Natubhai V. Patel College of Pure & Applied Sciences
S. Y. B.Sc. Semester-4
Industrial chemistry/ IC (Vocational)
USO4CICV01/US04CICH02: Chemical Plant Utilities
UNIT – 4

REFRIGERATION

COEFFICIENT OF PERFORMANCE OF A REFRIGERATOR

The coefficient of performance (briefly written as C.O.P.) is the ratio of heat extracted in the refrigerator to the work done on the refrigerant. It is also known as theoretical coefficient of performance. Mathematically,

Theoretical C.O.P.= Q/W

where, Q = *Amount of heat extracted in the refrigerator (or the amount* of refrigeration produced, OR the capacity of a refrigerator),

W= Amount of work done.

Notes :

- For per unit mass, C.O.P. =q/w
- The coefficient of performance is the reciprocal of the efficiency (i.e. 1/η) of a heat engine. It is thus obvious, that the value of C.O.P is always greater than unity.
- The ratio of the actual C.O.P to the theoretical C.O.P. is known as relative coefficient of performance. *Mathematically*,

$$\text{Relative C.O.P} = \frac{\text{Actual C.O.P}}{\text{Theoratical C.O.P}}$$

Example : Find the C.O.P. of a refrigeration system if the work input is 80 kJ/kg mid refrigeration effect produced is 160 kJ/kg of refrigerant flowing.

Solution. Given : w = 80 kJ/kg ; q = 160 kJ/kg

We know that C.O.P. of a refrigeration system

= q/w = 160/80 = 2 Ans.

Desirable Properties of an Ideal Refrigerant

We have discussed above that there is no ideal refrigerant. A refrigerant is said to be ideal if it has all of the following properties :

- Low boiling point
- High critical temperature
- High latent heat of vaporization
- 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 liquify at moderate pressure and temperature
- Easy of locating leaks by odour or suitable indicator
- Mixes well with oil

The standard comparison of refrigerants, as used in the refrigeration industry, is based on an evaporating temperature of -15° C and a condensing temperature of +30° C.

CLASSIFICATION OF REFRIGERANTS

The refrigerants may, broadly, be classified into the following two groups

- Primary refrigerants,
- Secondary refrigerants

The refrigerants which directly take part in the refrigeration system are called primary refrigerants whereas the refrigerants which are first cooled by primary refrigerants and then used for cooling purposes, are known as secondary refrigerants.

The primary refrigerants are further classified into the following four groups :

- Halo-carbon refrigerants,
- Azeotrope refrigerants,
- Inorganic refrigerants, and
- Hydro-carbon refrigerants.

Halo-carbon Refrigerants :

The American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHARAE) identifies 42 halo-carbon compounds as refrigerants, but only a few of them are commonly used. The following table gives some of the commonly used halo-carbon refrigerants :

Commonly used halo-carbon refrigerants :

Refrigerant number	Chemical name	Chemical formula
R-11	Trichloromonofluoromethane	CCl_3F
R-12	Dichlorodifluoromethane	CCl_2F_2
R-13	Monochlorotrifluoromethane	$CClF_3$
R-14	Carbentetrafluoride	CF_4
R-21	Dichloromonofluoromethane	$CHCl_2F$
R-22	Monochlorodifluoromethane	$CHClF_2$
R-30	Methylene chloride	CH_2Cl_2
R-40	Methyl chloride	CH_3Cl
R-100	Ethyl chloride	C_2H_5Cl
R-113	Trichlorotrifluorothane	CCl_2FCCF_2
R-114	Dichlorotetrafluoroethane	$CClF_2CClF_2$
R-115	Monochloropentafluoroethane	$CClF_2CF_3$

The halo-carbon compounds are all synthetically produced and were developed as Freon family of refrigerants. Freon is a registered trade mark of E.I. Du Pont de Nemours and Co.,America. Most of the halo-carbon refrigerants, are now available from other manufacturers under various trade names such as Genetron, Isotron etc. The first of the halo-carbon refrigerant i.e. R-12 was developed in 1930 by Thomas Midgley. The various halo-carbon refrigerants mentioned above are now discussed, in detail, as below :

1. R-ll, Trichloromonofluoromethane (CCl_3F).The R-ll is a synthetic chemical product which can be used as a refrigerant. It is stable, non-flammable and non-toxic. It is considered to be a low-pressure refrigerant. It has a low side pressure of 0.202 bar at -15°C and high side pressure of 1.2606 bar at 30°C. The latent heat at -15°C is 195 kJ/kg. The boiling point at atmospheric pressure is 23.77°C. Due to its low operating pressures, this refrigerant is exclusively used in large centrifugal compressor systems of 200 TR and above. The leaks may be detected by using a soap solution, a halide torch or by using an electronic detector.

R-11 is often used by service technicians as a flushing agent for cleaning the internal parts of a refrigerator compressor when overhauling systems. It is useful after a system had a motor burn out or after it has a great deal of moisture in the system . By flushing moisture from the system with R-ll, evacuation time is shortened. R-ll is one of the safest cleaning solvent that can be used for this purpose. The cylinder colour code for R-ll is orange.

