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Refrigeration & Air-conditioning

Mechanical Engineering

Comprehensive Theory *with* Solved Examples

Civil Services Examination

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Refrigeration & Air-conditioning

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Chapter 1

Introduction to Basic Concepts

1.1 Introduction

Refrigeration may be defined as the process of achieving and maintaining a temperature lower than that of surroundings, the aim being to cool some product or space to the required temperature.

Refrigeration systems are also used extensively for providing thermal comfort to human beings by means of air-conditioning. Air conditioning refers to 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 space.

1.2 Applications of Refrigeration

1. A refrigeration system may be used to cool the water, which may be further used to cool the air in comfort air-conditioning systems of auditoriums, theatres, hospitals, etc. The capacity of these air-conditioning units may range from 150 TR to 250 TR.
2. Refrigeration systems with open ammonia compressors are used. The capacity of the ice plants may be 20 tonnes per day or more.
3. Domestic refrigeration includes household refrigerators and home freezers. Domestic units are usually small in size, producing refrigerating effect in the range 300–500 W at about – 5°C evaporator temperature.
4. Refrigeration finds widespread applications in food processing and in storage units.
   (a) **Milk and milk products:** Whole milk for human consumption is pasteurized at 75°C for a short time, and then recooled to 4°C immediately. This cooling is done in a counterflow plate heat exchanger with the use of chilled water at 2°C. The pasteurisation of milk is carried out in the following stages:
      (i) Raw milk at 4°C is heated by the outgoing milk up to about 25°C.
      (ii) This milk is finally heated by hot water up to the pasteurizing temperature of 75°C and held for a few seconds.
      (iii) Then milk is cooled by the incoming milk down to about 10°C.
      (iv) The final stage of cooling from 10°C to 4°C is done by water at 2°C.

   Long-term storage of butter is at –25°C. Milk is treated at low temperature for other products as well.

(b) **Soft drinks:** Most of the soft drinks are carbonated, i.e. they have a proportion of dissolved carbon dioxide, which causes the bubbles and also the typical effervescent taste. Each litre of water will have dissolved in it 3.5–5 litre of carbon dioxide. The solubility of CO_2 in water depends on the pressure and temperature.

(c) **Storage of vegetables and food products :** Table shows the storage temperature of a few vegetables and food products and their approximate storage life.

Table: *Storage conditions for food products*

Product	Temperature, °C	Relative humidity, %	Approximate storage life
Mangoes	10	85–90	2–3 weeks
Potatoes	3 to 4.5	85–90	5–8 months
Tomatoes	14 to 21	85–90	2–4 weeks
Bananas	14.5	95	8–10 days for ripening
Fish fresh	0.5 to 1.5	90–96	5–15 days
Butter	– 18 to – 23	80–85	2 months
Pasteurised milk	0.5	–	7 days
Eggs	– 1.5 to – 0.5	80–85	6–9 months
Grapes	– 0.5	85–90	3–6 months

5. The progress in technology has facilitated better living conditions. Therefore, air conditioning is not only provided in auditoriums, hotels, etc. but also during transportation. The comfort air-conditioning systems are fitted in railway wagons and passenger cars.
6. Air conditioning improves the productivity by creating the required ambient conditions. For example:
   (a) While spinning cotton threads to the required quality one would require to maintain RH at more than 90% along with temperature control.
   (b) Printing industries achieve better print quality by maintaining the RH at less than 25% in the printing press.
   (c) Manufacturing industries can improve the life of various cutting tools, slip gauges, etc. by storing these in a tool room having RH less than 30% and temperature of about 20°C.
7. The cryogens (liquid N_2, O_2 and Ar) need to be produced and maintained at temperatures below 100 K and so require refrigeration systems.
8. Liquid nitrogen is used in transport refrigeration systems of ice creams which need to be maintained at temperature below – 25°C.
9. Gases like nitrogen, oxygen and argon are produced in their purest form through cryogenic distillation in cryogenic air separation plants. These gases have widespread applications as enumerated in the following sub-paragraphs:

1.2.1 Applications of Nitrogen

Air is the main source of nitrogen. Nitrogen in its purest form can be economically produced in large scale by cryogenic air separation technology that finds widespread applications.

