vaporise under the desired low pressure in the evaporator while at the same time condensing at a high pressure in the condenser. There are various types of refrigerant flow control devices, such as manual expansion valve, capillary tube, thermostatic expansion valve and electronic expansion valve.

Capillary tube is one of the most commonly used throttling devices in the refrigeration and the air conditioning systems. It is a fix metering device which acts as flow restricting device and cannot be altered to effect performance. It is used in household refrigerators, room air conditioners and in small package air conditioning units. The capillary tube is a copper tube of very small internal diameter. It is of very long length and it is coiled to several turns so that it will occupy less space. The internal diameter of the capillary used for the refrigeration and air conditioning applications varies from 0.5 to 2.28 mm.

The Filter Dryer of a Refrigeration System

The filter-dryer is a device that removes foreign matter from the refrigerant. This foreign matter can be dirt, flux from soldering, filling moisture and acid caused by moisture. The filter-dryer is fastened to the liquid line by a soldering connection. It is placed at the outlet of the condenser in household refrigerators and contains mesh screens to trap contaminants and chemicals to absorb moisture. This provides protection to the capillary tube which can become clogged and block the flow of liquid refrigerant to the evaporator. A completely blocked capillary tube will stop all refrigerant from reaching the evaporator and no cooling will take place. Filter-dryer comes in two different types: throw away and refillable type. The common use is thrown away if it is not functioning appropriately and it is replaced with a new filter. In case of refillable type, the desiccant granules are replaced by a fresh charge after removing the flange, thereafter the same is filled in the line. The desiccant for common use is aluminium sulphate, silica gel and zeolite.

CARNOT REFRIGERATION CYCLE.

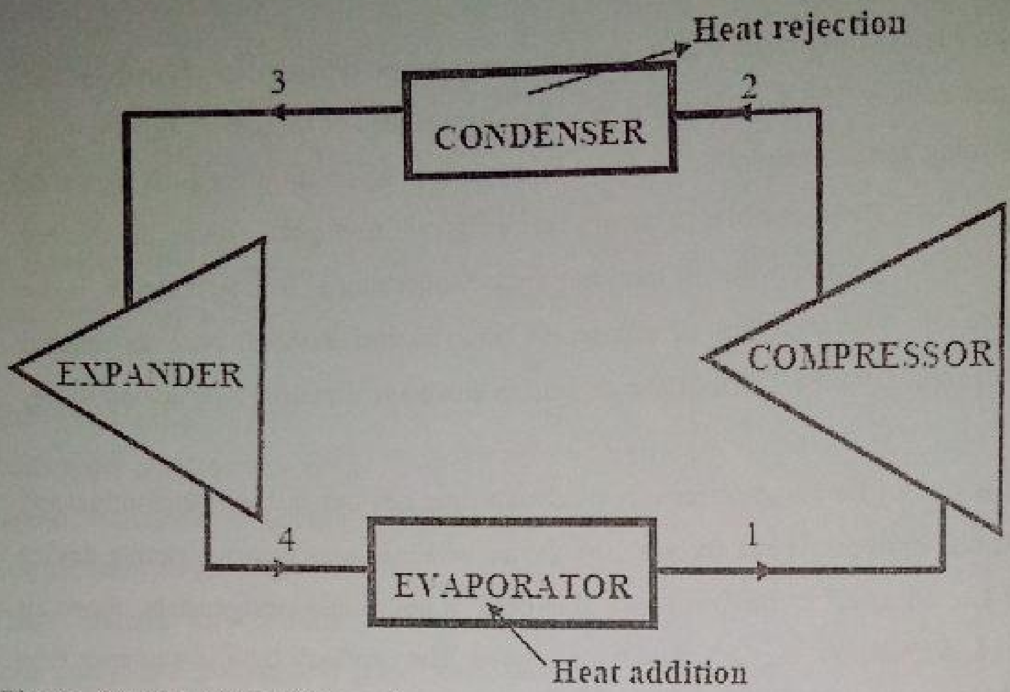

Fig. 4: Carnot refrigeration cycle.

