Lesson
1
History Of Refrigeration

Objectives of the lesson:

The objectives of this lesson are to:

1. Define refrigeration and air conditioning *(Section 1.1)*

2. Introduce aspects of various natural refrigeration methods, namely:

   a. Use of ice transported from colder regions *(Section 1.2)*
   b. Use of ice harvested in winter and stored in ice houses *(Section 1.2)*
   c. Use of ice produced by nocturnal cooling *(Section 1.2.1)*
   d. Use of evaporative cooling *(Section 1.2.2)*
   e. Cooling by salt solutions *(Section 1.2.3)*

3. Introduce historical aspects of various artificial refrigeration methods, namely:

   a. Vapour compression refrigeration systems, including
      i. Domestic refrigeration systems *(Section 1.3.1.1)*
      ii. Air conditioning systems *(Section 1.3.1.2)*
   b. Vapour absorption refrigeration systems *(Section 1.3.2)*
   c. Solar energy based refrigeration systems *(Section 1.3.3)*
   d. Air cycle refrigeration systems *(Section 1.3.4)*
   e. Steam and vapor jet refrigeration systems *(Section 1.3.5)*
   f. Thermoelectric refrigeration systems *(Section 1.3.6)*, and
   g. Vortex tubes *(Section 1.3.7)*

At the end of the lesson the student should be able to:

1. Identify various natural and artificial methods of refrigeration

2. List salient points of various refrigeration techniques, and

3. Name important landmarks in the history of refrigeration

1.1. Introduction

Refrigeration may be defined as the process of achieving and maintaining a temperature below that of the surroundings, the aim being to cool some product or space to the required temperature. One of the most important applications of refrigeration has been the preservation of perishable food products by storing them at low temperatures. 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, and its history dates back to centuries. The history of refrigeration is very interesting since every aspect of it, the availability of refrigerants, the prime movers and the developments in compressors and the methods of refrigeration all are a part of it. The French scientist Roger ThÝvenot has written an excellent book on the history of refrigeration throughout the world. Here we present only a brief history of the subject with special mention of the pioneers in the field and some important events.

Q: *Which of the following can be called as a refrigeration process?* a) Cooling of hot ingot from 1000°C to room temperature b) Cooling of a pot of water by mixing it with a large block of ice c) Cooling of human beings using a ceiling fan d) Cooling of a hot cup of coffee by leaving it on a table e) Cooling of hot water by mixing it with tap water f) Cooling of water by creating vacuum over it **Ans:** b) and f)

1.2. Natural Refrigeration

In olden days refrigeration was achieved by natural means such as the use of ice or evaporative cooling. In earlier times, ice was either:

1. Transported from colder regions,
2. Harvested in winter and stored in ice houses for summer use or,
3. Made during night by cooling of water by radiation to stratosphere.

In Europe, America and Iran a number of icehouses were built to store ice. Materials like sawdust or wood shavings were used as insulating materials in these icehouses. Later on, cork was used as insulating material. Literature reveals that ice has always been available to aristocracy who could afford it. In India, the Mogul emperors were very fond of ice during the harsh summer in Delhi and Agra, and it appears that the ice used to be made by nocturnal cooling.

In 1806, Frederic Tudor, (who was later called as the “ice king”) began the trade in ice by cutting it from the Hudson River and ponds of Massachusetts and exporting it to various countries including India. In India Tudor’s ice was cheaper than the locally manufactured ice by nocturnal cooling. The ice trade in North America was a flourishing business. Ice was transported to southern states of America in train compartments insulated by 0.3m of cork insulation. Trading in ice was also popular in several other countries such as Great Britain, Russia, Canada, Norway and France. In these countries ice was either transported from colder regions or was harvested in winter and stored in icehouses for use in summer. The ice trade reached its peak in 1872 when America alone exported 225000 tonnes of ice to various countries as far as China and Australia. However, with the advent of artificial refrigeration the ice trade gradually declined.

1.2.1. Art of Ice making by Nocturnal Cooling:

The art of making ice by nocturnal cooling was perfected in India. In this method ice was made by keeping a thin layer of water in a shallow earthen tray, and then exposing the tray to the night sky. Compacted hay of about 0.3 m thickness was used as insulation. The water looses heat by radiation to the stratosphere, which is at around -55°C and by early morning hours the water in the trays freezes to ice. This method of ice production was very popular in India.

1.2.2. Evaporative Cooling:

As the name indicates, evaporative cooling is the process of reducing the temperature of a system by evaporation of water. Human beings perspire and dissipate their metabolic heat by evaporative cooling if the ambient temperature is more than skin temperature. Animals such as the hippopotamus and buffalo coat themselves with mud for evaporative cooling. Evaporative cooling has been used in India for centuries to obtain cold water in summer by storing the water in earthen pots. The water permeates through the pores of earthen vessel to its outer surface where it evaporates to the surrounding, absorbing its latent heat in part from the vessel, which cools the water. It is said that Patliputra University situated on the bank of river Ganges used to induce the evaporative-cooled air from the river. Suitably located chimneys in the rooms augmented the upward flow of warm air, which was replaced by cool air. Evaporative cooling by placing wet straw mats on the windows is also very common in India. The straw mat made from "khus" adds its inherent perfume also to the air. Now-a-days desert coolers are being used in hot and dry areas to provide cooling in summer.

1.2.3. Cooling by Salt Solutions:

Certain substances such as common salt, when added to water dissolve in water and absorb its heat of solution from water (endothermic process). This reduces the temperature of the solution (water+salt). Sodium Chloride salt (NaCl) can yield temperatures up to -20˚C and Calcium Chloride ($CaCl_2$) up to - 50˚C in properly insulated containers. However, as it is this process has limited application, as the dissolved salt has to be recovered from its solution by heating.

Q. The disadvantages of natural refrigeration methods are:

a) They are expensive
b) They are uncertain
c) They are not environment friendly
d) They are dependent on local conditions

Ans: b) and d)

Q. Evaporative cooling systems are ideal for:

a) Hot and dry conditions
b) Hot and humid conditions
c) Cold and humid conditions
d) Moderately hot but humid conditions

Ans: a)

1.3. Artificial Refrigeration

Refrigeration as it is known these days is produced by artificial means. Though it is very difficult to make a clear demarcation between natural and artificial refrigeration, it is generally agreed that the history of artificial refrigeration began in the year 1755, when the Scottish professor William Cullen made the first refrigerating machine, which could produce a small quantity of ice in the laboratory. Based on the working principle, refrigeration systems can be classified as vapour compression systems, vapour absorption systems, gas cycle systems etc.