2. R-12, Dichlorodifluoromethane (CCl_2F_2):The R-12 is a very popular refrigerant. It is a colourless, almost odourless liquid with boiling point of - 29°C at atmospheric pressure. It is non-toxic, non-corrosive, non-irritating and non-flammable. It has a relatively low latent heat value which is an advantage in small refrigerating machines. The large amount of refrigerant circulated will permit the use of less sensitive and more positive operating and regulating mechanisms. It operates at a low but positive head and back pressure and with a good volumetric efficiency. This refrigerant is used in many different types of industrial and commercial applications such as refrigerators, freezers, water coolers, room and window air conditioning units etc. Its principal use is found in reciprocating and rotary compressors, but its use in centrifugal compressors for large commercial air conditioning is increasing.

R-12 has a pressure of 0.82 bar at -15°C and a pressure of 6.4 bar at 30°C. The latent heat of R-12 at - 15°C is 159 kJ/kg. The leak may be detected by soap solution, halide torch or an electronic leak detector. Water is only slightly soluble in R-12. At -18°C, it will hold six parts per million by mass. The solution formed is very slightly corrosive to any of the common metals used in refrigerator construction. The addition of mineral oil to the refrigerant has no effect upon the corrosive action.

R-12 is more critical as to its moisture content when compared to R-22 and R-502. It is soluble in oil down to -68°C. The oil will begin to separate at this temperature and due to its lightness than the refrigerant, it will collect on the surface of the liquid refrigerant. The refrigerant is available in a variety of cylinder sizes and the cylinder colour code is white.

3. R-13, Monochlorotrifluoromethane ($CClF_3$): The R-13 has a boiling temperature of -81.4°C at atmospheric pressure and a critical temperature of +28.8°C. This refrigerant is used for the low temperature side of cascade systems. It is suitable with reciprocating compressors.

4. R-14, Carbontetrafluoride (CF_4). The R-14 has a boiling temperature of - 128°C at atmospheric pressure and critical temperature of -45.5°C. It serves as an ultra-low temperature refrigerant for use in cascade systems.

5. R-21, Dichloromonofluoromethane ($CHCl_2F$): The R-21 has a boiling temperature of +9°C at atmospheric pressure. It has found its principal use in centrifugal compressor systems for relatively high temperature refrigeration requirements.

6. R-22, Monochlorodifluoromethane ($CHClF_2$): The R-22 is a man-made refrigerant developed for refrigeration installations that need a low evaporating temperature, as in fast freezing units which maintain a temperature of -29°C to -40°C. It has also been successfully used in air conditioning units and in household refrigerators. It is used with reciprocating and centrifugal compressors. It is not necessary to use R-22 at below atmospheric pressures in order to obtain the low temperatures.

The boiling point of R-22 is -41°C at atmospheric pressure. It has a latent heat of 216.5 kJ/kg at -15°C. The normal head pressure at 30°C is 10.88 bar. This refrigerant is stable and is non-toxic, non-corrosive, non-irritating and non-flammable. The evaporator pressure of this refrigerant at -15°C is 1.92 bar. Since water mixes better with R-22 than R- 12 by a ratio of 3 to 1, therefore driers (dessicants) should be used to remove most of the moisture to keep water to a minimum. This refrigerant has good solubility in oil down to -9°C. However, the oil remains fluid enough to flow down the suction line at temperatures as low as -40°C. The oil will begin to separate at this point. Since oil is lighter, therefore it will collect on the surface of the liquid refrigerant. The leaks may be detected with a soap solution, a halide torch or with an electronic leak detector. The cylinder colour code for R-22 is green.

7. R-30, Methylene Chloride (CH_2Cl_2): The R-30 is a clear, water-white liquid with a sweet, non-irritating odour similar to that of chloroform. It has a boiling point of 39.8°C at atmospheric pressure. It is non-flammable, non-explosive and non-toxic. Due to its high boiling point, this refrigerant may be stored in closed cans instead of in compressed gas cylinders. The high and low sides of refrigeration system using R-30 operate under a vacuum. Since the volume of vapour at suction conditions is very high, therefore the use of R-30 is restricted to rotary or centrifugal compressors. This refrigerant was extensively used for air conditioning of theatres, auditoriums, and office buildings. Now-a- days, the refrigerant R-l 1 is used in place of R-30.

In order to detect leaks in a system using R-30, the pressure must be increased above atmosphere. A halide torch is used for detecting leaks.

8. R-40, Methyl-chloride (CH_3Cl): The R-40 is a colourless liquid with a faint, sweet, and non-irritating odour. Its boiling point at atmospheric pressure is - 23.7°C and the usual condenser pressure is 5 to 6.8 bar. The latent heat of vaporisation at -15°C is 423.5 kJ/kg. It is flammable and explosive when mixed with air in concentrations from 8.1 to 17.2 percent. This refrigerant is non-corrosive in its pure state, but it becomes corrosive in the presence of moisture. Aluminium, zinc and magnesium alloys should never be used with this refrigerant as they will corrode considerably and pollute the lubricating oil. Since the refrigerant R-40 is a solvent for many materials used in ordinary refrigeration compressors, therefore rubber and gaskets containing rubber should never be used. However, synthetic rubber is not affected by R-40. Thus metallic or asbestos-fiber gaskets containing insoluble binders should be used. The mineral oils are soluble in this refrigerant to a small extent.