The Carnot cycle is one whose efficiency cannot be exceeded when operating between two given temperatures. The Carnot heat engine receives energy at a high level of temperature, converts a portion of the energy into work, and discharges the remainder to a heat sink at a low level of temperature. The Carnot refrigeration cycle performs the reverse effect of the heat engine, because it transfers energy from a low level of temperature to a high level of temperature. The diagram of the equipment and the temperature – entropy diagram of the refrigeration cycle are shown below.

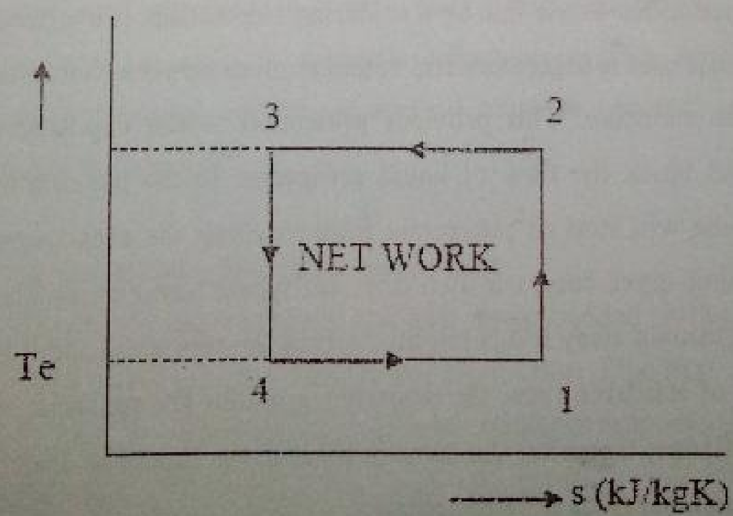

Fig. 5: Temperature – entropy diagram of the Carnot refrigeration cycle.

The processes that constitute the cycle are:

Process 1 – 2 Isentropic compression, $S_1 = S_2$

Process 2 – 3 Isothermal rejection of heat at Tc = Constant i.e. $T_2 = T_3$.

Process 3 – 4 Isentropic expansion, $S_3 = S_4$.

Process 4 – 1 Isothermal addition of heat (heat absorption from the cold reservoir) at Te = constant i.e $T_1 = T_4$.

All the processes in the Carnot cycle are thermodynamically reversible. Processes 1 –2 and 3 – 4 are consequently reversible adiabatic (isentropic). The withdrawal of heat from the low temperature source in process 4 –1 is the refrigeration step and is the entire purpose of the cycle. All the other processes in the cycle function so that the low – temperature energy can be discharged to some convenient high - temperature sink.

The Carnot cycle, consists of reversible process which make its efficiency higher than could be achieved in an actual cycle. Although Carnot cycle is an unattainable ideal cycle, it necessary to study the cycle because of the following reasons.

(i) It serves as a standard of comparison, and

(ii) It provides a convenient guide to the temperatures that should be maintained to achieve maximum effectiveness.

COEFFICIENT OF PERFORMANCE.

Before any evaluation of the performance of a refrigeration system can be made, an effectiveness term must be defined. The index of performance is not called efficiency, however, because that term is usually reserved for the ratio of output to input. The ratio of output to input would be misleading applied to a refrigeration system because the output in process 2-3 (Fig. 2.1) is usually wasted. The concept of the performance index of the refrigeration cycle is the same as efficiency. The performance term in the refrigeration cycle is called the coefficient of performance; defined as

$$\text{Coefficient of Performance} = \frac{\text{Useful refrigeration}}{\text{Net work done}}$$

or $$COP_{ref} = \frac{\text{Refrigeration effect}\,(Q_e)}{\text{Net work done}\,(W)}$$

