A Study on Refrigeration

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Abstract: ***Refrigeration is a basic method of food preservation. All the refrigeration methods for food preservation are based on Reverse Carnot cycle, which explains Adiabatic and Isothermal Expansion and Compression. Basic components used in these cycles are Evaporator, Compressor, Condenser and Expansion Valve. Generally used cycle is Vapor Compression Cycle. Other cycles are Vapor Absorption Cycle, Gas Cycle. Other new methods of Refrigeration are Thermoelectric and Magnetic Refrigeration. Various types of refrigerants are used in these cycles based upon their properties. Commercially Refrigeration is used as preservation method in various food industries like Dairy and Meat Processing industry.***

Keywords: Food preservation, reverse carnot cycle, evaporator, compressor, condenser, vapor compression cycle, Thermoelectric and Magnetic Refrigeration

1. Introduction [1] [4]

Refrigeration is a process in which work is done to remove heat from one location to another. Refrigeration has many applications including but not limited to household refrigerators, industrial freezers, cryogenics, air conditioning, and heat pumps. In order to satisfy the Second Law of Thermodynamics, some form of work must be performed to accomplish this. The work is traditionally done by mechanical work but can also be done by magnetism, laser or other means. Since the turn of the century, there has been steady growth of application of refrigeration in preservation of perishable food products, agriculture and fishery.

The purpose of refrigeration for food is to retard deterioration by micro-organisms, chemical and physical processes. By cooling at temperatures just above freezing it is possible to achieve a limited extension of storage time which is often sufficient for safe distribution and marketing. By freezing to temperature as low as -30^{O}C, deterioration can be slowed down further and this increases the storage time. Refrigeration has applications in diverse industries, such as manufacturing chemicals, petroleum, refineries, paper and pulp industries also.

2. Review of Literature [6]

Ice harvesting:- The use of ice to refrigerate and thus preserve food goes back to prehistoric times. Through the ages, the seasonal harvesting of snow and ice was a regular practice of most of the ancient cultures: Chinese, Hebrews, Greeks, Romans, Persians. Ice and snow were stored in caves or dugouts lined with straw or other insulating materials. The Persians stored ice in pits called yakhchals. Rationing of the ice allowed the preservation of foods over the warm periods. This practice worked well down through the centuries, with ice houses remaining in use into the twentieth century. In the 16th century, the discovery of chemical refrigeration was one of the first steps toward artificial means of refrigeration. **Sodium nitrate or potassium nitrate**, when added to water, lowered the water temperature and created a sort of refrigeration bath for cooling substances. During the first half of the 19th century, ice harvesting became big business in America. **New Englander Frederic Tudor**, who became known as the **"Ice King"**, worked on developing better insulation products for the long distance shipment of ice, especially to the tropics.

First refrigeration systems:- The first known method of artificial refrigeration was demonstrated by **William Cullen** at the University of Glasgow in Scotland in 1756. Cullen used a pump to create a partial vacuum over a container of **diethyl ether**, which then boiled, absorbing heat from the surrounding air. The experiment even created a small amount of ice, but had no practical application at that time.

In 1758, **Benjamin Franklin** and **John Hadley**, professor of chemistry at Cambridge University, conducted an experiment to explore the principle of evaporation as a means to rapidly cool an object. Franklin and Hadley confirmed that evaporation of highly volatile liquids such as alcohol and ether could be used to drive down the temperature of an object past the freezing point of water. They conducted their experiment with the bulb of a mercury thermometer. They lowered the temperature of the thermometer bulb down to 7 °F (−14 °C) while the ambient temperature was 65 °F (18 °C). Franklin noted that soon after they passed the freezing point of water (32 °F) a thin film of ice formed on the surface of the thermometer's bulb and that the ice mass was about a quarter inch thick when they stopped the experiment upon reaching 7 °F (−14 °C).
In 1820, the British scientist **Michael Faraday** liquefied ammonia and other gases by using high pressures and low temperatures.

An American living in Great Britain, **Jacob Perkins**, obtained the first patent for a vapor-compression refrigeration system in 1834. In 1842, an American physician, **John Gorrie**, designed the first system for refrigerating water to produce ice. His system compressed air, then partially cooled the hot compressed air with water before allowing it to expand while doing part of the work required to drive the air compressor. That isentropic (the process takes place from initiation to completion without an increase or decrease in the entropy of the system, i.e., the entropy of the system remains constant) expansion cooled the air to a temperature low enough to freeze water and produce ice, or to flow "through a pipe for effecting refrigeration otherwise" as stated in his patent granted by the U.S. Patent Office in 1851.Gorrie built a working prototype (A prototype is an early sample or model built to test a concept or process or to act as a thing to be replicated or learned from), but his system was a commercial failure.

Alexander Twining began experimenting with vapor-compression refrigeration in 1848 and obtained patents in 1850 and 1853. He is credited with having initiated commercial refrigeration in the United States by 1856.

The first gas absorption refrigeration system using gaseous ammonia dissolved in water (referred to as "aqua ammonia") was developed by **Ferdinand Carré** of France in 1859 and patented in 1860. Due to the toxicity of ammonia, such systems were not developed for use in homes, but were used to manufacture ice for sale.