This refrigerant has been used in domestic units with both reciprocating and rotary compressors and in commercial units with reciprocating compressors up to approximately 10 TR capacity. The leaks with R-40 may be detected by soap solution or electronic leak detector.

9. R-100, Ethyl Chloride (C_2H_5Cl): The refrigerant R-100 is a colourless liquid and in many respects it is similar to R-40 (Methyl chloride) but with low operating pressures. It has a boiling point of 13.1°C at atmospheric pressure. It is both toxic and flammable. Due to its low operating pressure, it is not used in refrigerating equipment.

10. R-l 13, Trichlorotrifluoroethane (CCl_2FCClF_2 or $C_2Cl_3F_3$): The R-l 13 has a boiling point of 47.6° C at atmospheric pressure. It is used in commercial and industrial air- conditioning.

These refrigerants are discussed, in detail, as below :

1. R-717 (Ammonia): The R-717, *i.e.* ammonia (NH_3) is one of the oldest and most widely used of all the refrigerants. Its greatest application is found in large and commercial reciprocating compression systems where high toxicity is secondary. It is also widely used in absorption systems. It is a chemical compound of nitrogen and hydrogen and under ordinary conditions, it is a colourless gas. Its boiling point at atmospheric pressure is -33.3°C and its melting point from the solid is -78°C. The low boiling point makes it possible to have refrigeration at temperatures considerably below 0°C without using pressures below atmospheric in the evaporator. Its latent heat of vaporisation at -15°C is 1315 kJ/kg. Thus, large refrigerating effects are possible with relatively small sized machinery. The condenser pressure at 30°C is 10.78 bar. The condensers for R-717 are usually of water cooled type.

It is a poisonous gas if inhaled in large quantities. In lesser quantities, it is irritating to the eyes, nose and throat. This refrigerant is somewhat flammable and when mixed with air in the ratio of 16% to 25% of gas by volume, will form an explosive mixture. The leaks of this refrigerant may be quickly and easily detected by the use of burning sulphur candle which in the presence of ammonia forms white fumes of ammonium sulphite. This refrigerant attacks copper and bronze in the presence of a little moisture but does not corrode iron or steel. It presents no special problems in connection with lubricant unless extreme temperatures are encountered. Since the refrigerant R-717 is lighter than oil, therefore, its separation does not create any problem. The excess oil in the evaporator may be removed by opening a valve in the bottom of the evaporator. This refrigerant is used in large compression machines using reciprocating compressors and in many absorption type systems. The use of this refrigerant is extensively found in cold storage, warehouse plants, ice cream manufacture, ice manufacture, beer manufacture, food freezing plants etc.

2. R-729 (Air): The dry air is used as a gaseous refrigerant in some compression systems, particularly in air-craft air conditioning.

3. R-744 (Carbon dioxide): The principal refrigeration use of carbon dioxide is same as that of dry ice. It is non-toxic, non-irritating and non-flammable. The boiling point of this refrigerant is so extremely low (-73.6°C) that at -15°C, a pressure of well over 20.7 bar is required to prevent its evaporation. At a condenser temperature of +30°C, a pressure of approximately 70 bar is required to liquify the gas. Its critical temperature is 31°C and triple point is -56.6°C. Due to its high operating pressure, the compressor of a carbon dioxide refrigerator unit is very small even for a comparatively large refrigerating capacity. However, because of its low efficiency as compared to other common refrigerants, it is seldom used in household units, but is used in some industrial applications and aboard ships.

4. R-764 (Sulphur dioxide): This refrigerant is produced by the combustion of sulphur in air. In the former years, it was widely used in household and small commercial units. The boiling point of sulphur dioxide is -10°C at atmospheric pressure. The condensing pressure varies between 4.1 bar and 6.2 bar under normal operating conditions. The latent heat of sulphur dioxide at -15°C is 396 kJ/kg. It is a very stable refrigerant with a high critical temperature and it is non-flammable and non-explosive. It has a very unpleasant and irritating odour. This refrigerant is not injurious to food and is used commercially as a ripener and preservative of foods. It is however, extremely injurious to flowers, plants and shrubbery. The sulphur dioxide in its pure state is not corrosive, but when there is moisture present, the mixture forms sulphurous acid which is corrosive to steel. Thus it is very important that the moisture in the refrigerating system be held to a minimum.

The sulphur dioxide does not mix readily with oil. Therefore, an oil lighter than that used with other refrigerants may be used in the compressors. The refrigerant in the evaporator with oil floating on the top has a tendency to have a higher boiling point than that corresponding to its pressure. The modern evaporators overcome this by having the liquid introduced in such a way that the refrigerant is kept agitated while the unit is in operation. The leaks in the system with sulphur dioxide may be easily detected by means of soap solution or ammonia swab. A dense white smoke forms when sulphur dioxide and ammonia fumes come in contact.