The two terms which make up the coefficient of performance must be in the same units, so that the coefficient of performance is dimensionless. The heat transferred in a reversible process is: Qrev = ΣTds. Areas beneath reversible processes on the temperature – entropy diagram therefore represent transfers of heat. Area shown in Fig. 2.2 can represent the amount of useful refrigeration and network. The useful refrigeration is the heat transferred in process 4 –1, or the area beneath line 4 –1. The area under line 2 –3 represents the heat rejected from the cycle and heat added to the cycle is the net heat which for a cyclic process equals the network. The area enclosed in rectangle 1-2-3-4 represents the network. An expression for the coefficient of performance of the Carnot refrigeration cycle is therefore;

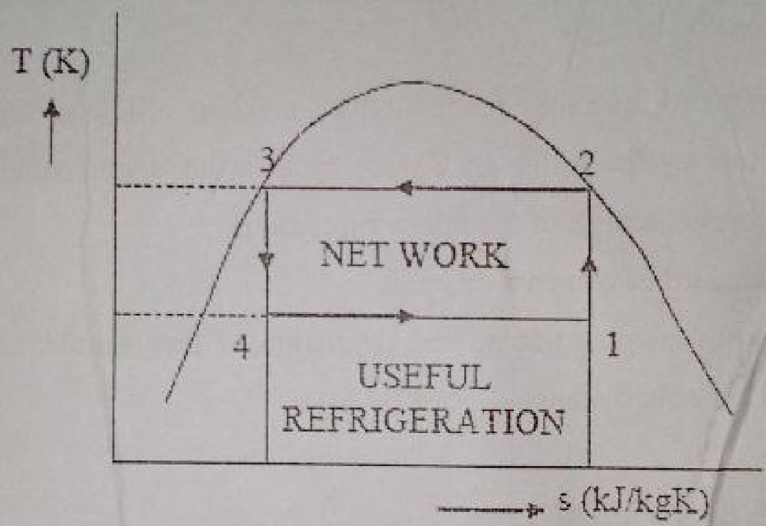

Fig. 6: T-s diagram of the Carnot Cycle showing useful Refrigeration and Net Work.

$$COP_{ref} = \frac{\text{Useful refrigeration } (Q_e)}{\text{Net workdone } (W)} = \frac{T_1(s_1 - s_4)}{T_2(s_2 - s_3) - T_1(s_1 - s_4)}$$

$S_2 - S_3 = S_1 - S_4$ Since $S_2 = S_1$ and $S_3 = S_4$.

Therefore, $$COP_{ref} = \frac{T_1(s_1 - s_4)}{(T_2 - T_1)(s_1 - s_4)} = \frac{T_1}{T_2 - T_1}$$

or, $$COP_{ref} = \frac{T_e}{T_c - T_e}$$

Where T_e = temperature in the evaporator

T_c = temperature in the condenser.

For Heat Pump

$$COP_{hp} = \frac{\text{Heat rejected from the cycle}(Q_c)}{\text{Net work done (W)}}$$

$$COP_{hp} = \frac{T_2(s_2 - s_3)}{T_2(s_2 - s_3) - T_1(s_1 - s_4)} = \frac{T_2(s_1 - s_4)}{(T_2 - T_1)(s_1 - s_4)}$$

$$COP_{hp} = \frac{T_2}{T_2 - T_1} \text{ or } \frac{T_c}{T_c - T_e}$$

The coefficient of performance of the Carnot cycles is entirely a function of the temperature limits and vary from zero to infinity.

CONDITIONS FOR HIGHEST COEFFICIENT OF PERFORMANCE.

A low value of T_c will make the coefficient of performance high. A high value of T_e increases the numerator and decreases the denominator, both of which increase the coefficient of performance. The value of T_e, therefore, has a more pronounced effect upon the coefficient of performance than T_c.

EXAMPLE

The temperature in a refrigerator evaporator coil is - 6 °C and that in the condenser coil is 22 °C. Assuming that the machine operates on these reversed Carnot cycle, calculate

(i) the COP_{ref},

(ii) the refrigerating effect per kilowatt of input work, and

(iii) the heat rejected to the condenser.