1.3.1. Vapour Compression Refrigeration Systems:

The basis of modern refrigeration is the ability of liquids to absorb enormous quantities of heat as they boil and evaporate. Professor William Cullen of the University of Edinburgh demonstrated this in 1755 by placing some water in thermal contact with ether under a receiver of a vacuum pump. The evaporation rate of ether increased due to the vacuum pump and water could be frozen. This process involves two thermodynamic concepts, the vapour pressure and the latent heat. A liquid is in thermal equilibrium with its own vapor at a pressure called the saturation pressure, which depends on the temperature alone. If the pressure is increased for example in a pressure cooker, the water boils at higher temperature. The second concept is that the evaporation of liquid requires latent heat during evaporation. If latent heat is extracted from the liquid, the liquid gets cooled. The temperature of ether will remain constant as long as the vacuum pump maintains a pressure equal to saturation pressure at the desired temperature. This requires the removal of all the vapors formed due to vaporization. If a lower temperature is desired, then a lower saturation pressure will have to be maintained by the vacuum pump. The component of the modern day refrigeration system where cooling is produced by this method is called *evaporator*.

If this process of cooling is to be made continuous the vapors have to be recycled by condensation to the liquid state. The condensation process requires heat rejection to the surroundings. It can be condensed at atmospheric temperature by increasing its pressure. The process of condensation was learned in the second half of eighteenth century. U.F. Clouet and G. Monge liquefied SO_2 in 1780 while van Marum and Van Troostwijk liquefied NH_3 in 1787. Hence, a compressor is required to maintain a high pressure so that the evaporating vapours can condense at a temperature greater than that of the surroundings.

Oliver Evans in his book "Abortion of a young Steam Engineer's Guide" published in Philadelphia in 1805 described a closed refrigeration cycle to produce ice by ether under vacuum. Jacob Perkins, an American living in London actually designed such a system in1835. The apparatus described by Jacob Perkins in his patent specifications of 1834 is shown in Fig.1.1. In his patent he stated "I am enabled to use volatile fluids for the purpose of producing the cooling or freezing of fluids, and yet at the same time constantly condensing such volatile fluids, and bringing them again into operation without waste".

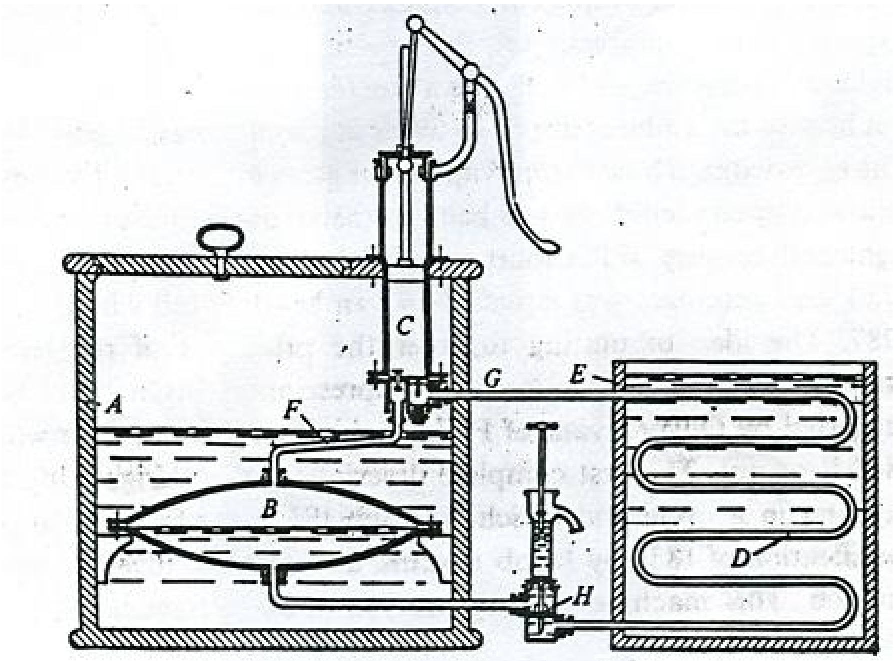


Fig. 1.1. *Apparatus described by Jacob Perkins in his patent specification of 1834. The refrigerant (ether or other volatile fluid) boils in evaporator B taking heat from surrounding water in container A. The pump C draws vapour away and compresses it to higher pressure at which it can condense to liquids in tubes D, giving out heat to water in vessel E. Condensed liquid flows through the weight loaded valve H, which maintains the difference of pressure between the condenser and evaporator. The small pump above H is used for charging the apparatus with refrigerant.*

John Hague made Perkins's design into working model with some modifications. This Perkins machine is shown in Fig.1.2. The earliest vapour compression system used either sulphuric (ethyl) or methyl ether. The American engineer Alexander Twining (1801-1884) received a British patent in 1850 for a vapour compression system by use of ether, NH_3 and CO_2.

The man responsible for making a practical vapor compression refrigeration system was James Harrison who took a patent in 1856 for a vapour compression system using ether, alcohol or ammonia. Charles Tellier of France patented in 1864, a refrigeration system using dimethyl ether which has a normal boiling point of –23.6˚C.

***Fig.1.2**. Perkins machine built by John Hague*

Carl von Linde in Munich introduced double acting ammonia compressor. It required pressures of more than 10 atmospheres in the condenser. Since the normal boiling point of ammonia is -33.3˚C, vacuum was not required on the low pressure side. Since then ammonia is used widely in large refrigeration plants.

David Boyle, in fact made the first NH_3 system in 1871 in San Francisco. John Enright had also developed a similar system in 1876 in Buffalo N.Y. Franz Windhausen developed carbon dioxide (CO_2) based vapor compression system in Germany in 1886. The carbon dioxide compressor requires a pressure of about 80 atmospheres and therefore a very heavy construction. Linde in 1882 and T.S.C. Lowe in 1887 tried similar systems in USA. The CO_2 system is a very safe system and was used in ship refrigeration until 1960s. Raoul Pictet used SO_2 (NBP -10˚C) as refrigerant. Its lowest pressure was high enough to prevent the leakage of air into the system.

Palmer used C_2H_5Cl in 1890 in a rotary compressor. He mixed it with C_2H_5Br to reduce its flammability. Edmund Copeland and Harry Edwards used iso-butane in 1920 in small refrigerators. It disappeared by 1930 when it was replaced by CH_3Cl. Dichloroethylene (Dielene or Dieline) was used by Carrier in centrifugal compressors in 1922-26.