5. R-118 (Water): The principal refrigeration use of water is as ice. The high freezing temperature of water limits its use in vapour compression systems. It is used as the refrigerant vapour in some absorption systems and in systems with steam jet compressors.

CHEMICAL PROPERTIES OF REFRIGERANTS

The chemical properties of refrigerants are discussed as follows :

1. **Flammability:** We have already discussed that hydro-carbon refrigerants such as ethane, propane etc., are highly flammable. Ammonia is also somewhat flammable and becomes explosive when mixed with air in the ratio of 16 to 25 percent of gas by volume. The halo-carbon refrigerants are neither flammable nor explosive.

2. **Toxicity:** The toxicity of refrigerant may be of prime or secondary importance depending upon the application. Some non- toxic refrigerants (i.e. all fluorocarbon refrigerants) when mixed with certain percentage of air become toxic.

The following table shows the relative toxicity of the common refrigerants, based upon the concentration and exposure time required to produce serious results.

3. **Solubility of water:** Water is only slightly soluble in R-I 2. At -18°C, it will hold six parts per million by weight. The solution formed is very slightly corrosive to any of the common metals. The solubility of water with R-22 is more than R-I2 by a ratio of 3 to 1. If more water is present than can be dissolved by the refrigerant, the ice will be formed which chokes the expansion valve or capillary tube used for throttling in the system. This may be avoided by the proper dehydration of the refrigerating unit before charging and by the use of silica gel drier of the liquid line. Ammonia is highly soluble in water. Due to this reason, a wetted cloth is put at the point of leak to avoid harm to the persons working in ammonia refrigerating plants.

4. **Miscibility:** The ability of a refrigerant to mix with oil is called miscibility. This property of refrigerant is considered to be a secondary factor in the selection of a refrigerant. The degree of miscibility depends upon the temperature of the oil and pressure of the refrigerating vapour. The Freon group of refrigerants are highly miscible refrigerants while ammonia, carbon dioxide, sulphur dioxide and methyl chloride are relatively non-miscible.

The non-miscible refrigerants require larger heat transfer surfaces due to poor heat condition properties of oil. The miscible refrigerants are advantageous from the heat transfer point of view. They give better lubrication as the refrigerant acts as a carrier of oil to the moving parts. The miscible refrigerants also eliminate oil-separation problems and aid in the return of oil from the evaporator.

5. **Effect on perishable materials:** The refrigerants used in cold storage plant and in domestic refrigerators should be such that in case of leakage, it should have no effect on the perishable materials. The Freon group of refrigerants have no effect upon dairy products, meats, vegetables, flowers and furs. There will be no change in colour, taste or texture of the material when exposed to Freon.

Methyl chloride vapours have no effect upon furs, flowers, eating foods or drinking beverages. Sulphur dioxide destroys flowers, plants and furs, but it does not effect foods. Ammonia dissolves easily in water and becomes alkaline in nature. Since most fruits and vegetables are acidic in nature, therefore ammonia reacts with these products and spoils the taste.

PHYSICAL PROPERTIES OF REFRIGERANTS

The physical properties of refrigerants are discussed as follows :

1. Stability and inertness: An ideal refrigerant should not decompose at any temperature normally encountered in the refrigerating system. It should not form higher boiling point liquids or solid substances through polymerization. Some refrigerants disintegrate forming non-condensable gases which causes high condensing pressure and vapour lock. The disintegration of refrigerant may be due to reaction with metals. In order to avoid this, a refrigerant should be inert with respect to all materials used in refrigerating system.

The Freon group of refrigerants are stable up to a temperature of 535°C. Above this temperature, it decomposes and forms corrosive and poisonous products. The Freon refrigerants are not used with rubber gaskets as it acts as a solvent with rubber. Since sulphur dioxide do not decompose below 1645°C, therefore it is one of the most stable refrigerants.

2. **Corrosive property:** The corrosive property of a refrigerant must be taken into consideration while selecting the refrigerant. The Freon group of refrigerants are non-corrosive with practically all metals. Ammonia is used only with iron or steel. Sulphur dioxide is non-corrosive to all metals in the absence of water because sulphur dioxide reacts with water and forms sulphuric acid.

3. **Viscosity:** The refrigerant in the liquid and vapour states should have low viscosity. The low viscosity of the refrigerant is desirable because the pressure drops in passing through liquid and suction lines are small. The heat transfer through condenser and evaporator is improved at low viscosities. The following table shows the viscosities (in centipoises) at atmospheric pressure for the common refrigerants.

4. **Thermal conductivity:** The refrigerant in the liquid and vapour states should have high thermal conductivity. This property is required in finding the heat transfer coefficients in evaporators and condensers. The following table shows the thermal conductivities of common refrigerants.

5. **Dielectric strength:** The dielectric strength of a refrigerant is important in hermetically sealed units in which the electric motor is exposed to the refrigerant. The relative dielectric strength of the refrigerant is the ratio of the dielectric strength of nitrogen and the refrigerant vapour mixture to the dielectric strength of nitrogen at atmospheric pressure and room temperature. The following table shows the relative dielectric strengths of common refrigerants.