Thaddeus Lowe, an American balloonist from the Civil War, had experimented over the years with the properties of gases. One of his mainstay enterprises was the high-volume production of hydrogen gas. He also held several patents on ice making machines. His "Compression Ice Machine" would revolutionize the cold storage industry. In 1869 he and other investors purchased an old steamship onto which they loaded one of Lowe's refrigeration units and began shipping fresh fruit from New York to the Gulf Coast area, and fresh meat from Galveston, Texas back to New York. Because of Lowe's lack of knowledge about shipping, the business was a costly failure, and it was difficult for the public to get used to the idea of being able to consume meat that had been so long out of the packing house.

Domestic mechanical refrigerators became available in the United States around 1911.

a) Widespread commercial use

By the 1870s breweries had become the largest users of commercial refrigeration units, though some still relied on harvested ice. Though the ice-harvesting industry had grown immensely by the turn of the 20th century, pollution and sewage had begun to creep into natural ice making it a problem in the metropolitan suburbs. Eventually breweries began to complain of tainted ice. This raised demand for more modern and consumer-ready refrigeration and ice-making machines. In 1895, German engineer **Carl von Linde** set up a large-scale process for the production of liquid air and eventually liquid oxygen for use in safe household refrigerators.

Refrigerated railroad cars were introduced in the US in the 1840s for the short-run transportation of dairy products.

By 1900, the meat packing houses of Chicago had adopted ammonia-cycle commercial refrigeration. By 1914, almost every location used artificial refrigeration. The big meat packers, **Armour, Swift, and Wilson**, had purchased the most expensive units which they installed on train cars and in branch houses and storage facilities in the more remote distribution areas.It was not until the middle of the 20th century that refrigeration units were designed for installation on tractor-trailer rigs (trucks or Lorries). Refrigerated vehicles are used to transport perishable goods, such as frozen foods, fruit and vegetables, and temperature-sensitive chemicals. Most modern refrigerators keep the temperature between -40 and 20 °C and have a maximum payload of around 24,000 kg gross weight (in Europe).

b) Home and consumer use

With the invention of synthetic refrigerants based mostly on a chlorofluorocarbon (CFC) chemical, safer refrigerators were possible for home and consumer use. Freon is a trademark of the **DuPont Corporation** and refers to these CFC, and later hydro chlorofluorocarbon (HCFC) and hydro fluorocarbon (HFC), refrigerants developed in the late 1920s. These refrigerants were considered at the time to be less harmful than the commonly used refrigerants of the time, including methyl formate, ammonia, methyl chloride, and sulfur dioxide. The intent was to provide refrigeration equipment for home use without danger: these CFC refrigerants answered that need. However, in the 1970s the compounds were found to be reacting with atmospheric ozone, an important protection against solar ultraviolet radiation, and their use as a refrigerant worldwide was curtailed in the **Montreal** Protocol of 1987.

3. Basic Refrigeration Principle [4] [5]

If you were to place a hot cup of coffee on a table and leave it for a while, the heat in the coffee would be transferred to the materials in contact with the coffee, i.e. the cup, the table and the surrounding air. As the heat is transferred, the coffee in time cools. Using the same principle, refrigeration works by removing heat from a product and transferring that heat to the outside air.

Refrigeration is used to cool products. The refrigeration system (R) transfers heat from a cooler low-energy reservoir to a warmer high-energy reservoir

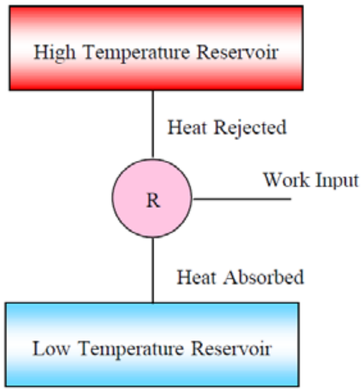


Figure 1: Schematic representation of refrigeration system

4. Refrigeration System Components [5]

There are five basic components of a refrigeration system, these are: Evaporator, Compressor, Condenser, Expansion Valve and Refrigerant- to conduct the heat from the product. In order for the refrigeration cycle to operate successfully each component must be present within the refrigeration system.

4.1 The Evaporator

The purpose of the evaporator is to remove unwanted heat from the product, via the liquid refrigerant. The liquid refrigerant contained within the evaporator is boiling at a low-pressure. The level of this pressure is determined by two factors:

- The rate at which the heat is absorbed from the product to the liquid refrigerant in the evaporator
- The rate at which the low-pressure vapour is removed from the evaporator by the compressor
- To enable the transfer of heat, the temperature of the liquid refrigerant must be lower than the temperature of the product being cooled. Once transferred, the liquid refrigerant is drawn from the evaporator by the compressor via the suction line. When leaving the evaporator coil the liquid refrigerant is in vapor form.

4.2 The Compressor

The purpose of the compressor is to draw the low-temperature, low-pressure vapour from the evaporator via the suction line. When vapour is compressed it rises in temperature. Therefore, the compressor transforms the vapour from a low-temperature vapor to a high-temperature vapour, in turn increasing the pressure. The vapor is then released from the compressor in to the discharge line.