SOLUTION.

Tc = - 6 °C = 273 – 6 = 267K;

Tc = 22°C = 273 + 22 = 295K

Work input (W) = 1 kW

(i) $$COP_{ref} = \frac{Te}{T_c - T_e}$$

$$COP_{ref} = \frac{267}{295 - 267} = \frac{267}{28}$$

$$= 9.54$$

(ii) $$\text{COP}_{ref} = \frac{\text{Refrigeration effect}}{\text{Work input}} = \frac{Q_e}{W}$$

$$\begin{aligned} \text{Refrigerating Effect} &= \text{COP}_{ref} \times \text{Net Work} \\ &= 9.54 \times 1\text{ kW} \\ &= 9.54\text{ kW} \end{aligned}$$

(iii) Heat rejected at condenser Q_c is equal to the sum of heat absorbed from the evaporator Q_e and work input W

i.e.
$$\begin{aligned} Q_c &= (Q_e + W)\text{ kW} \\ Q_c &= (9.54 + 1)\text{ kW} \\ Q_c &= 10.54\text{ kW} \end{aligned}$$

VAPOUR AS A REFRIGERANT IN REVERSED CARNOT CYCLE.

The reversed Carnot cycle can be made almost completely practical by operating in the liquid – vapour region of a pure substance as shown below.

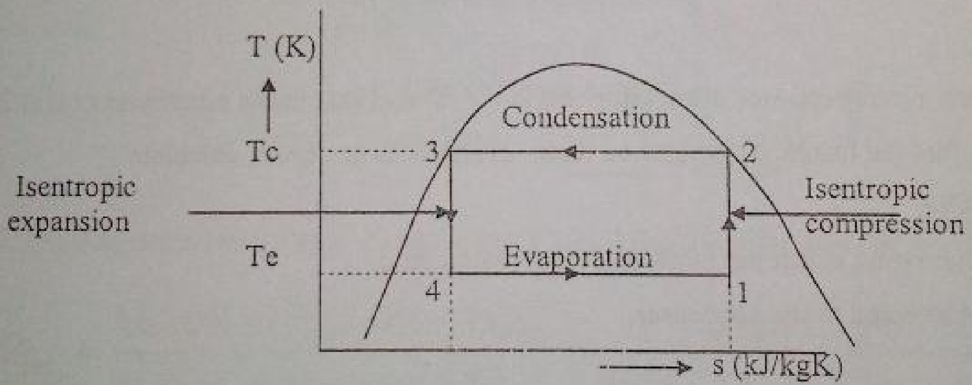

Fig. 7: Reversed Carnot cycle with vapour as a refrigerant.

The isothermal processes of heat rejection (2 – 3) and heat absorption (4 – 1) of the Carnot cycle are achieved by making use of the phenomena of condensation and evaporation of a pure substance at constant pressure and temperature. This alternate condensation and evaporation of a working substance is accompanied by alternate isentropic compression (1-2) and expansion (3 –4) processes. It may be noted that the vapour during compression is wet although it is dry-saturated at the end of compression. Such a compression is called ***wet compression***. It may also be seen that the isentropic expansion of the liquid from 3 to 4 results in flashing of the refrigerant with a consequent temperature drop from Tc to Te. But such an expansion of a liquid with partial vaporization is practically difficult to achieve in a fast – moving piston and cylinder mechanism.

The thermodynamic analysis per unit mass of the refrigerant is given below.

Refrigerating effect,	Q_e	=	$h_1 - h_4$
Heat rejected,	Q_c	=	$h_2 - h_3 = (h_{fg})c$
Compressor work,	W_{cp}	=	$h_2 - h_1$
Expander Work,	W_{ex}	=	$h_3 - h_4$
Net work,	W	=	$W_{cp} - W_{ex}$
	W	=	$(h_2 - h_1) - (h_3 - h_4)$
	W	=	$Q_c - Q_e$
		=	$(h_2 - h_3) - (h_1 - h_4)$

$$COP_{ref} = \frac{Q_e}{W} = \frac{Q_e}{Q_c - Q_e} = \frac{h_1 - h_4}{(h_2 - h_3) - (h_1 - h_4)}$$

EXAMPLE

A Carnot refrigerator has working temperatures of - 30 °C and 35 °C. If it operates with R12 as a working substance, calculate the work of isentropic compression, the work of isentropic expansion, refrigerating effect and heat rejected per kg of the refrigerant, and COP of the Cycle.