The quality of nitrogen product required differs significantly from one industry to another. Though electronics industry demands the highest purity of 1 ppm O_2, dust level 1/std ft^3 and moisture level at 0.1 ppm, the purity of 2 to 100 ppm O_2 is sufficient for aluminium, rubber, glass, textile, chemicals and steel industries. The purity of

10 ppm O_2 at a pressure of 300 – 400 bar (30 – 40 MPa) will meet its requirements in petroleum industry. However, the product pressure at POU depends on the specific applications.

Liquid Nitrogen (LIN) is a useful source of cold and finds diverse applications. Some of these applications are mentioned here:

(a) With liquid nitrogen, food can be frozen in a few seconds thus preserving much of its original taste, colour and texture. It is reported that weight losses can be reduced considerably when food is frozen cryogenically rather than by any other means. The purity of LIN from 95–98% is sufficient for freezing the food.

(b) Cryosurgery is a technique that destroys cancer cells by freezing. It has been used in some top medical centres for the treatment of tumors of prostate, liver, lung, breast and brain as well as for cataracts, gynaecological problems and other diseases.

(c) LIN is used for storing biological specimens, especially bull semen for the cattle industry.

(d) In ground freezing, LIN enables tunnelling and excavation operations performed in wet and unstable soils.

(e) In heat treatment of metals, LIN is known to transform metallurgical properties, which improve the wear resistances of carbon tool steels.

(f) The automobile tyres have been one of the most difficult items to recycle or even worse—to discard. Cryogenic provides the necessary technology for the effective recovery, separation, and reuse of all materials used in the tyre. In fact, the use of LIN is the only known way to recover rubber from the steel radial tyre.

(g) Mechanical breakdown of solids into smaller particles is known as grinding. Cryogenic grinding is a method of powdering materials at sub-zero temperatures. The materials are frozen with LIN when they are ground.

NOTE

- Liquid nitrogen is often referred to by abbreviation, LIN or LN2 or LN

1.2.2 Applications of Oxygen

Oxygen was one of the first atmospheric gases liquefied by Cailletet and Pictet in 1877. Later the Polish scientists Olzewski and Wroblewski at Cracow in 1883 produced stable liquid oxygen in a U-tube whose properties could be studied. Henceforth, oxygen began its useful life in industry early in the twentieth century.

(a) A huge quantity of oxygen is consumed in steelmaking industry following LD or BOF process. These processes need 99.5% (conventional standard grade) purity of oxygen to accelerate the oxidation and conversion of iron to steel. The daily consumption amounts to several thousand tonnes, and all the modern steel plants, therefore, have sufficient tonnage oxygen plants.

(b) One of the most common usages of oxygen is in the fabrication and cutting of metals using an oxy-acetylene torch.

(c) Another major use of oxygen is in the field of medicine. The purity of oxygen needed is 99.999%.

(d) Oxygen is used in the preparation of chemicals. For example, the manufacture of ethylene oxide requires 40% oxygen while acetylene consumes almost 20%. Titanium dioxide, propylene oxide and vinyl acetate need 10-15% O_2 for their manufacture.

In glass manufacturing, oxygen is added to enrich the combustion air in glass-melting furnaces. Jet aircraft for high altitude missions are equipped with oxygen systems for breathing purposes. Coal gasification is also one of the large consumers of gaseous oxygen.

1.2.3 Applications of Argon

Usually argon is obtained from air which contains 0.0093% of argon by volume. It is highly inert and finds its applications in a wide range of conditions, both at cryogenic and at high temperatures. Argon is relatively expensive and its use is limited to applications where its highly inert properties are essential.

(a) The largest consumption of argon worldwide is in the argon-oxygen decarburisation process for producing low carbon stainless steels.

(b) MIG welding developed by Airco in the 1940s and TIG welding represent large markets for argon.

(c) The light bulb industry uses argon to fill light bulbs. This gives longer life to the filament because argon does not react, even at high temperatures.

1.3 Refrigeration Systems

Refrigeration systems are grouped into the following three systems:

(i) **Non-cyclic refrigeration systems:** Such system include refrigeration using ice, refrigeration by evaporation, and refrigeration by dry ice. These systems were used before the invention of cyclic refrigeration systems. For example, natural ice was used to preserve flesh during its shipment from one country to another.