4.3 The Condenser

The purpose of the condenser is to extract heat from the refrigerant to the outside air. Fans mounted above the condenser unit are used to draw air through the condenser coils. The temperature of the high-pressure vapour determines the temperature at which the condensation begins. As heat has to flow from the condenser to the air, the condensation temperature must be higher than that of the air; usually between - 12°C and -1°C. The high-pressure vapour within the condenser is then cooled to the point where it becomes a liquid refrigerant once more, whilst retaining some heat. The liquid refrigerant then flows from the condenser in to the liquid line.

4.4 The Expansion Valve

Within the refrigeration system, the expansion valve is located at the end of the liquid line, before the evaporator. The high-pressure liquid reaches the expansion valve, having come from the condenser. The valve then reduces the pressure of the refrigerant as it passes through the orifice, which is located inside the valve. On reducing the pressure, the temperature of the refrigerant also decreases to a level below the surrounding air. This low-pressure, low temperature liquid is then pumped in to the evaporator.

5. Methods of Refrigeration [4] [6]

Methods of refrigeration can be classified as;

- Non-Cyclic
- Cyclic
- Thermoelectric
- Magnetic Refrigeration
- Other Methods

5.1 Non-cyclic refrigeration

In non-cyclic refrigeration, cooling is accomplished by melting ice or by subliming dry ice (frozen carbon dioxide). These methods are used for small-scale refrigeration such as in laboratories and workshops, or in portable coolers. Ice owes its effectiveness as a cooling agent to its constant melting point of 0 °C (32 °F). In order to melt, ice must absorb 333.55 kJ/kg (approx. 144 Btu/lb) of heat. Foodstuffs maintained at this temperature or slightly above have an increased storage life. Solid carbon dioxide has no liquid phase at normal atmospheric pressure, so sublimes directly from the solid to vapor phase at a temperature of -78.5 °C (-109.3 °F), and is therefore effective for maintaining products at low temperatures during the period of sublimation (Sublimation refers to the process of transition of a substance from the solid phase to the gas phase without passing through an intermediate liquid phase). Systems such as this where the refrigerant evaporates and is vented into the atmosphere are known as "total loss refrigeration".

5.1.1 Ice Refrigeration

In this method the ordinary ice is used for keeping the space at temperature below the surrounding temperature. The temperature of ice is considered to be 0 degree Celsius hence it can be used to maintain the temperatures of about 5 to 10 degree Celsius. To use the ice for refrigerating effect a closed and insulated chamber is required. On one side of the chamber ice is kept while on the other side there is a space which is to be cooled where some material to be cooled can be placed. If the temperature below 0 degree Celsius is required, then the mixture of ice and salt is used. This method of cooling is still being used for cooling the cold drinks, keeping the water chilled in thermos, etc.

5.1.2 Dry ice refrigeration

Dry ice is the solid carbon dioxide having the temperature of -78 degree Celsius. Dry ice converts directly from solid state to gaseous; this process is called as sublimation. Dry ice can be pressed into various sizes and shapes as blocks or slabs. Dry ice is usually packed in the frozen food cartons along with the food that has to be kept frozen for long intervals of time. When the dry ice gets converted into vapor state it keeps the food frozen. The process of dry ice refrigeration is now-a-days being used for freezing the food in aircraft transportation. The non-cyclic methods of refrigeration can be used only in places where small amount of refrigeration is required in places like laboratories, workshops, water coolers, small old drink shops, small hotels etc.

5.2 Cyclic Refrigeration [2]

This consists of a refrigeration cycle, where heat is removed from a low-temperature space or source and rejected to a high-temperature sink with the help of external work, and its inverse, the thermodynamic power cycle. In the power cycle, heat is supplied from a high-temperature source to the engine, part of the heat being used to produce work and the rest being rejected to a low-temperature sink. This satisfies the second law of thermodynamics.

A refrigeration cycle describes the changes that take place in the refrigerant as it alternately absorbs and rejects heat as it circulates through a refrigerator. It is also applied to HVACR (HVACR (Heating, Ventilating, Air Conditioning & Refrigeration) refers to technology of indoor or automotive environmental comfort) work, when describing the "process" of refrigerant flow through an HVACR unit, whether it is a packaged or split system. Heat naturally flows from hot to cold. Work is applied to cool a living space or storage volume by pumping heat from a lower temperature heat source into a higher temperature heat sink. Insulation (Thermal insulation is the reduction of the effects of the various processes of heat transfer between objects in thermal contact or in range of radiative influence) is used to reduce the work and energy required to achieve and maintain a lower temperature in the cooled space. The operating principle of the refrigeration cycle was described mathematically by Sadi Carnot in 1824 as a heat engine. The most common types of refrigeration systems use the reverse-Rankin vapor-compression refrigeration cycle.