SOLUTION

Referring to Fig. 2.3, from the table of properties of R12, we have

at 35°C $\quad s_f = s_3 = s_4 = 0.2559$ kJ/kg.K

$s_g = s_2 = s_1 = 0.6839$ kJ/kgK

$h_f = h_3 = 69.5$ kJ/kg

$h_g = h_2 = 201.5$ kJ/kg.

At 30 °C, $\quad s_{f4} = s_{f1} = 0.0371$ kJ/kg.K; $\quad (s_{g4} = s_{g1} = 0.7171$ kJ/kg.K)

$h_{f4} = h_{f1} = 8.9$kJ/kg; $\quad (h_{g4} = h_{g1} = 174.2$ kJ/kg)

Hence, dryness fractions at 1 and 4 are $\quad s_1 = s_{f1} + x_1(s_{g1} - s_{f1})$

$$x_1 = \frac{s_1 - s_{f1}}{s_{g1} - s_{f1}} = \frac{0.6839 - 0.0371}{0.7171 - 0.0371} = 0.951$$

$s_4 = s_{f4} + x_4(s_{g4} - s_{f4})$

$$x_4 = \frac{s_4 - s_{f4}}{s_{g4} - s_{f4}} = \frac{0.2559 - 0.0371}{0.7171 - 0.0371} = 0.322$$

$h_1 = h_{f1} + x_1(h_{g1} - h_{f1})$

$= 8.9 + 0.951\ (174.2 - 8.9) = 166$ kJ/kg

$h_4 = h_{f4} + x_4(h_{g4} - h_{f4}) = 8.9 + 0.322\ (174.2 - 8.9) = 62.1$ kJ/kg

(i) Work of compression, $W_{cp} = h_2 - h_1 = 201.5 - 166 = 35.5$ kJ/kg

(ii) Work of expansion, $W_{ex} = h_3 - h_4 = 69.5 - 62.1 = 7.4$ kJ/kg

(iii) Refrigerating effect, $Q_e = h_1 - h_4 = 166 - 62.1 = 103.9$ kJ/kg

(iv) Heat rejected, $Q_c = h_2 - h_3 = 201.5 - 69.5 = 132$ kJ/jg

(v) Net work $W = W_{ep} - W_{ex} = 35.5 - 7.4 = 28.1$ kJ/kg

Or $W = Q_c - Q_c = 132 - 103.9 = 28.1$ kJ/kg

$$COP_{ref} = \frac{Q_e}{W} = \frac{103.9}{28.1} = 3.7$$

Also, we have for $COP_{ref(Carnot)} = \frac{Te}{T_c - T_e}$

$$COP_{ref\,(Carnot)} = \frac{243}{308 - 243} = \frac{243}{65}$$

$$= 3.74$$

TONS OF REFRIGERATION

It was common practise to measure amounts of refrigeration in tons of refrigeration. One ton of refrigeration (abbreviation: TR) is the amount of cooling produced by one U.S. ton of ice in melting over a period of 24 hours. Since an American ton is 907.2 kg and the latent heat of fusion of water amounts to 334.9 kJ/kg, we

$$1\,TR = \frac{907.2 \times 334.9}{24 \times 3600} = 3.5165\,kW$$

If cooling required is X kW of refrigeration, the rate of refrigerant circulation necessary is given as

$$m' = \frac{\text{Useful refrigeration in } kW}{\text{Refrigeration effect in } kJ/kg} = \frac{Q_e'}{Q_e}$$

$$m' = \frac{X}{h_1 - h_4} kg/s$$

Where m' = mass flow rate of the refrigerant.