(ii) **Cyclic refrigeration systems:** These include the air refrigeration cycle, the vapour compression refrigeration cycle, and the vapour absorption cycle.

(iii) **Other refrigeration systems:** These are thermoelectric refrigeration cycle, steam-jet refrigeration cycle, vortex tube refrigeration system, magnetic refrigeration system, solar refrigeration systems, and so on.

A few of the above systems are discussed in the following sub-sections.

1.3.1 Ice Refrigeration

The quantity of heat required to convert one kg of ice from and at 0°C is 335 kJ. (Latent heat of fusion, h_L = 335 kJ). Therefore, ice can be used to produce cold in a confined chamber, which can be used to store vegetables or food. The mechanism of cooling the vegetables and food products using ice is shown in Fig. (a) and (b).

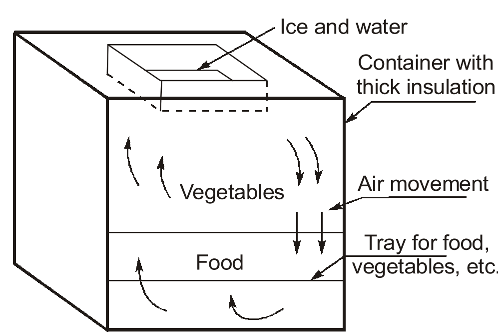


Fig. (a): *Ice refrigeration for food and vegetables storage.*

Ice is kept in a small cabin at the top level of the insulated container. The arrangement is such that air comes in contact with the metallic surface in which ice is kept and gets cooled. Due to this phenomenon, its density increases and it starts moving downwards and the low density air from the low level moves upwards creating convection currents. Therefore, food, vegetables, etc. kept in the trays at different levels are cooled down and are preserved. The cooling of the commodities would continue till ice melts completely. The melted ice water is drained out.

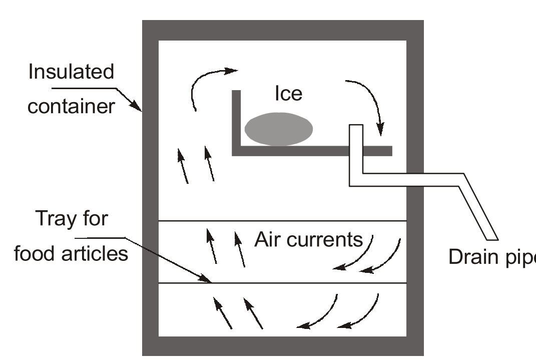


Fig. (b): *Ice refrigeration (cut section)*

Ice is also used to produce refrigeration on a large scale as shown in Fig (c). This system of refrigeration is suitable for transport refrigeration, and for the storage of food and vegetables for a limited period in case one does not want to invest in purchasing a refrigeration system.

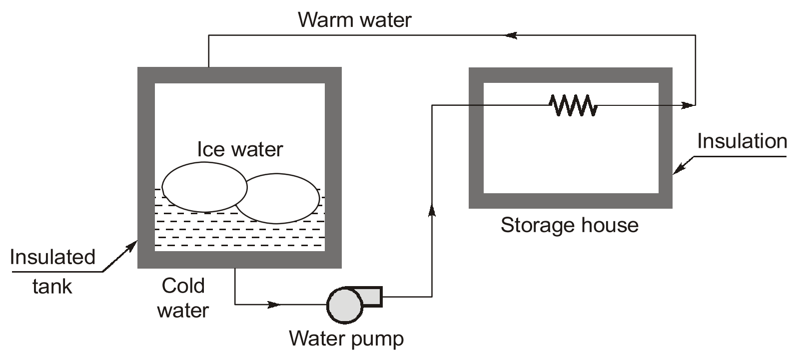


Fig. (c): *Indirect refrigeration system using ice.*

1.3.2 Evaporative Refrigeration

This method of generating cold or refrigeration is very old and used by common people. It can be explained with a simple example of cooling water in a porous pot, shown in figure.

Water in the pot percolates through the porous pot. The air surrounding the pot comes in contact with this water and cools down. This is due to the evaporation of water. The heat required for the evaporation of water is partially from water and air. In turn, both air and water cool down. Since air is free to move, one does not feel the cold air but the cold water in the pot can be felt.