1.3.1.1. Domestic refrigeration systems:

The domestic refrigerator using natural ice (domestic ice box) was invented in 1803 and was used for almost 150 years without much alteration. The domestic ice box used to be made of wood with suitable insulation. Ice used to be kept at the top of the box, and low temperatures are produced in the box due to heat transfer from ice by natural convection. A drip pan is used to collect the water formed due to the melting of ice. The box has to be replenished with fresh ice once all the ice melts. Though the concept is quite simple, the domestic ice box suffered from several disadvantages. The user has to replenish the ice as soon as it is consumed, and the lowest temperatures that could be produced inside the compartment are limited. In addition, it appears that warm winters caused severe shortage of natural ice in USA. Hence, efforts, starting from 1887 have been made to develop domestic refrigerators using mechanical systems. The initial domestic mechanical refrigerators were costly, not completely automatic and were not very reliable. However, the development of mechanical household refrigerators on a large scale was made possible by the development of small compressors, automatic refrigerant controls, better shaft seals, developments in electrical power systems and induction motors. General Electric Company introduced the first domestic refrigerator in 1911, followed by Frigidaire in 1915. Kelvinator launched the domestic mechanical refrigerator in 1918 in USA. In 1925, USA had about 25 million domestic refrigerators of which only 75000 were mechanical. However, the manufacture of domestic refrigerators grew very rapidly, and by 1949 about 7 million domestic refrigerators were produced annually. With the production volumes increasing the price fell sharply (the price was 600 dollars in 1920 and 155 dollars in 1940). The initial domestic refrigerators used mainly sulphur dioxide as refrigerant. Some units used methyl chloride and methylene chloride. These refrigerants were replaced by Freon-12 in 1930s. In the beginning these refrigerators were equipped with open type compressors driven by belt drive. General Electric Company introduced the first refrigerator with a hermetic compressor in 1926. Soon the open type compressors were completely replaced by the hermetic compressors. First refrigerators used water-cooled condensers, which were soon replaced by air cooled-condensers. Though the development of mechanical domestic refrigerators was very rapid in USA, it was still rarely used in other countries. In 1930 only rich families used domestic refrigerators in Europe. The domestic refrigerator based on absorption principle as proposed by Platen and Munters, was first made by Electrolux Company in 1931 in Sweden. In Japan the first mechanical domestic refrigerator was made in 1924. The first dual temperature (freezer-refrigerator) domestic refrigerator was introduced in 1939. The use of mechanical domestic refrigerators grew rapidly all over the world after the Second World War. Today, a domestic refrigerator has become an essential kitchen appliance not only in highly developed countries but also in countries such as India. Except very few almost all the present day domestic refrigerators are mechanical refrigerators that use a hermetic compressor and an air cooled condenser. The modern refrigerators use either HFC-134a (hydro-fluoro-carbon) or iso-butane as refrigerant.

1.3.1.2. Air conditioning systems:

Refrigeration systems are also used for providing cooling and dehumidification in summer for personal comfort (air conditioning). The first air conditioning systems were used for industrial as well as comfort air conditioning. Eastman Kodak installed the first air conditioning system in 1891 in Rochester, New York for the storage of photographic films. An air conditioning system was installed in a printing press in 1902 and in a telephone exchange in Hamburg in 1904. Many systems were installed in tobacco and textile factories around 1900. The first domestic air conditioning system was installed in a house in Frankfurt in 1894. A private library in St Louis, USA was air conditioned in 1895, and a casino was air conditioned in Monte Carlo in 1901. Efforts have also been made to air condition passenger rail coaches using ice. The widespread development of air conditioning is attributed to the American scientist and industrialist Willis Carrier. Carrier studied the control of humidity in 1902 and designed a central air conditioning plant using air washer in 1904. Due to the pioneering efforts of Carrier and also due to simultaneous development of different components and controls, air conditioning quickly became very popular, especially after 1923. At present comfort air conditioning is widely used in residences, offices, commercial buildings, air ports, hospitals and in mobile applications such as rail coaches, automobiles, aircrafts etc. Industrial air conditioning is largely responsible for the growth of modern electronic, pharmaceutical, chemical industries etc. Most of the present day air conditioning systems use either a vapour compression refrigeration system or a vapour absorption refrigeration system. The capacities vary from few kilowatts to megawatts.

Figure 1.3 shows the basic components of a vapour compression refrigeration system. As shown in the figure the basic system consists of an evaporator, compressor, condenser and an expansion valve. The refrigeration effect is obtained in the cold region as heat is extracted by the vaporization of refrigerant in the evaporator. The refrigerant vapour from the evaporator is compressed in the compressor to a high pressure at which its saturation temperature is greater than the ambient or any other heat sink. Hence when the high pressure, high temperature refrigerant flows through the condenser, condensation of the vapour into liquid takes place by heat rejection to the heat sink. To complete the cycle, the high pressure liquid is made to flow through an expansion valve. In the expansion valve the pressure and temperature of the refrigerant decrease. This low pressure and low temperature refrigerant vapour evaporates in the evaporator taking heat from the cold region. It should be observed that the system operates on a closed cycle. The system requires input in the form of mechanical work. It extracts heat from a cold space and rejects heat to a high temperature heat sink.