EXAMPLE

In the example 2.2, If the actual refrigerator operating on the same temperatures has a COP of 0.75 of the maximum, calculate the power consumption and heat rejected to the surroundings per ton of refrigeration.

SOLUTION

From the previous example; maximum COP = 3.74

Therefore; actual COP = 0.75 x 3.74 = 2.8

Qe = 1 ton of refrigeration = 3.5165 kW

(i) Power consumption per ton, $W' = \frac{Q_c'}{COP_{Actual}} = \frac{3.5165}{2.68}$

$W' = 1.256kW$

(i) Heat rejected per ton, $Q_c' = Q_e' + W'$

$Q_c' = 3.5165 + 1.256$

$Q_c' = 4.7725$ kW.

GAS AS A REFRIGERANT IN REVERSED CARNOT CYCLE

Fig 2.4 shows the Carnot cycle with gas as a refrigerant, illustrated on P-v diagram.

The processes are as follows:

1-2	Isentropic compression;	$Q = O$
	Pressure increases from	$P_1 = P_2$
	Specific volume reduces from	V_1 to V_2
	Temperature increases from	$T_e = T_1$ to $T_c = T_2$

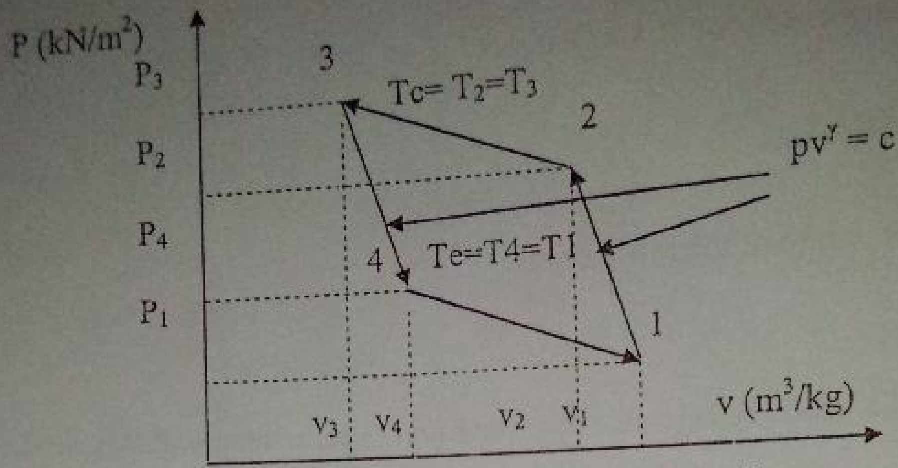

Fig. 8: Reversed Carnot cycle with gas as a refrigerant on P-v diagram.

Work done, $$W_{1-2} = \frac{P_2 v_2 - P_1 v_1}{\gamma - 1} = \frac{R(T_c - T_e)}{\gamma - 1}$$

2-3 Isothermal compression and heat rejection: $T_2 = T_3 = T_c$

Pressure increases from P_2 to P_3

Specific volume reduces from v_2 to v_3

Work done, $W_{2\text{-}3} = P_2V_2 \ln(v_2/v_3) = RT_c(v_2/v_3)$

Heat rejected $Q_c = Q_{2\text{-}3} = W_{2\text{-}3}$ (for a perfect gas)

3-4 Isentropic expansion: $Q = 0$

Pressure falls from P_3 to P_4

Specific volume increases from v_3 to v_4

Temperature decreases from $T_c = T_3$ to $T_e = T_4$

Work done, $$W_{3-4} = \frac{P_3 v_3 - P_4 v_4}{\gamma - 1} = \frac{R(T_c - T_e)}{\gamma - 1}$$