Cyclic refrigeration can be classified as:
1. Vapor cycle, and
2. Gas cycle

Vapor cycle refrigeration can further be classified as:
1. Vapor-compression refrigeration
2. Vapor-absorption refrigeration

5.2.1 Vapor-compression Cycle

The vapor-compression cycle is used in most household refrigerators as well as in many large commercial and industrial refrigeration systems. Figure 1 provides a schematic diagram of the components of a typical vapor-compression refrigeration system.

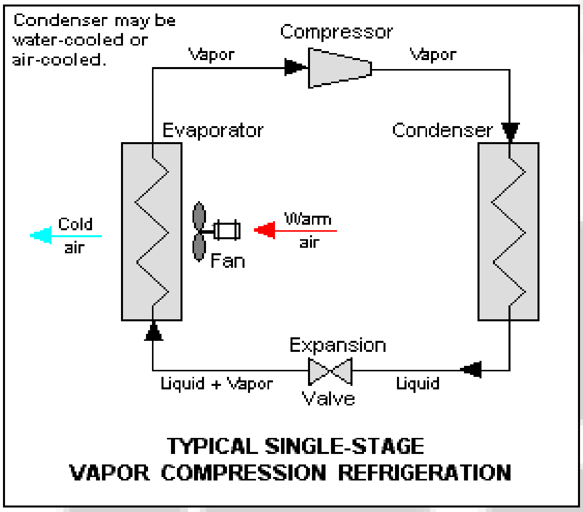


Figure 1: Vapor compression refrigeration

The thermodynamics of the cycle can be analyzed on a diagram as shown in Figure 2. In this cycle, a circulating refrigerant such as Freon enters the compressor as a vapor. From point 1 to point 2, the vapor is compressed at constant entropy and exits the compressor as a vapor at a higher temperature, but still below the vapor pressure at that temperature. From point 2 to point 3 and on to point 4, the vapor travels through the condenser which cools the vapor until it starts condensing, and then condenses the vapor into a liquid by removing additional heat at constant pressure and temperature. Between points 4 and 5, the liquid refrigerant goes through the expansion valve (also called a throttle valve) where its pressure abruptly decreases, causing flash evaporation and auto-refrigeration of, typically, less than half of the liquid.

That results in a mixture of liquid and vapor at a lower temperature and pressure as shown at point 5. The cold liquid-vapor mixture then travels through the evaporator coil or tubes and is completely vaporized by cooling the warm air (from the space being refrigerated) being blown by a fan across the evaporator coil or tubes. The resulting refrigerant vapor returns to the compressor inlet at point 1 to complete the thermodynamic cycle.

The above discussion is based on the ideal vapor-compression refrigeration cycle, and does not take into account real-world effects like frictional pressure drop in the system, slight thermodynamic irreversibility during the compression of the refrigerant vapor, or non-ideal gas behavior (if any).

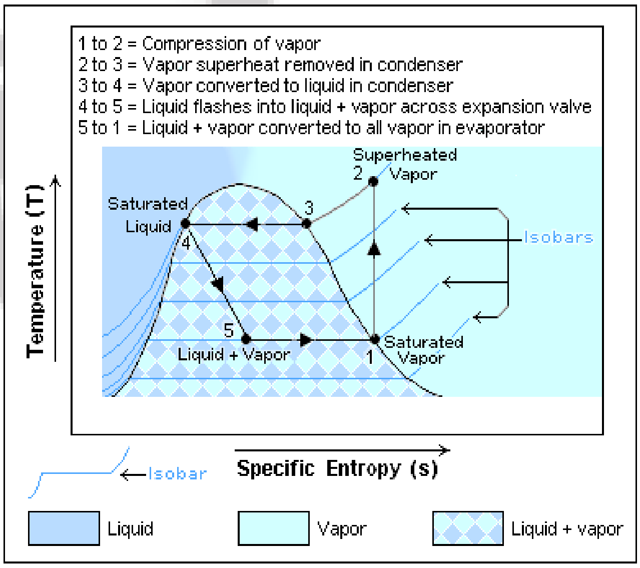


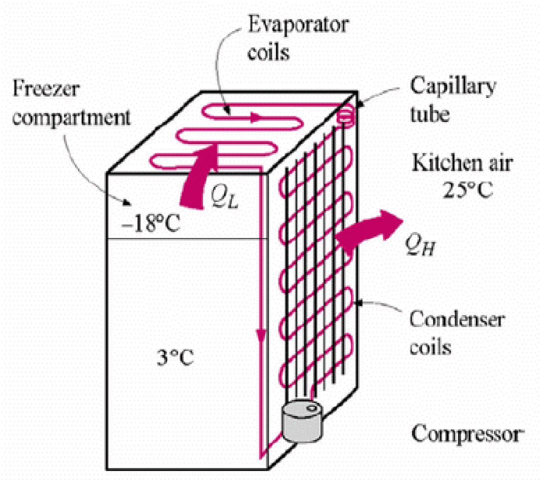
Figure 2: Temperature–Entropy diagram

Here are the various processes of vapor compression cycle (refer the figure):

1) **Compression**: The vapors of refrigerant enter the compressor and get compressed to high pressure and high temperature. During this process the entropy of the refrigerant ideally remains constant and it leaves in superheated state.
2) **Condensation**: The superheated refrigerant then enters the condenser where it is cooled either by air or water due to which its temperature reduces, but pressure remains constant and it gets converted into liquid state.
3) **Expansion**: The liquid refrigerant then enters the expansion valve or throttling valve where sudden expansion of the refrigerant occurs, due to which its temperature and pressure falls down. The refrigerant leaves expansion valve in partially liquid state and partially in gaseous state.