6. Leakage tendency: The leakage tendency of a refrigerant should be low. If there is a leakage of refrigerant, it should be easily detectable. The leakage occurs due to opening in the joints or flaws in material used for construction. Since the fluorocarbon refrigerants are colourless, therefore, their leakage will increase the operating cost. The ammonia leakage is easily detected due to its pungent odour.

The leakage of fluorocarbon refrigerants may be detected by soap solution, a halide torch or an electronic leak detector. The latter is generally used in big refrigerating plants. The ammonia leakage is detected by using burning sulphur candle which in the presence of ammonia forms white fumes of ammonium sulphite.

7. Cost: The cost of refrigerant is not so important in small refrigerating units but it is very important in high capacity refrigerating systems like industrial and commercial. The ammonia, being the cheapest, is widely used in large industrial plants such as cold storages mi. ice plants. The refrigerant R-22 is costlier than refrigerant R-12. The cost of losses due to leakage is also important.

SECONDARY REFRIGERANTS – BRINES

Brines are secondary refrigerants and are generally used where temperatures are required to be maintained below the freezing point of water i.e. 0°C. In case the temperature involved is above the freezing point of water (0°C), then water is commonly used as a secondary refrigerant.

Brine is a solution of a salt in water. It may be noted that when a salt is mixed in water, then the freezing temperature of the solution becomes lower than that of the water. This is due to the fact that the salt while dissolving in water takes off its latent heat from the solution and cools it below the freezing point of water. The mass of the salt in the 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 if the concentration of the salt is increase;! beyond a certain point, the freezing point increases instead of decreasing. The point at which the freezing temperature is minimum, is known as eutectic temperature and the concentration at this point is known as eutectic concentration. The brine used in a particular application should have a concentration for which the freezing point of the brine is at least 5°C to 8°C lower than the brine temperature required.

The brines commonly used are calcium chloride ($CaCl_2$), Sodium chloride i.e. common salt (NaCl) and glycols such as ethylene glycol, propylene glycol etc.

The calcium chloride brine has the eutectic temperature of -55°C at salt concentration of 30% by mass. This brine is primarily used where temperatures below -18°C are required, it is generally used in industrial process cooling and product freezing.

UNITS OF REFRIGERATION

The practical unit of refrigeration is expressed in terms of 'tonne of refrigeration' (briefly written as TR). A tonne of refrigeration is defined as the amount of refrigeration effect produced
by the uniform melting of one tonne (1000 kg) of ice from and at 0°C in 24 hours.

Since the latent heat of ice is 335 kJ/kg, therefore one tonne of refrigeration,

$$1TR = 1000 \times 335 \text{ kJ in 24 hours}$$

$$= \frac{1000 \times 335}{24 \times 60} = 232.6 \text{ kJ/min}$$

In actual practice, one tonne of refrigeration is taken as equivalent to 210 kJ/min or 3.5kW (i.e. 3.5kJ/s).

AIR REFRIGERATOR WORKING ON A BELL-COLEMAN CYCLE (OR REVERSED BRAYTON OR JOULE CYCLE)

A Bell-Coleman air refrigeration machine was developed by Bell-Caieman and Light Foot by reversing the Joule's air cycle. It was one of the earliest types of refrigerators used in ships carrying frozen meat. Figure 1 shows a schematic diagram of such a machine which consists of a compressor, a cooler, an expander and a refrigerator.