4-1 Isothermal expansion and heat absorption: $T_4 = T_1 = Te$

Pressure increases from P_4 to P_1

Specific volume reduces from V_4 to V_1

Work done, $W_{4\text{-}1} = P_4v_4 \ln(v_1/v_4)$

$= RT_c(v_1/v_4)$

Refrigerating effect, $Q_e = Q_{4\text{-}1}$

$= W_{4\text{-}1}$ (for a perfect gas)

ACTUAL REFRIGERATION SYSTEMS

For the purpose of comparison between the actual and Carnot values the following term is often used.

$$\text{Relative efficiency} = \frac{COP_{\text{ref}\,(actual)}}{COP_{\text{ref}\,(Carnot)}}$$

The reverse Carnot cycle with vapour as a refrigerant can be used as a practical cycle with modifications.

- The isothermal processes of heat rejection and absorption with condensation and evaporation respectively, are easily achievable in practice.
- But, the isentropic compression and expansion processes have certain limitation that required the following modifications:

REPLACEMENT OF THE EXPANSION DEVICE WITH THROTTLE VALVE

- Throttling process occur such that the initial enthalpy equals the final enthalpy.
- Refrigerating Effect, Q_e, is reduced by replacing the expansion device with a simple throttle valve.
- The Throttling process (3-4) is highly irreversible that the whole cycle becomes irreversible.

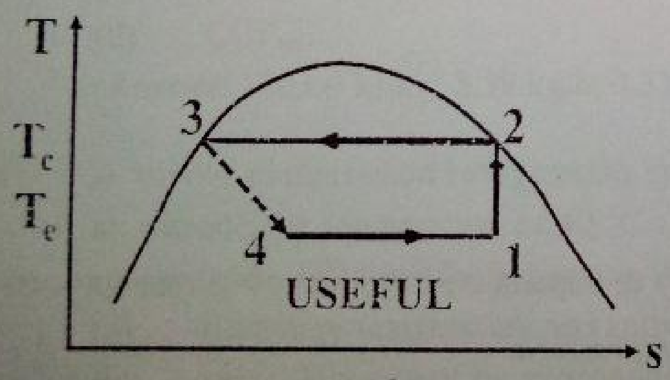

Fig. 9: Replacement of the expansion device with throttle valve

MODIFYING THE CONDITION AT INLET

(i) Wet Compression (Fig. 10)

- Compression of wet-refrigerant (process 1'-2') in the Figure below, is called ***wet compression***.
- Wet-compression is not suitable in the reciprocating compressor due to the following reasons:
  a. Liquid refrigerant may be trapped in the head of the cylinder and may damage the compressor valves and the cylinder itself.
  b. Liquid-refrigerant droplets may wash away the lubricating oil from the walls of the cylinder.

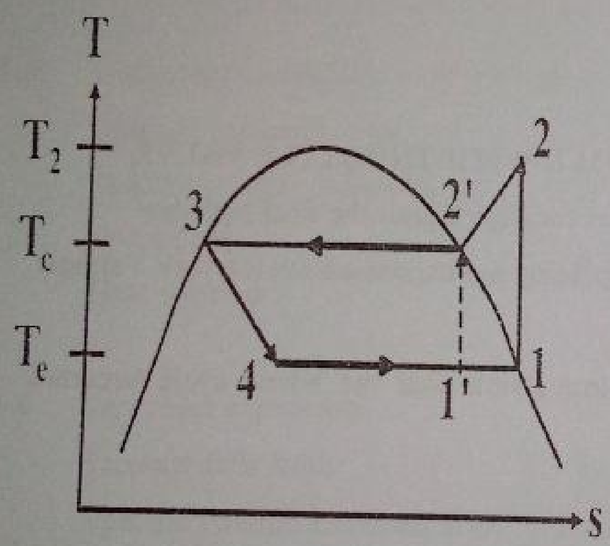

Fig. 10: Wet and dry compressions

(ii) Dry Compression

- It desirable to have compression with dry or superheated vapour refrigerant (process 1-2) as shown below, this is called ***dry compression***.
- With dry compression:
  a) Discharge pressure P_2 = condensing pressure P_c
  b) Discharge temperature T_2> condensing temperature T_c or T_3.