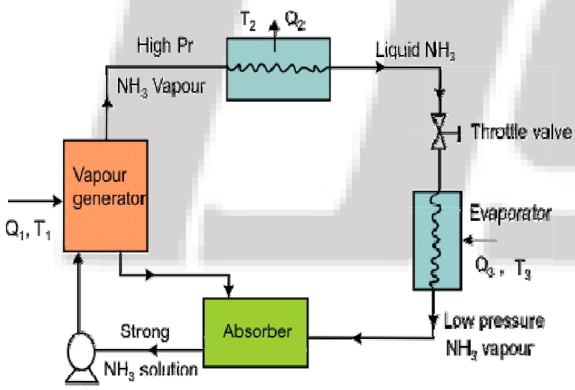
4) **Evaporation or cooling**: The partially liquid and partially gaseous refrigerant at very low temperature enters the evaporator where the substance to be cooled is kept. It is here where the refrigeration effect is produced. The refrigerant absorbs the heat from the substance to be cooled and gets converted into vapor state.

This low pressure refrigerant is then absorbed by the compressor where it is compressed again and the whole cycle of refrigeration repeats again. The vapor compression cyclic process is used for refrigeration in domestic as well as commercial applications. The ordinary household refrigerator is a good example of the application of this cycle.



5.2.2 Vapor absorption cycle

In the early years of the twentieth century, the vapor absorption cycle using water-ammonia systems was popular and widely used. After the development of the vapor compression cycle, the vapor absorption cycle lost much of its importance because of its low coefficient of performance (about one fifth of that of the vapor compression cycle). Today, the vapor absorption cycle is used mainly where fuel for heating is available but electricity is not, such as in recreational vehicles that carry LP gas. It is also used in industrial environments where plentiful waste heat overcomes its inefficiency.



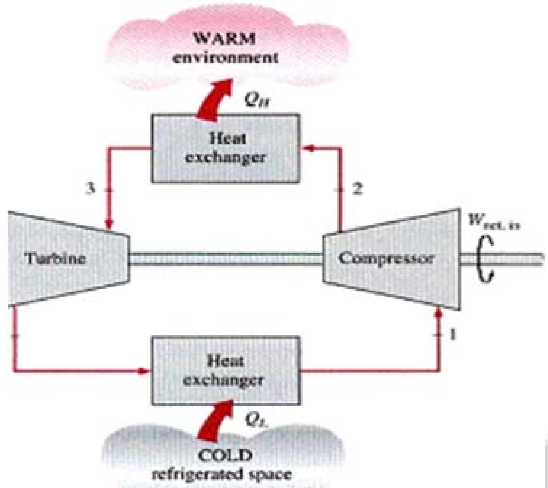
The absorption cycle is similar to the compression cycle, except for the method of raising the pressure of the refrigerant vapor. In the absorption system, the compressor is replaced by an absorber which dissolves the refrigerant in a suitable liquid, a liquid pump which raises the pressure and a generator which, on heat addition, drives off the refrigerant vapor from the high-pressure liquid. Some work is required by the liquid pump but, for a given quantity of refrigerant, it is much smaller than needed by the compressor in the vapor compression cycle. In an absorption refrigerator, a suitable combination of refrigerant and absorbent is used. The most common combinations are ammonia (refrigerant) and water (absorbent), and water (refrigerant) and lithium bromide [absorbent].

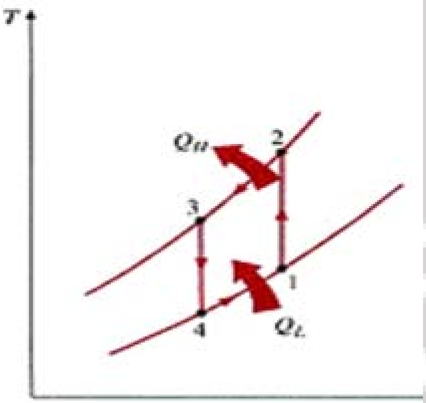
The various processes of the vapor absorption cycle are similar to the one in vapor compression cycle, only the method of compression of the refrigerant is different. In vapor absorption system ammonia is used as the refrigerant, which has very high affinity to dissolve in water. Here are various processes of vapor absorption cycle:

1) Compression or absorption of the refrigerant: In vapor absorption system there is no traditional compressor, instead there is absorber. The absorber consists of water, called as absorbent, in which the refrigerant, ammonia, dissolves. This mixture of water and ammonia is then pumped and heated thus increase in temperature and pressure of the ammonia occurs. Ammonia leaves the absorber at high pressure and high temperature. Some work has to be provided to the pump and heating is carried out by the steam. The amount of electricity required by the pump is much lesser than that required by the compressor hence there is lots of saving of electricity, however, the additional source of heat in the form of steam has to be provided.
2) Condensation: The refrigerant at pressure and temperature then enters condenser where it is cooled by water and its temperature and pressure reduces.
3) Expansion: Thereafter the expansion of refrigerant occurs in throttling valve due to which the temperature and pressure of the ammonia refrigerant reduces drastically and suddenly.
4) Evaporation: Finally the refrigerant enters the evaporator where it produces the cooling effect. It leaves the evaporator in vapor state and then enters absorber, where it is absorbed by absorbent, water and compressed by the pump. This process repeats again and cycle continues.
There are different types absorbents like water and lithium bromide that can be used with refrigerant ammonia. These systems are called water absorption system or lithium bromide absorption system.

5.2.3 Gas cycle [3]

When the working fluid is a gas that is compressed and expanded but doesn't change phase, the refrigeration cycle is called a *gas cycle*. Air is most often this working fluid. As there is no condensation and evaporation intended in a gas cycle, components corresponding to the condenser and evaporator in a vapor compression cycle are the hot and cold gas-to-gas heat exchangers in gas cycles.



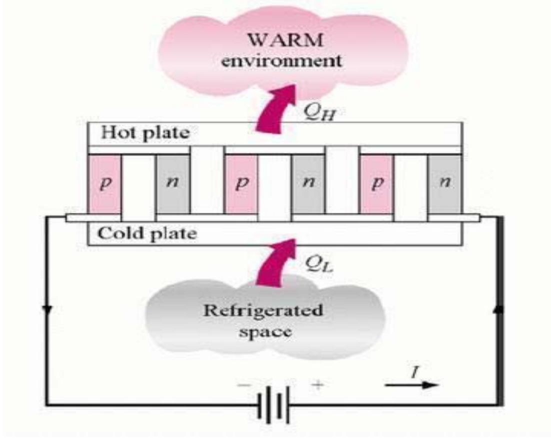


The gas cycle is less efficient than the vapor compression cycle. As such the working fluid does not receive and reject heat at constant temperature. In the gas cycle, the refrigeration effect is equal to the product of the specific heat of the gas and the rise in temperature of the gas in the low temperature side. Therefore, for the same cooling load, a gas refrigeration cycle will require a large mass flow rate and would be bulky.

Because of their lower efficiency and larger bulk, *air cycle* coolers are not often used nowadays in terrestrial cooling devices. The air cycle machine is very common, however, on gas turbine-powered jet aircraft because compressed air is readily available from the engines' compressor sections. These jet aircraft's cooling and ventilation units also serve the purpose of pressurizing the aircraft.

5.3 Thermoelectric refrigeration [1] [6]

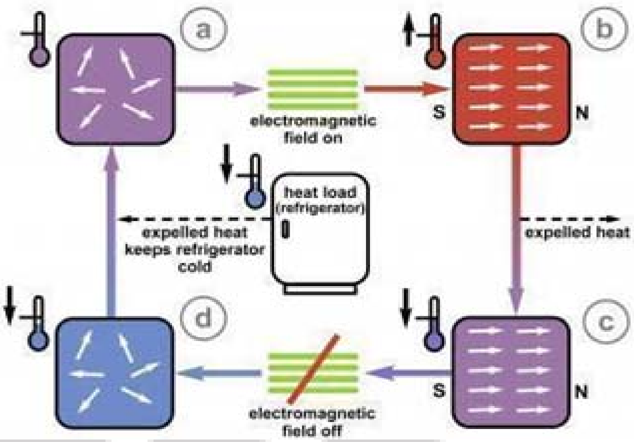
Thermoelectric cooling uses the Peltier effect to create a heat flux between the junctions of two different types of materials. This effect is commonly used in camping and portable coolers and for cooling electronic components and small instruments.



5.4 Magnetic refrigeration [1] [6]

Magnetic refrigeration, or adiabatic demagnetization, is a cooling technology based on the magnetocaloric effect, an intrinsic property of magnetic solids. The refrigerant is often a paramagnetic salt, such as cerium magnesium nitrate. The active magnetic dipoles in this case are those of the electron shells of the paramagnetic atoms.

A strong magnetic field is applied to the refrigerant, forcing its various magnetic dipoles to align and putting these degrees of freedom of the refrigerant into a state of lowered entropy. A heat sink then absorbs the heat released by the refrigerant due to its loss of entropy. Thermal contact with the heat sink is then broken so that the system is insulated, and the magnetic field is switched off. This increases the heat capacity of the refrigerant, thus decreasing its temperature below the temperature of the heat sink. Because few materials exhibit the required properties at room temperature, applications have so far been limited to cryogenics and research.