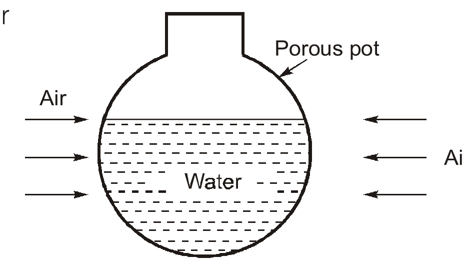


Fig. *Evaporative cooling of water in porous port.*

The temperature of water in the porous pot may be reduced by 5 – 15°C compared to the temperature of ambient air.

Based on this principle, one can answer as to why the flowing water is always cold? Why does one feel cool breeze near lakes and oceans? Human body is kept cold due to evaporative cooling in hot climate conditions as well as during physical exertion. The use of desert bag is another example of evaporative cooling to keep drinking water cold. Evaporative refrigeration phenomenon can also be employed to produce artificial ice. Such a system can be explained with the help of a sketch shown in figure.

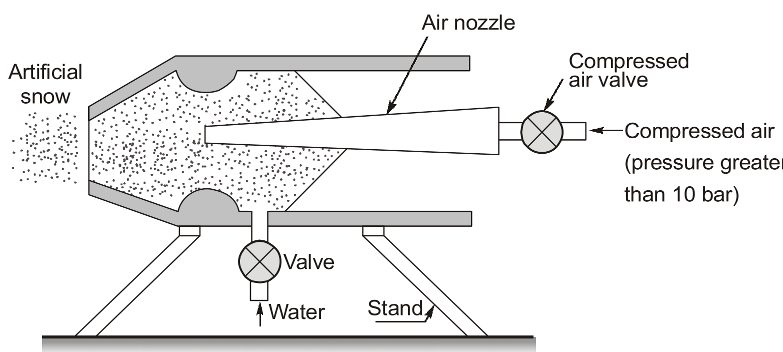


Fig. *Evaporative refrigeration for making artificial ice.*

The arrangement consists of an air expansion nozzle and water supply line. When air is expanded from a pressure of the order of 5 bar and temperature 25°C, to atmospheric pressure (1.0 bar), its temperature would even fall to sub-zero. Therefore, air is expanded from its high pressure to ambient pressure producing cold environment and simultaneously water is supplied in the form of tiny droplets (fog). Since the surrounding air temperature is below sub-zero, the water droplets may condense and freeze forming small particles of ice. In this method, artificial snow is produced when the temperature of the surrounding air is 0°C or below 0°C. Evaporative cooling phenomenon is employed in cooling towers and water-cooled condensers.

1.3.3 Refrigeration by Dry Ice

Solid carbon dioxide is known as 'dry ice'. The critical point of CO_2 is 31°C, whereas its critical pressure is 73.8 bar. To manufacture solid gaseous CO_2, carbon dioxide is compressed to a pressure of about 69 bar and is cooled at constant pressure (69 bar) to a temperature of 28°C at which it condenses to liquid completely. Expansion of liquid CO_2 to 1 bar pressure would result into solid CO_2 (–78.5°C) in a good insulated container.

The specialty of the solid CO_2 is that it sublimates into vapour directly, producing cold. Therefore, it is used to preserve the eye-ball during the eye surgery.

The drawbacks of ice refrigeration system are :

1. There is no working substance that can be utilized to produce a refrigeration effect at the required temperature.
2. The temperature of the refrigerated space cannot be controlled accurately.
3. One has to replenish the ice periodically to produce cold, otherwise it may not be possible to maintain the refrigeration temperature.

1.3.4 Liquid Gas Refrigeration

Liquid nitrogen (boiling point 77 K) boils at atmospheric temperature. It requires about 200 kJ to convert 1 kg liquid into dry vapour. If used, it produces a cooling effect of 200 kJ/kg. Nitrogen is an inert gas so it can be used for producing the refrigeration effect. The cost of liquid nitrogen is very low as it is produced in cryogenic air separation plants. Liquid nitrogen finds its application in providing cooling effect for transporting ice-creams, frozen foods, etc.