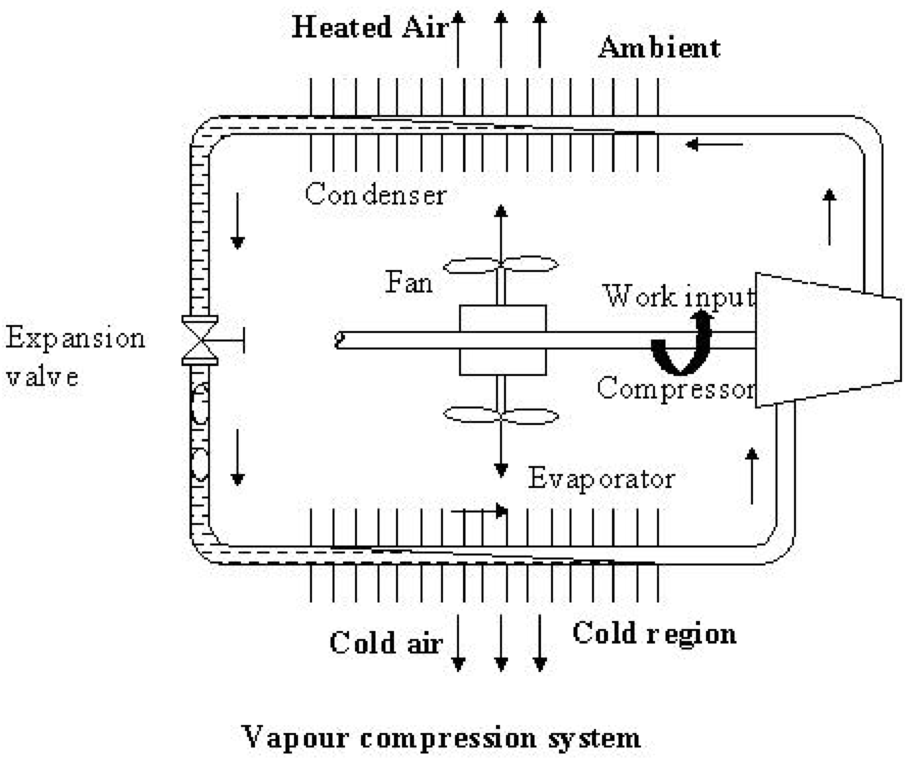


***Fig.1.3**. Schematic of a basic vapour compression refrigeration system*

A refrigeration system can also be used as a heat pump, in which the useful output is the high temperature heat rejected at the condenser. Alternatively, a refrigeration system can be used for providing cooling in summer and heating in winter. Such systems have been built and are available now.

Q. Compared to natural refrigeration methods, artificial refrigeration methods are:
a) Continuous
b) Reliable
c) Environment friendly
d) Can work under almost all conditions
Ans. a), b) and d)

Q. In the evaporator of a vapour compression refrigeration system:
a) A low temperature is maintained so that heat can flow from the external fluid
b) Refrigeration effect is produced as the refrigerant liquid vaporizes
c) A low pressure is maintained so that the compressor can run
d) All of the above
Ans. a) and b)

Q. The function of a compressor in a vapour compression refrigeration system is to:
a) To maintain the required low-side pressure in the evaporator
b) To maintain the required high-side pressure in the condenser
c) To circulate required amount of refrigerant through the system
d) To safeguard the refrigeration system
Ans. a), b) and c)

Q. In a vapour compression refrigeration system, a condenser is primarily required so that:
a) A high pressure can be maintained in the system
b) The refrigerant evaporated in the evaporator can be recycled
c) Performance of the system can be improved
d) Low temperatures can be produced
Ans. b)

Q. The function of an expansion valve is to:
a) Reduce the refrigerant pressure
b) Maintain high and low side pressures
c) Protect evaporator
d) All of the above
Ans. b)

Q. In a domestic icebox type refrigerator, the ice block is kept at the top because:
a) It is convenient to the user
b) Disposal of water is easier
c) Cold air can flow down due to buoyancy effect
d) None of the above
Ans. c)

Q. An air conditioning system employs a refrigeration system to:
a) Cool and dehumidify air supplied to the conditioned space
b) To heat and humidify the air supplied to the conditioned space
c) To circulate the air through the system
d) To purify the supply air
Ans. a)

1.3.2. Vapour Absorption Refrigeration Systems:

John Leslie in 1810 kept H_2SO_4 and water in two separate jars connected together. H_2SO_4 has very high affinity for water. It absorbs water vapour and this becomes the principle of removing the evaporated water vapour requiring no compressor or pump. H_2SO_4 is an absorbent in this system that has to be recycled by heating to get rid of the absorbed water vapour, for continuous operation. Windhausen in 1878 used this principle for absorption refrigeration system, which worked on H_2SO_4. Ferdinand Carre invented aqua-ammonia absorption system in 1860. Water is a strong absorbent of NH_3. If NH_3 is kept in a vessel that is exposed to another vessel containing water, the strong absorption potential of water will cause evaporation of NH_3 requiring no compressor to drive the vapours. A liquid pump is used to increase the pressure of strong solution. The strong solution is then heated in a generator and passed through a rectification column to separate the water from ammonia. The ammonia vapour is then condensed and recycled. The pump power is negligible hence; the system runs virtually on low- grade energy used for heating the strong solution to separate the water from ammonia. These systems were initially run on steam. Later on oil and natural gas based systems were introduced. Figure 1.4 shows the essential components of a vapour absorption refrigeration system. In 1922, Balzar von Platen and Carl Munters, two students at Royal Institute of Technology, Stockholm invented a three fluid system that did not require a pump. A heating based bubble pump was used for circulation of strong and weak solutions and hydrogen was used as a non-condensable gas to reduce the partial pressure of NH_3 in the evaporator. Geppert in 1899 gave this original idea but he was not successful since he was using air as non-condensable gas. The Platen-Munters refrigeration systems are still widely used in certain niche applications such as hotel rooms etc. Figure 1.5 shows the schematic of the triple fluid vapour absorption refrigeration system.