5.5 Other Methods [1] [6]

Other methods of refrigeration include the:-

5.5.1)Air cycle machine: - An air cycle machine (ACM) is the refrigeration unit of the environmental control system (ECS) used in pressurized gas turbine-powered aircrafts. The Air Cycle cooling process uses air instead of Freon in a gas cycle

5.5.2) The vortex tube: - It is a mechanical device that separates a compressed gas into hot and cold streams. It has no parts. It is used for spot cooling, when compressed air is available; and

5.5.3) Thermo acoustic refrigeration: - Thermo acoustic engines are thermo acoustic devices which use high-amplitude sound waves to pump heat from one place to another. It is using sound waves in a pressurized gas to drive heat transfer and heat exchange.

5.5.4)Steam jet cooling: - Steam jet cooling uses a high-pressure jet of steam to cool water or other fluid media. Its principle is, steam is passed through a vacuum ejector of high efficiency to exhaust a separate, closed vessel which forms part of a cooling water circuit. The partial vacuum in the vessel causes some of the water to evaporate, thus giving up heat through evaporative cooling. The chilled water is pumped through the circuit to air coolers, while the evaporated water from the ejector is recovered in separate condensers and returned to the cooling circuit. Steam jet cooling experienced a wave of popularity during the early 1930s for air conditioning large buildings. Steam ejector refrigeration cycles were later supplanted by systems using mechanical compressors.

6. Unit of refrigeration [6]

The units of refrigeration are always a unit of power. Domestic and commercial refrigerators may be rated in kJ/s, or Btu/h of cooling. For commercial and industrial refrigeration systems most of the world uses the kilowatt (kW) as the basic unit refrigeration. Typically, commercial and industrial refrigeration systems North America are rated in Tons of Refrigeration (TR). Historically, one Ton of Refrigeration was defined as the energy removal rate that will freeze one short ton of water at 0 °C (32 °F) in one day. This was very important because many early refrigeration systems were in ice houses. The simple unit allowed owners of this refrigeration systems measure a days output of ice against energy consumption and compare their plant to one down the street. While ice houses make up a much smaller part of the refrigeration industry than they once did the unit of Tons of Refrigeration has remained in North America. The unit's value as historically defined is approximately 11,958 BTU/hr (3.505 kW) has been redefined to be exactly 12,000 BTU/hr (3.517 kW).

While not truly a unit, a refrigeration system's Coefficient of Performance (CoP) is very important in determining a system's overall efficiency. It is defined as refrigeration capacity in kW divided by the energy input in kW. While CoP is a very simple measure, like the kW, it is typically not used for industrial refrigeration in North America. Owners and manufacturers of these systems typically use Performance Factor. A system's Performance Factor is defined as a system's energy input in horsepower divided by its refrigeration capacity in Tons of Refrigeration. Both Coefficient of Performance and Performance Factor can be applied to either the entire system or to system components. For example an individual compressor can be rated by looking at the energy required to run the compressor versus the expected refrigeration capacity based on inlet volume flow rate. It is important to note that both Coefficient of Performance and Performance Factor for a refrigeration system are only defined at specific operating conditions. Moving away from those operating conditions can dramatically change a system's performance.

7. Assessment of Refrigeration [4]

7.1 TR

TR is the cooling effect produced is quantified as tons of refrigeration, also referred to as “chiller tonnage.

§ TR = Q x Cp x (Ti – To) / 3024
Where **Q** is mass flow rate of coolant in kg/hr, **Cp** is coolant specific heat in kCal /kg deg C, **Ti** is inlet temperature of coolant to evaporator (chiller) in 0C, **To** is outlet temperature of coolant from evaporator (chiller) in 0C.
1 TR of refrigeration = **3024 kCal/hr** heat rejected

7.2 Specific Power Consumption

The specific power consumption kW/TR is a useful indicator of the performance of a refrigeration system. By measuring the refrigeration duty performed in TR and the kW inputs, kW/TR is used as an energy performance indicator.

7.3 Coefficient of Performance

The theoretical Coefficient of Performance (Carnot), {COP (Carnot), a standard measure of refrigeration efficiency of an ideal refrigeration system} depends on two key system temperatures:

Evaporator temperature (Te) and Condenser temperature (Tc)

COP is given as: COP (Carnot) = Te / (Tc - Te)

This expression also indicates that higher COP (Carnot) is achieved with higher evaporator temperatures and lower condenser temperatures. But COP (Carnot) is only a ratio of temperatures, and does not take into account the type of compressor.

Hence the COP normally used in industry is calculated as follows:

$$\text{COP} = \frac{\text{Cooling effect (kW)}}{\text{Power input to compressor (kW)}}$$

where the cooling effect is the difference in enthalpy across the evaporator and expressed as kW.

8. Common Refrigerants [7]

There are several fluorocarbon refrigerants that have been developed for use in VCRC.