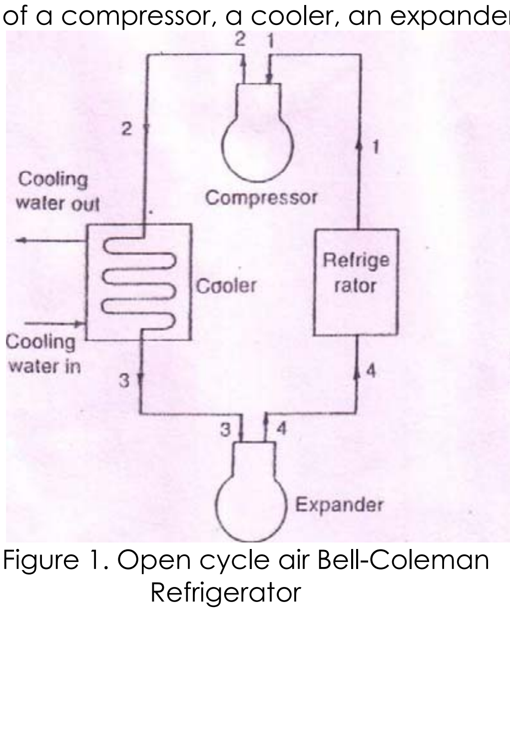


Figure 1. Open cycle air Bell-Coleman Refrigerator

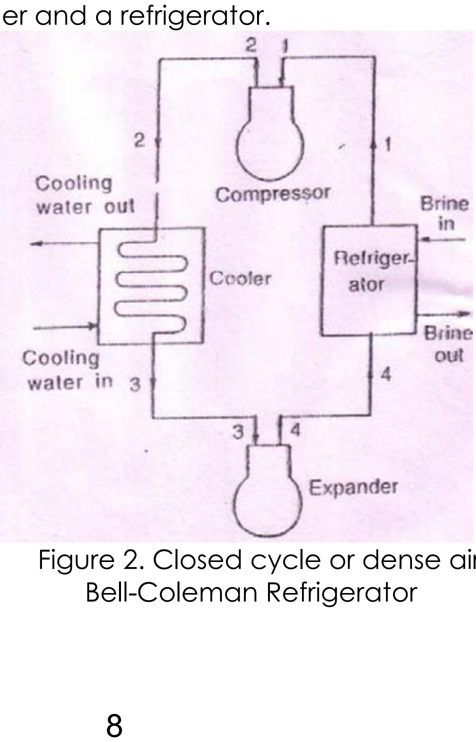
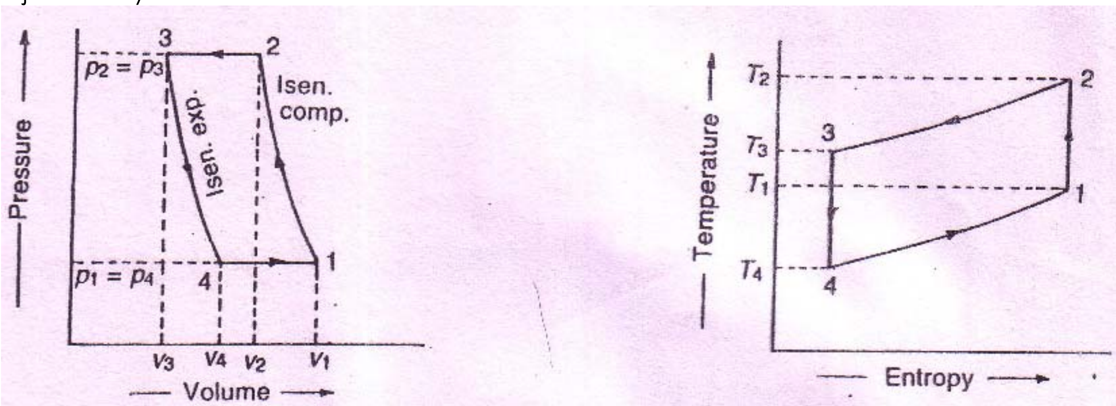


Figure 2. Closed cycle or dense air Bell-Coleman Refrigerator

The Bell-Coleman cycle (also known as reversed Brayton or Joule cycle) is a modification of reversed Carnot cycle. The cycle is shown on *p-v* and *T*-s diagrams in figure 3 *(a)* and *(b).* At point 1, let p1,v1 *and* T1 be the pressure, volume and temperature of air respectively. The four processes of the cycle are as follows :

1. Isentropic compression process. The cold air from the refrigerator is drawn into the compressor cylinder where it is compressed isentropically in the compressor as shown by the curve 1-2 on *p-v* and *T*-s diagrams. During the compression stroke, both the pressure and temperature increases and the specific volume of air at delivery from compressor reduces from V_1 to V_2. We know that during isentropic compression process, no heat is absorbed or rejected by the air.



(a) *p-v* diagram. (b) *T*-s diagram.

Figure 3: Bell-Coleman cycle.

2. Constant pressure cooling process. The warm air from the compressor is now passed into the cooler where it is cooled at constant pressure p_3 (equal to p_2), reducing the temperature from T_2 to T_3 (the temperature of cooling water) as shown by the curve 2-3 on *p-v* and *T*-s diagrams. The specific volume also reduces from v_2 to v_3. We know that heat rejected by the air during constant pressure per kg of air,

$$Q_{2-3} = c_p\ (T_2-T_3)$$

3. Isentropic expansion process. The air from the cooler is now drawn into the expander cylinder where it is expanded isentropically from pressure p_3 to the refrigerator pressure p_4 which is equal to the atmospheric pressure. The temperature of air during expansion falls from T_3 to T_4 *(i.e.* the temperature much below the temperature of cooling water, T_3*).* The expansion process is shown by the curve 3-4 on the *p-v* and *T*-s diagrams. The specific volume of air at entry to the refrigerator increases from v_3 to v_4. We know that during isentropic expansion of air, no heat is absorbed or rejected by the air.