QUESTIONS

(1) A domestic refrigerator was designed to operate at evaporator coil temperature of -25 °C, condenser coil temperature of 30 °C, and to produce refrigerating effect of 10.1 kW. If the actual COP of the refrigerator is 80 % of the maximum possible COP for the system, calculate the:

(a) maximum possible COP,

(b) actual COP, and

(c) power required for the designed refrigerating effect.

(Answer: 4.51; 3.61; 2.8 kW).

(2) The temperature in the evaporator of an ammonia refrigerator is -20 °C and the temperature in the condenser is 32 °C. Calculate the refrigerating effect per unit mass of refrigerant and the COP_{ref} for the following cycles:

(a) the ideal reversed Carnot cycle

(b) Dry saturated vapour delivered to the condenser after isentropic compression, the liquid leaves the condenser and is throttled to the evaporator pressure

(c) Dry saturated vapour delivered to the compressor where it is compressed isentropically, the liquid leaves the condenser and is throttled to the evaporator pressure

(Answer: 942.8 kJ/kg; 4.86; 919.0 kJ/kg; 4.2; 1087.2 kJ/kg; 3.9)

(3) An ammonia refrigerator operates between evaporating and condensing temperatures of -16 and 50 °C. The vapour is dry saturated at the compressor inlet, and there is no sub-cooling of the condensate. Determine the:

(a) refrigerating effect (in kJ/kg),

(b) mass flow rate per kW of refrigeration capacity (in kg/h),

(c) power input per kW of refrigeration capacity (in kW), and

(d) COP_{ref}.

(Answer: 1003.4 kJ/kg; 3.59 kg/h; 0.338 kW; 2.96).

(4) A vapour compression refrigeration system, working with R12 refrigerant, operating at a condenser temperature of 40 °C and an evaporator of -5 °C develops 15 tons of refrigeration. If 1 ton of refrigeration is 3.5165 kW of refrigeration, calculate the:

(a) discharge temperature and enthalpy,

(b) mass flow rate of the refrigerant,

(c) theoretical piston displacement of the compressor,

(d) power consumption,

(e) heat rejected in the condenser, and

(f) actual COP of the cycle and Carnot COP.

(Answer: 46.29 °C; 208.24 kJ/kg; 0.476 kg/s; 0.03094 m^3/s; 10. 88 kW; 63.62 kW; 4.85; 5.96).

(5) Consider the ideal theoretical vapour compression cycle using R134a as refrigerant, and operating with a condenser temperature of 40 °C and evaporator temperature of -20 °C. Calculate the:

(a) refrigerating effect and compressor discharge enthalpy,

(b) work input required and heat rejected from the system,

(c) COP_{ref}, and the COP_{hp},

(d) mass flowrate of refrigerant that would be required to achieve 2 kW of cooling

(Answer: 130 kJ/kg; 430 kJ/kg; 45 kJ/kg; 175 kJ/kg; 2.89; 3.89; 0.0154 kg/s)

(6) An ideal theoretical vapour compression cycle using R134a operates with a suction pressure of 0.2 MPa and a discharge pressure of 1.0 MPa. Determine the:

(a) evaporator and condenser temperatures,

(b) temperature and enthalpy at the compressor discharge,

(c) work input and the heat rejected from the system,

(d) the COP_{hp} and COP_{ref}.

(Answer: -10 °C; 40 °C; 45 °C; 425.4 kJ/kg; 32.7 kJ/kg; 169 kJ/kg; 5.2; 4.2)

Refrigeration Processes

A refrigeration process indicates the change of thermodynamic properties of the refrigerant and the energy transfer between the refrigerant and the surroundings. The following refrigeration processes occur during the operation of a vapour compression refrigerating system:

Evaporation: In this process, the refrigerant evaporates at a lower temperature than that of its surroundings, absorbing its latent heat of vaporization.

Superheating: Saturated refrigerant vapour is usually superheated to ensure that liquid