Dichlorofluoromethane	CCl_2F_2	R12
- used for refrigeration systems at higher temperature levels typically, water chillers and air conditioning.		
has less chlorine, a little better for the environment than R12 and used for lower temperature applications	$CHClF_2$	R22
tetrafluorethane - no chlorine ,it went into production in 1991 and acted as replacement for R12	CFH_2CF_3	R134a
Dichlorofluoroethane	$C2H_3FCl_2$	R141b
corrosive and toxic, used in absorption systems	NH_3	Ammonia
behaves in the supercritical region, low efficiency	CO_2	R744
Combustible	propane	R290

9. How to Choose a Refrigerant [7]

Factors needed to be considered are Ozone Depletion Potential, Global Warming Potential, Combustibility, Thermal Factors**.**

- **Ozone Depletion Potential**: these are chlorinated and brominated refrigerants, acts as a catalyst to destroy ozone molecules and reduces the natural shielding effect from incoming ultra violet B radiation.
- **Global Warming Potential**: Gases that absorb infrared energy, with a high number of carbon-fluorine bonds and generally have a long atmospheric lifetime.
- **Combustibility**: All hydro-carbon fuels, such as propane
- **Thermal Factors:-**The heat of vaporization of the refrigerant should be high. The higher ***h(fg)***, the greater the refrigerating effect per ***kg*** of fluid circulated. The specific heat of the refrigerant should be low. The lower the specific heat, the less heat it will pick up for a given change in temperature during the throttling or in flow through the piping and consequently the greater the refrigerating effect per ***kg*** of refrigerant. The specific volume of the refrigerant should be low to minimize the work required per ***kg*** of refrigerant circulated. Since evaporation and condenser temperatures are fixed by the temperatures of the surroundings. Selection is based on the suitability of the pressure-temperature relationship of the refrigerant
- **Other factors include**:- Chemical Stability, Toxicity, Cost, Environmental Friendliness, Does not result in very low pressures in the evaporator (air leakage), Does not result in very high pressures in the condenser (refrigerant leakage)

The vapor compression cycle is most commonly used for refrigeration.

Comparison of vapor compression and gas compression refrigerating cycles based on following parameters: [4]

1) **Type of refrigerant used**: In vapor compression cycle liquids like Freon and ammonia are used as the refrigerant. In the gas cycle the gas like air is used as the refrigerant.
2) **Heat exchangers**: In the vapor compression refrigeration cycle condenser and evaporator are the two heat exchangers where the refrigerant gives up and absorbs heat respectively. The refrigerant undergoes change in phase in both the heat exchangers. In the gas cycle the refrigerant exchanges heat in the heat exchangers, but there is no phase change of the gas.
3) **Efficiency of the cycle**: The efficiency of the vapor compression cycle is more than that of the gas cycle. For producing the same amount of refrigerating effect in the gas cycle, large volume of gas is required; hence the systems tend to become very large, bulky and expensive, which are not affordable for the domestic applications.
4) **Applications**: The vapor compression cycle is most widely used for the refrigeration purposes. It is used in household refrigerators, air-conditioners, water cooler, ice and ice cream makers, deep freezers, large industrial refrigeration and air-conditioning systems, etc. Since the size of the gas compression systems is very large, they are not used for the domestic and industrial purposes. They are used widely in the aircraft air-conditioning systems since in aircrafts air at very high pressures is available readily and there won't be the need of air compressors. This makes the air-conditioning system in the aircraft light weight and less power consuming. The use of air as the refrigerant in aircraft prevents the dangers of fire of from the flammable refrigerants.

Differences between an absorption refrigeration system and a VCRC [4]

Absorption RS	*VCRC*
• The refrigerant is absorbed by an absorbent material to form a liquid solution.	• Vapour is compressed between the evaporator and the condenser.
• Heat is added to the process to retrieve the refrigerant vapour from the liquid solution.	• Process is driven by work
• Process is driven by heat	

10. Current Applications of Refrigeration [6]

Probably the most widely used current applications of refrigeration are for the refrigeration of foodstuffs in homes, restaurants and large storage warehouses. The use of refrigerators in kitchens for the storage of fruits and vegetables has permitted the addition of fresh salads to the modern diet year round, and to store fish and meats safely for long periods.

In commerce and manufacturing, there are many uses for refrigeration. Refrigeration is used to liquefy gases like oxygen, nitrogen, propane and methane for example. In compressed air purification, it is used to condense water vapor from compressed air to reduce its moisture content. In oil refineries, chemical plants, and petrochemical plants, refrigeration is used to maintain certain processes at their required low temperatures (for example, in the alkylation of butenes and butane to produce a high octane gasoline component). Metal workers use refrigeration to temper steel and cutlery. In transporting temperature-sensitive foodstuffs and other materials by trucks, trains, airplanes and sea-going vessels, refrigeration is a necessity.

Dairy products are constantly in need of refrigeration, and it was only discovered in the past few decades that eggs needed to be refrigerated during shipment rather than waiting to be refrigerated after arrival at the grocery store. Meats, poultry and fish all must be kept in climate-controlled environments before being sold. Refrigeration also helps keep fruits and vegetables edible longer. One of the most influential uses of refrigeration was in the development of the sushi/sashimi industry in Japan. Prior to the discovery of refrigeration, many sushi connoisseurs suffered great morbidity and mortality from diseases such as hepatitis A However the dangers of unrefrigerated sashimi was not brought to light for decades due to the lack of research and healthcare distribution across rural Japan. Around mid-century, the Zojirushi Corporation based in Kyoto made breakthroughs in refrigerator designs making refrigerators cheaper and more accessible for restaurant proprietors and the general public.

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