4. Constant pressure expansion process. The cold air from the expander is now passed to the refrigerator where it is expanded at constant pressure p_4 (equal to p_x*).* The temperature of air increases from T_A to T_1*.* This process is shown by the curve 4-1 on the *p-v* and *T*-s diagrams. Due to heat from the refrigerator, the specific volume of the air changes from v_4 to V_1. We know that the heat absorbed by the air (or heat extracted from the refrigerator) during constant pressure expansion per kg of air is

$$q_{4-1} = c_p\ (T_1-T_4)$$

We know that work done during the cycle per kg of air

= Heat rejected - Heat absorbed

$= Cp(T_2-T_3)-Cp(T_1-T_4)$

Coefficient of performance,

$$C.O.P. = \frac{Heat absorbed}{Work done} = \frac{c_p(T_1-T_4)}{c_p(T_2-T_3)-c_p(T_2-T_3)}$$

$$= \frac{(T_1-T_4)}{(T_2-T_3)-c_p(T_1-T_4)}$$

$$= \frac{T_4\left(\frac{T_1}{T_4}-1\right)}{T_3\left(\frac{T_2}{T_3}-1\right)-T_4\left(\frac{T_1}{T_4}-1\right)} \quad ...(i)$$

We know that for isentropic compression process 1-2,

$$\frac{T_2}{T_1}=\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \quad ...(ii)$$

Similarly, for isentropic expansion process 3-4,

$$\frac{T_3}{T_4}=\left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}} \quad ...(iii)$$

Since p2=p3 and p1=p4, therefore from equation (ii) and (iii),

$$\frac{T_2}{T_1}=\frac{T_3}{T_4} or \frac{T_2}{T_3}=\frac{T_1}{T_4} \quad ...(iv)$$

Now substituting these value in equation(i), we get

$$C.O.P.=\frac{T_4}{T_3-T_4}=\frac{1}{\frac{T_3}{T_4}-1}$$

$$=\frac{1}{\left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}}-1}=\frac{1}{\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}-1}=\frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}-1} \quad .... V$$

Where, r_p= Compression or expansion ratio = $\frac{p_2}{p_1}=\frac{p_3}{p_4}$

Sometimes, the compression and expansion processes take place according to the law pv^n = Constant. In such a case, the C.O.P. is obtained from the fundamentals as discussed below :

We know that work done by the compressor during the process 1-2 per kg of air,

$$w_1=\frac{n}{n-1}(p_2v_2-p_1v_1)=\frac{n}{n-1}(RT_2-RT_1) \quad ...(\because pv=RT)$$

and work done by the expander during the process 3-4 per kg of air,

$$w_2=\frac{n}{n-1}(p_3v_3-p_4v_4)=\frac{n}{n-1}(RT_3-RT_4)$$

Net work done during the cycle per kg of air,

$$=w_2-w_1=\frac{n}{n-1}xR\left[(T_2-T_1)-(T_3-T_4)\right]$$

The vapour compression refrigeration system is now-a-days used for all purpose refrigeration. It is generally used for all industrial purposes from a small domestic refrigerator to a big air conditioning plant.

ADVANTAGES AND DISADVANTAGES OF VAPOUR COMPRESSION REFRIGERATION SYSTEM OVER AIR REFRIGERATION SYSTEM

Following are the advantages and disadvantages of the vapour compression refrigeration system over air refrigeration system :

Advantages

- It has smaller size for the given capacity of refrigeration.
- It has less running cost.

- It can be employed over a large range of temperatures.
- The coefficient of performance is quite high.

Disadvantages

- The initial cost is high.
- The prevention of leakage of the refrigerant is the major problem in vapour compression system.

MECHANISM OF A SIMPLE VAPOUR COMPRESSION REFRIGERATION SYSTEM

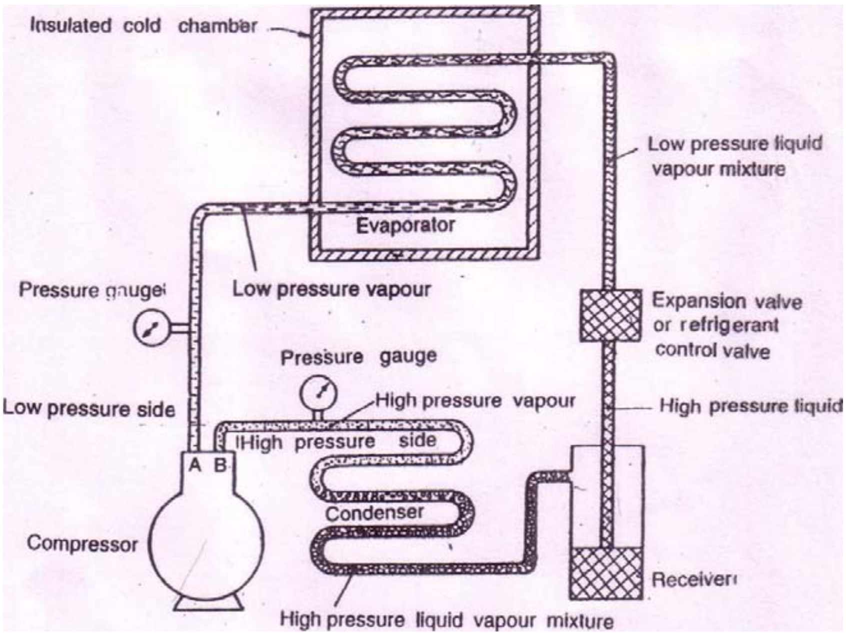


Figure: 4 Simple vapour compression refrigeration system.