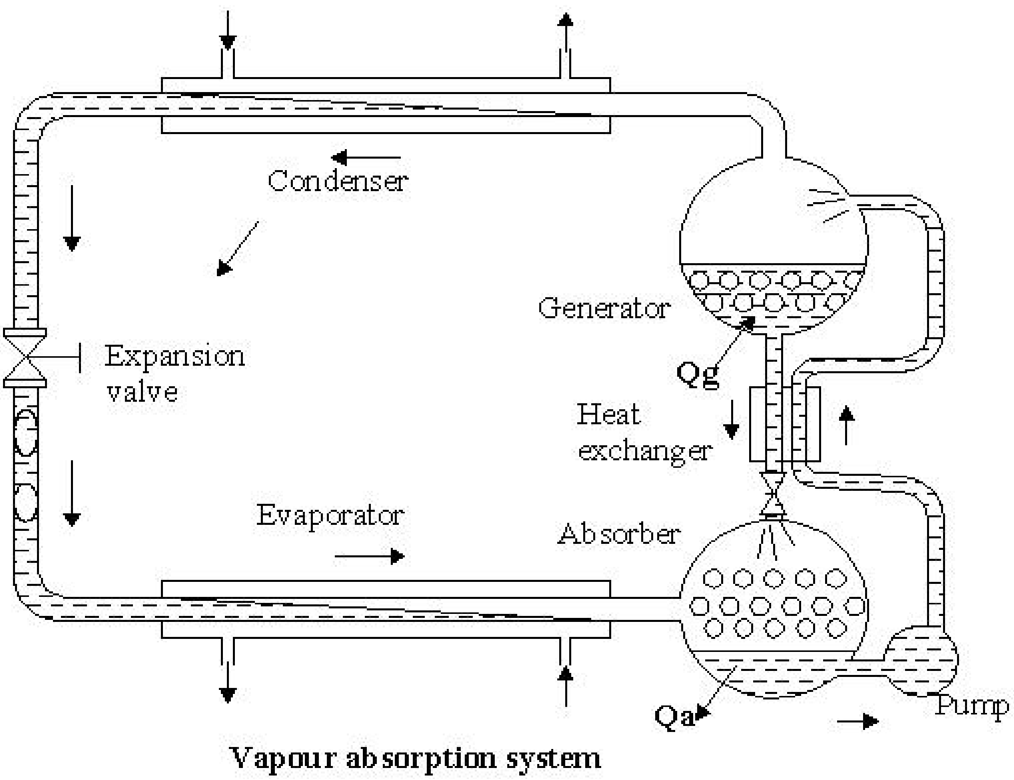


Fig.1.4. *Essential components of a vapour absorption refrigeration system*

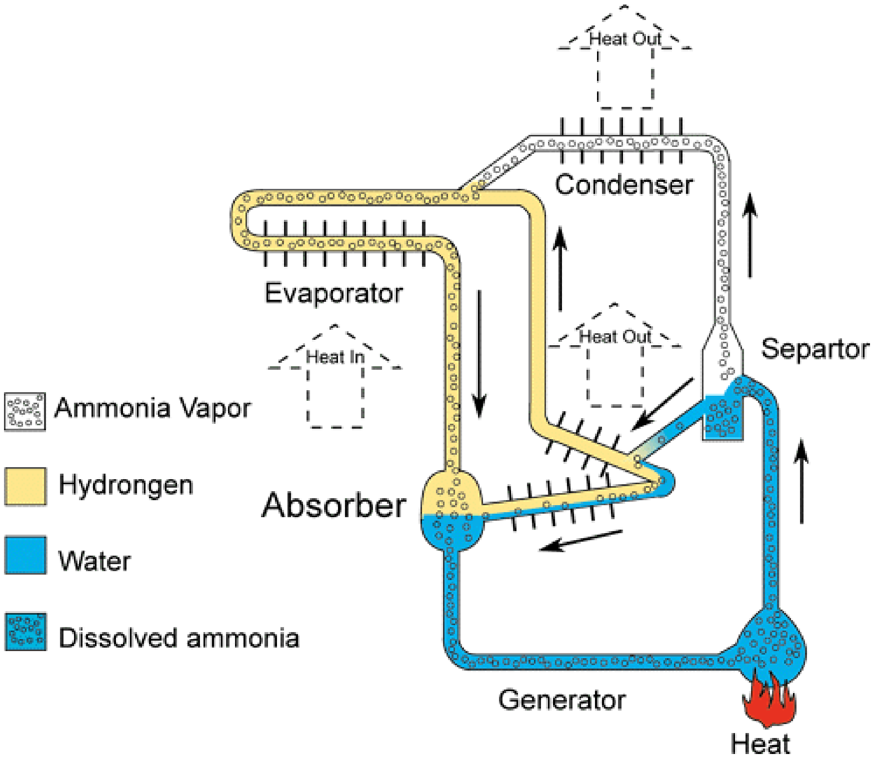


***Fig.1.5**. Schematic of a triple fluid vapour absorption refrigeration system*

Another variation of vapour absorption system is the one based on Lithium Bromide (LiBr)-water. This system is used for chilled water air-conditioning system. This is a descendent of Windhausen's machine with LiBr replacing H_2SO_4. In this system LiBr is the absorbent and water is the refrigerant. This system works at vacuum pressures. The condenser and the generator are housed in one cylindrical vessel and the evaporator and the absorber are housed in second vessel. This also runs on low-grade energy requiring a boiler or process steam.

1.3.3. Solar energy based refrigeration systems:

Attempts have been made to run vapour absorption systems by solar energy with concentrating and flat plate solar collectors. Several small solar absorption refrigeration systems have been made around 1950s in several countries. Professor G.O.G. L f of America is one of the pioneers in the area of solar refrigeration using flat plate collectors. A solar refrigeration system that could produce 250 kg of ice per day was installed in Tashkent, USSR in 1953. This system used a parabolic mirror of 10 m^2 area for concentrating the solar radiation. F. Trombe installed an absorption machine with a cylindro-parabolic mirror of 20 m^2 at Montlouis, France, which produced 100 kg of ice per day.

Serious consideration to solar refrigeration systems was given since 1965, due to the scarcity of fossil fuel based energy sources. LiBr-water based systems have been developed for air conditioning purposes. The first solar air conditioning system was installed in an experimental solar house in University of Queensland, Australia in 1966. After this several systems based on solar energy were built in many parts of the world including India. In 1976, there were about 500 solar absorption systems in USA alone. Almost all these were based on LiBr-water as these systems do not require very high heating temperatures. These systems were mainly used for space air conditioning.

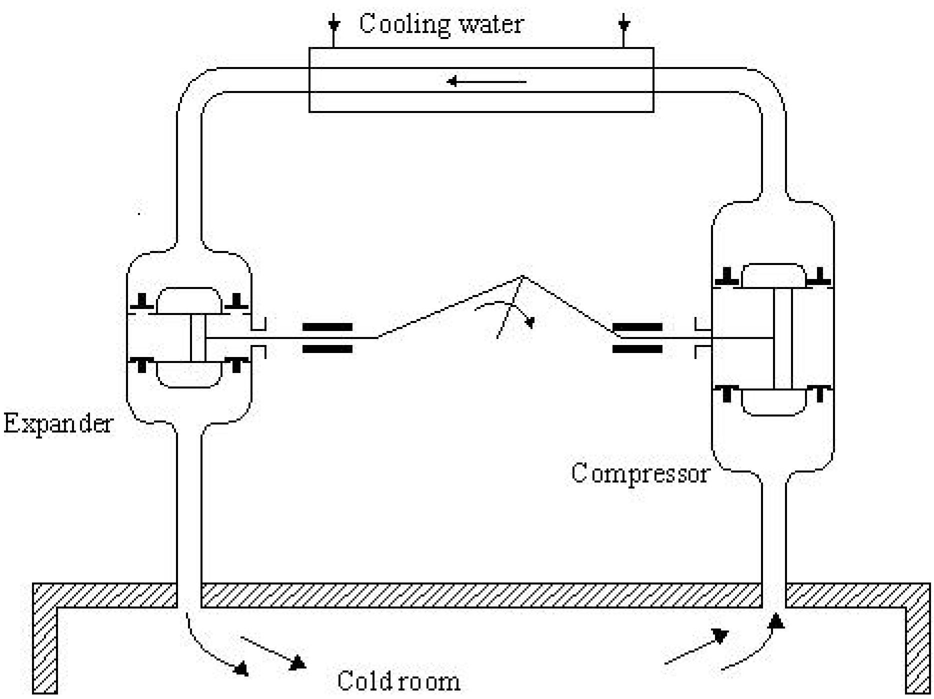
Intermittent absorption systems based on solar energy have also been built and operated successfully. In these systems, the cooling effect is obtained during the nighttime, while the system gets "charged" during the day using solar energy. Though the efficiency of these systems is rather poor requiring solar collector area, they may find applications in remote and rural areas where space is not a constraint. In addition, these systems are environment friendly as they use eco-friendly refrigerants and run on clean and renewable solar energy.