Figure: 4 shows the schematic diagram of a simple vapour compression refrigeration system. It consists of the following five essential parts :

Compressor

The low pressure and temperature vapour refrigerant from evaporator is drawn into the compressor through the inlet or suction valve A, where it is compressed to a high pressure and temperature. This high pressure and temperature vapour refrigerant is discharged into the condenser through the delivery or discharge valve B.

Condenser

The condenser or cooler consists of coils of pipe in which the high pressure and temperature vapour refrigerant is cooled and condensed. The refrigerant, while passing through the condenser, gives up its latent heat to the surrounding condensing medium which is normally air or water.

Receiver

The condensed liquid refrigerant from the condenser is stored in a vessel known as receiver from where it is supplied to the evaporator through the expansion valve or refrigerant control valve.

Expansion valve

It is also called throttle valve or refrigerant control valve. The function of the expansion valve is to allow the liquid refrigerant under high pressure and temperature to pass at a controlled rate after reducing its pressure and temperature. Some of the liquid refrigerant evaporates as it passes through the expansion valve, but the greater portion is vaporised in the evaporator at the low pressure and temperature.

Evaporator

An evaporator consists of coils of pipe in which the liquid-vapour- refrigerant at low pressure and temperature is evaporated and changed into vapour refrigerant at low pressure and temperature. In evaporating, the liquid vapour refrigerant absorbs its latent heat of vaporisation from the medium (air, water or brine) which is to be cooled.

In any compression refrigeration system, there are two different pressure conditions. One is called the high pressure side and other is known as low pressure side. The high pressure side includes the discharge line (i.e. piping from delivery valve B to the condenser), condenser, receiver and expansion valve. The low pressure side includes the evaporator, piping from the expansion valve to the evaporator and the suction line (i.e. piping from the evaporator to the suction valve A)

SIMPLE VAPOUR ABSORPTION SYSTEM

The simple vapour absorption system, as shown in Fig. 7.1, consists of an absorber, a pump, a generator and a pressure reducing valve to replace the compressor of vapour compression system. The other components of the system are condenser, receiver, expansion valve and evaporator as in the vapour compression system.

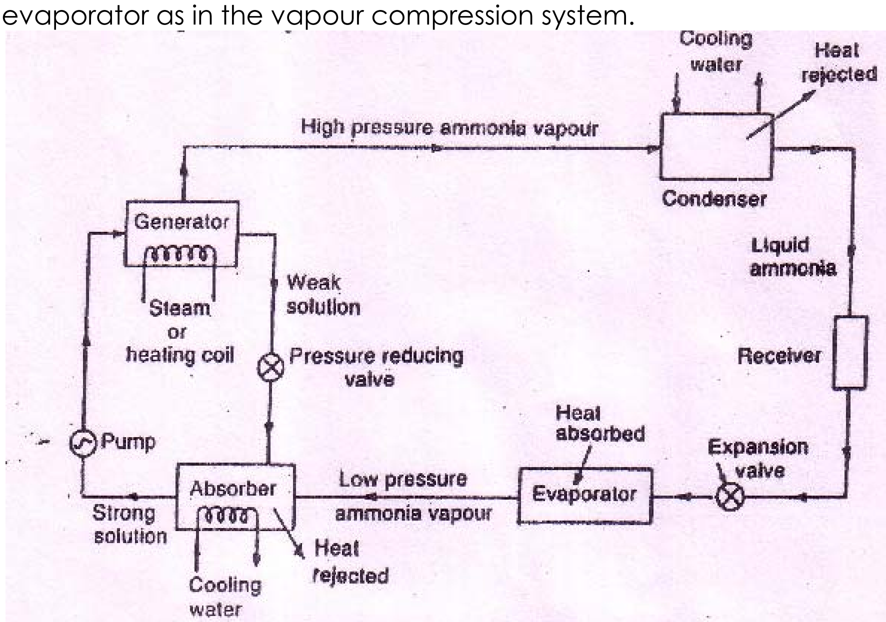


Figure: 5 Simple vapour absorption system

In this system, the low pressure ammonia vapour leaving the evaporator, enters the absorber where it is absorbed by the cold water in the absorber. The water has the ability to absorb very large quantities of ammonia vapour and the solution thus formed, is known as aqua-ammonia. The absorption of ammonia vapour in water lowers the pressure in the absorber which in turn draws more ammonia vapour from the evaporator and thus raises the temperature of solution. Some form of cooling arrangement (usually water cooling) is employed in the absorber to remove the heat of solution evolved there. This is necessary in order to increase the absorption capacity of water, because at higher temperature water absorbs less ammonia vapour. The strong solution thus formed in the absorber is pumped to the generator by the liquid pump. The pump increases the pressure of the solution upto 10 bar.

The strong solution of ammonia in the generator is heated by some external source such as gas or steam. During the heating process, the ammonia vapour is driven off the solution at high pressure leaving behind the hot weak ammonia solution in the generator. This weak ammonia solution flows back to the absorber at low pressure after passing through the pressure reducing valve. The high pressure ammonia vapour from the generator is condensed in the condenser to a high pressure liquid ammonia. This liquid ammonia is passed to the expansion valve through the receiver and then to the evaporator. This completes the simple vapour absorption cycle.