Solar adsorption refrigeration system with ammoniacates, sodium thiocyanate, activated charcoal, zeolite as adsorbents and ammonia, alcohols or fluorocarbons as refrigerants have also been in use since 1950s. These systems also do not require a compressor. The refrigerant vapour is driven by the adsorption potential of the adsorbent stored in an adsorbent bed. This bed is connected to an evaporator/condenser, which consists of the pure refrigerant. In intermittent adsorption systems, during the night the refrigerant evaporates and is adsorbed in activated charcoal or zeolite providing cooling effect. During daytime the adsorbent bed absorbs solar radiation and drives off the refrigerant stored in the bed. This refrigerant vapour condenses in the condenser and stored in a reservoir for nighttime use. Thus this simple system consists of an adsorbent bed and a heat exchanger, which acts as a condenser during the nighttime and, as an evaporator during the night. Pairs of such reactors can be used for obtaining a continuous cooling

Q. Compared to the compression systems, vapour absorption refrigeration systems:
a) Are environment friendly
b) Use low-grade thermal energy for operation
c) Cannot be used for large capacity refrigeration systems
d) Cannot be used for small capacity refrigeration systems
Ans. a) and b)
Q. In absorption refrigeration systems, the compressor of vapour compression systems is replaced by:
a) Absorber
b) Generator
c) Pump
d) All of the above
Ans. d)
Q. In a triple fluid vapour absorption refrigeration system, the hydrogen gas is used to:
a) Improve system performance
b) Reduce the partial pressure of refrigerant in evaporator
c) Circulate the refrigerant
d) Provide a vapour seal
Ans. b)
Q. Solar energy based refrigeration systems are developed to:
a) Reduce fossil fuel consumption
b) Provide refrigeration in remote areas
c) Produce extremely low temperatures
d) Eliminate compressors
Ans. a) and b)
Q. Solar energy based refrigeration systems:
a) Cannot be used for large capacity systems
b) Cannot be made continuous
c) Are not environment friendly
d) None of the above
Ans. d)

1.3.4. Gas Cycle Refrigeration:

If air at high pressure expands and does work (say moves a piston or rotates a turbine), its temperature will decrease. This fact is known to man as early as the 18th century. Dalton and Gay Lusaac studied this in 1807. Sadi Carnot mentioned this as a well-known phenomenon in 1824. However, Dr. John Gorrie a physician in Florida developed one such machine in 1844 to produce ice for the relief of his patients suffering from fever. This machine used compressed air at 2 atm. pressure and produced brine at a temperature of –7°C, which was then used to produce ice. Alexander Carnegie Kirk in 1862 made an air cycle cooling machine. This system used steam engine to run its compressor. Using a compression ratio of 6 to 8, Kirk could produce temperatures as low as 40°C. Paul Gifford in 1875 perfected the open type of machine. This machine was further improved by T B Lightfoot, A Haslam, Henry Bell and James Coleman. This was the main method of marine refrigeration for quite some time. Frank Allen in New York developed a closed cycle machine employing high pressures to reduce the volume flow rates. This was named dense air machine. These days air cycle refrigeration is used only in aircrafts whose turbo compressor can handle large volume flow rates. Figure 1.6 shows the schematic of an open type air cycle refrigeration system. The basic system shown here consists of a compressor, an expander and a heat exchanger. Air from the cold room is compressed in the compressor. The hot and high pressure air rejects heat to the heat sink (cooling water) in the heat exchanger. The warm but high pressure air expands in the expander. The cold air after expansion is sent to the cold room for providing cooling. The work of expansion partly compensates the work of compression; hence both the expander and the compressor are mounted on a common shaft.



Schematic diagram of the cold air system

Fig.1.6. *Schematic of a basic, open type air cycle refrigeration system*

1.3.5. Steam Jet Refrigeration System:

If water is sprayed into a chamber where a low pressure is maintained, a part of the water will evaporate. The enthalpy of evaporation will cool the remaining water to its saturation temperature at the pressure in the chamber. Obviously lower temperature will require lower pressure. Water freezes at 0^oC hence temperature lower than 4^oC cannot be obtained with water. In this system, high velocity steam is used to entrain the evaporating water vapour. High-pressure motive steam passes through either convergent or convergent-divergent nozzle where it acquires either sonic or supersonic velocity and low pressure of the order of 0.009 kPa corresponding to an evaporator temperature of 4^oC. The high momentum of motive steam entrains or carries along with it the water vapour evaporating from the flash chamber. Because of its high velocity it moves the vapours against the pressure gradient up to the condenser where the pressure is 5.6-7.4 kPa corresponding to condenser temperature of $35\text{-}45^oC$. The motive vapour and the evaporated vapour both are condensed and recycled. This system is known as steam jet refrigeration system. Figure 1.7 shows a schematic of the system. It can be seen that this system requires a good vacuum to be maintained. Sometimes, booster ejector is used for this purpose. This system is driven by low- grade energy that is process steam in chemical plants or a boiler.

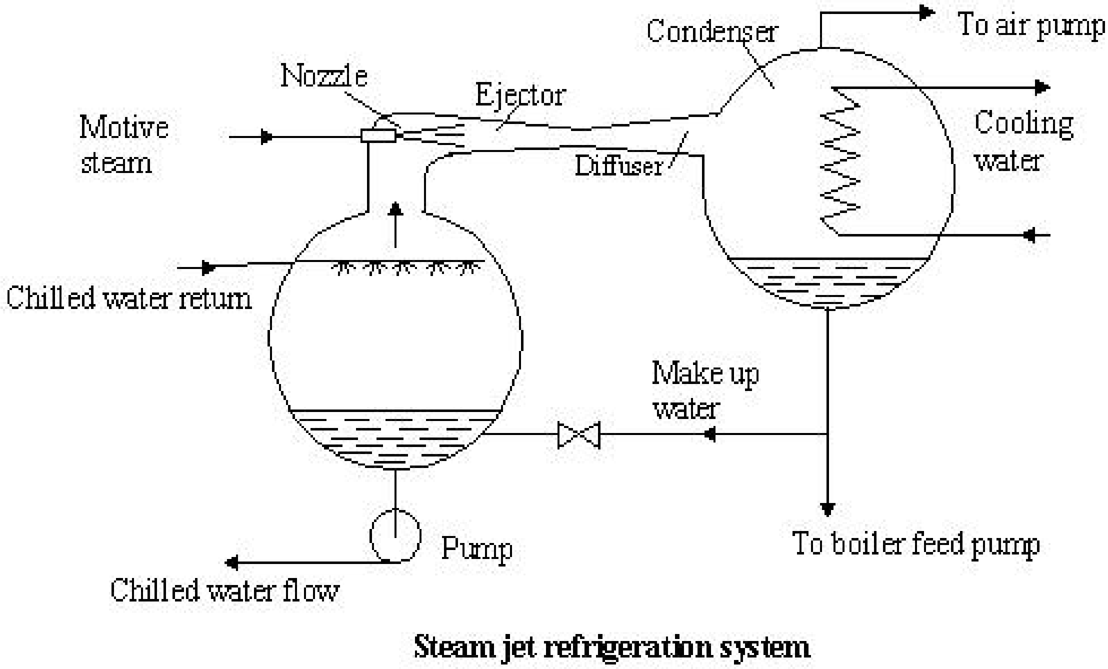


***Fig.1.7**. Schematic of a steam jet refrigeration system*

In 1838, the Frenchman Pelletan was granted a patent for the compression of steam by means of a jet of motive steam. Around 1900, the Englishman Charles Parsons studied the possibility of reduction of pressure by an entrainment effect from a steam jet. However, the credit for constructing the steam jet refrigeration system goes to the French engineer, Maurice Leblanc who developed the system in 1907-08. In this system, ejectors were used to produce a high velocity steam jet ($\approx$ 1200 m/s). Based on Leblanc's design the first commercial system was made by Westinghouse in 1909 in Paris. Even though the efficiency of the steam jet refrigeration system was low, it was still attractive as water is harmless and the system can run using exhaust steam from a steam engine. From 1910 onwards, stem jet refrigeration systems were used mainly in breweries, chemical factories, warships etc. In 1926, the French engineer Follain improved the machine by introducing multiple stages of vaporization and condensation of the suction steam. Between 1928-1930, there was much interest in this type of systems in USA. In USA they were mainly used for air conditioning of factories, cinema theatres, ships and even railway wagons. Several companies such as Westinghouse, Ingersoll Rand and Carrier started commercial production of these systems from 1930. However, gradually these systems were replaced by more efficient vapour absorption systems using LiBr-water. Still, some east European countries such as Czechoslovakia and Russia manufactured these systems as late as 1960s. The ejector principle can also be used to provide refrigeration using fluids other than water, i.e., refrigerants such as CFC-11, CFC-21, CFC-22, CFC-113, CFC-114 etc. The credit for first developing these closed vapour jet refrigeration systems goes to the Russian engineer, I.S. Badylkes around 1955. Using refrigerants other than water, it is possible to achieve temperatures as low as -100^oC with a single stage of compression. The advantages cited for this type of systems are simplicity and robustness, while difficult design and economics are its chief disadvantages.

1.3.6. Thermoelectric Refrigeration Systems:

In 1821 the German physicist T.J. Seebeck reported that when two junctions of dissimilar metals are kept at two different temperatures, an electro motive force (emf) is developed, resulting in flow of electric current. The emf produced is found to be proportional to temperature difference. In 1834, a Frenchmen, J. Peltier observed the reverse effect, i.e., cooling and heating of two junctions of dissimilar materials when direct current is passed through them, the heat transfer rate being proportional to the current. In 1838, H.F.E. Lenz froze a drop of water by the Peltier effect using antimony and bismuth (it was later found that Lenz could freeze water as the materials used were not pure metals but had some impurities in them). In 1857, William Thomson (Lord Kelvin) proved by thermodynamic analysis that Seebeck effect and Peltier effect are related and he discovered another effect called Thomson effect after his name. According to this when current flows through a conductor of a thermocouple that has an initial temperature gradient in it, then heat transfer rate per unit length is proportional to the product of current and the temperature. As the current flow through thermoelectric material it gets heated due to its electrical resistance. This is called the Joulean effect, further, conduction heat transfer from the hot junction to the cold junction transfers heat. Both these heat transfer rates have to be compensated by the Peltier Effect for some useful cooling to be produced. For a long time, thermoelectric cooling based on the Peltier effect remained a laboratory curiosity as the temperature difference that could be obtained using pure metals was too small to be of any practical use. Insulating materials give poor thermoelectric performance because of their small electrical conductivity while metals are not good because of their large thermal conductivity. However, with the discovery of semiconductor materials in 1949-50, the available temperature drop could be increased considerably, giving rise to commercialization of thermoelectric refrigeration systems. Figure 1.8 shows the schematic of the thermoelectric refrigeration system based on semiconductor materials. The Russian scientist, A. F. Ioffe is one of the pioneers in the area of thermoelectric refrigeration systems using semiconductors. Several domestic refrigerators based on thermoelectric effect were made in USSR as early as 1949. However, since 1960s these systems are used mainly used for storing medicines, vaccines etc and in electronic cooling. Development also took place in many other countries. In USA domestic refrigerators, air conditioners, water coolers, air conditioned diving suits etc. were made

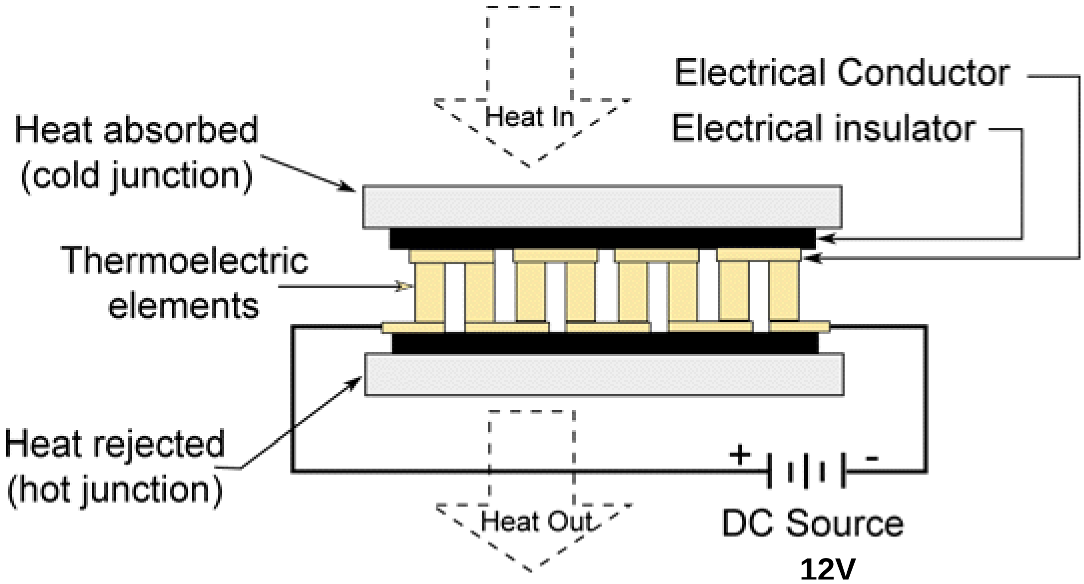


Fig. 1.8. *Schematic of a thermoelectric refrigeration system*

using these effects. System capacities were typically small due to poor efficiency. However some large refrigeration capacity systems such as a 3000 kcal/h air conditioner and a 6 tonne capacity cold storage were also developed. By using multistaging temperatures as low as –145^{o}C were obtained. These systems due to their limited performance (limited by the materials) are now used only in certain niche applications such as electronic cooling, mobile coolers etc. Efforts have also been made to club thermoelectric systems with photovoltaic cells with a view to develop solar thermoelectric refrigerators.

1.3.7. Vortex tube systems:

In 1931, the French engineer Georges Ranque (1898-1973) discovered an interesting phenomenon, which is called “Ranque effect” or “vortex effect”. The tangential injection of air into a cylindrical tube induces to quote his words “ a giratory expansion with simultaneous production of an escape of hot air and an escape of cold air”. Ranque was granted a French patent in 1928 and a US patent in 1934 for this effect. However, the discovery was neglected until after the second world war, when in 1945, Rudolph Hilsch, a German physicist, studied this effect and published a widely read scientific paper on this device. Thus, the vortex tube has also been known as the *"Ranque-Hilsch Tube”*. Though the efficiency of this system is quite low, it is very interesting due to its mechanical simplicity and instant cooling. It is convenient where there is a supply of compressed air. The present day vortex tube uses compressed air as a power source, it has no moving parts, and produces hot air from one end and cold air from the other. The volume and temperature of these two airstreams are adjustable with a valve built into the hot air exhaust. Temperatures as low as –46°C and as high as 127°C are possible. Compressed air is supplied to the vortex tube and passes through nozzles that are tangential to an internal counter bore. These nozzles set the air in a vortex motion. This spinning stream of air turns 90° and passes down the hot tube in the form of a spinning shell, similar to a tornado. A valve at one end of the tube allows some of the warmed air to escape. What does not escape, heads back down the tube as a second vortex inside the low-pressure area of the larger vortex. This inner vortex loses heat and exhausts through the other end as cold air. Currently vortex tube is used for spot cooling of machine parts, in electronic cooling and also in cooling jackets for miners, firemen etc.

Q. In an air cycle refrigeration system, low temperatures are produced due to:

a) Evaporation of liquid air
b) Throttling of air
c) Expansion of air in turbine
d) None of the above
Ans. c)

Q. Air cycle refrigeration systems are most commonly used in:

a) Domestic refrigerators
b) Aircraft air conditioning systems
c) Cold storages
d) Car air conditioning systems
Ans. b)

Q. The required input to the steam jet refrigeration systems is in the form of:

a) Mechanical energy
b) Thermal energy
c) High pressure, motive steam
d) Both mechanical and thermal energy
Ans. c)

Q. A nozzle is used in steam jet refrigeration systems to:

a) To convert the high pressure motive steam into high velocity steam
b) To reduce energy consumption
c) To improve safety aspects
d) All of the above
Ans. a)

Q. The materials used in thermoelectric refrigeration systems should have:

a) High electrical and thermal conductivity
b) High electrical conductivity and low thermal conductivity
c) Low electrical conductivity and high thermal conductivity
c) Low electrical and thermal conductivity
Ans. b)

Q. A thermoelectric refrigeration systems requires:

a) A high voltage AC (alternating current) input
b) A low voltage AC input
c) A high voltage DC (direct current) input
d) A low voltage DC input
Ans. d).

1.3.8. Summary:

In this lecture the student is introduced to different methods of refrigeration, both natural and artificial. Then a brief history of artificial refrigeration techniques is presented with a mention of the pioneers in this field and important events. The working principles of these systems are also described briefly. In subsequent chapters the most important of these refrigeration systems will be discussed in detail.

Questions:

Q. Explain why ice making using nocturnal cooling is difficult on nights when the sky is cloudy?

Ans. In order to make ice from water, water has to be first sensibly cooled from its initial temperature to its freezing point (0^oC) and then latent heat has to be transferred at 0^oC. This requires a heat sink that is at a temperature lower than 0^oC. Ice making using nocturnal cooling relies on radiative heat transfer from the water to the sky (which is at about 55^oC) that acts as a heat sink. When the sky is cloudy, the clouds reflect most of the radiation back to earth and the effective surface temperature of clouds is also much higher. As a result, radiative heat transfer from the water becomes very small, making the ice formation difficult.

Q. When you add sufficient amount of glucose to a glass of water, the water becomes cold. Is it an example of refrigeration, if it is, can this method be used for devising a refrigeration system?

Ans. Yes, this is an example of refrigeration as the temperature of glucose solution is lower than the surroundings. However, this method is not viable, as the production of refrigeration continuously requires an infinite amount of water and glucose or continuous recovery of glucose from water.

Q. To what do you attribute the rapid growth of refrigeration technology over the last century?

Ans. The rapid growth of refrigeration technology over the last century can be attributed to several reasons, some of them are:

i. Growing global population leading to growing demand for food, hence, demand for better food processing and food preservation methods. Refrigeration is required for both food processing and food preservation (Food Chain)
ii. Growing demand for refrigeration in almost all industries
iii. Growing demand for comfortable conditions (air conditioned) at residences, workplaces etc.
iv. Rapid growth of technologies required for manufacturing various refrigeration components
v. Availability of electricity, and
vi. Growing living standards