The block diagram of a liquid nitrogen cooling arrangement is shown in figure.

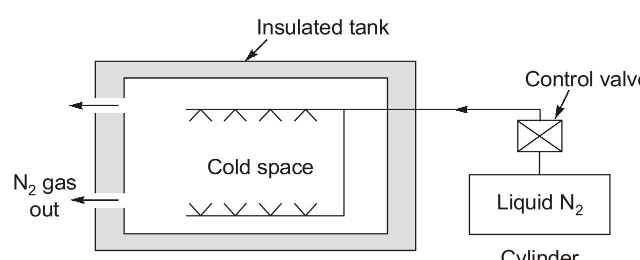


Fig. *Liquid nitrogen cooling*

The control valve of the liquid nitrogen is shown outside the tank but in practice, it may be placed inside the tank. Liquid nitrogen is allowed to flow through the coil of tubes inside the tank and while absorbing heat from the cold space, it evaporates and produces cold.

The temperature inside the tank is sensed by an electronic sensor, which gives feedback to the control valve so that the regulation of liquid nitrogen is possible. The nitrogen gas passes to the atmosphere through the vents provided. Liquid nitrogen cylinders are available in the capacity of 50 litre, 100 litre, and 200 litre commercially.

Another way of producing cold in a refrigerated space is shown in figure.

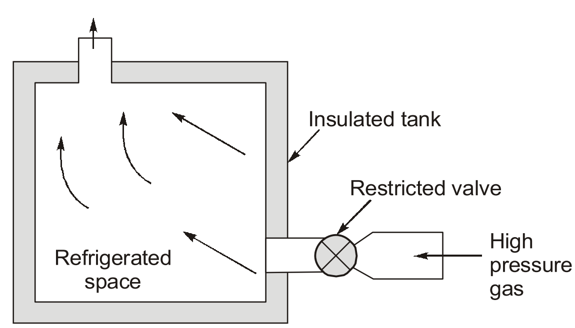


Fig. *Refrigeration by throttling of gas*

1.3.5 Steam Jet Refrigeration

It is a well-known fact that the boiling point of water changes as per the pressure. Water boils at 100°C at 1 atm pressure. It boils at 150°C if the pressure is 4.758 bar, but it boils at 10°C if its pressure is kept at 1.2276 kPa. Such a low pressure (vacuum) on the surface water is maintained by throttling the steam through nozzles.

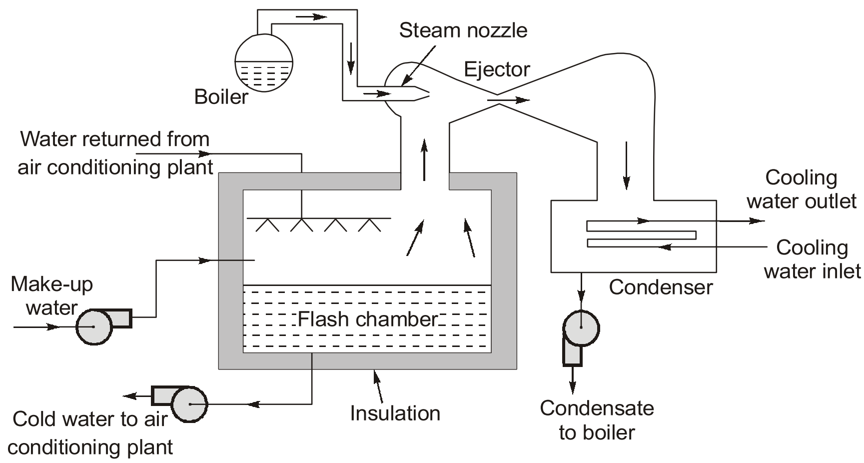


Fig. *Steam jet refrigeration system.*

Suppose a pressure of 5.593 kPa (vacuum) is maintained in a flash chamber which contains 100 kg of water. If 1 kg of water is allowed to flash at such a low pressure, it absorbs heat of about 2394 kJ from the remaining water of 99 kg. The fall in the temperature of water in the chamber is

$$\Delta T = \frac{2394}{(4.186)(99)} = 5.77°\text{C}$$

If 2 kg of water evaporates, then decrease in temperature of the chamber water is

$$= \frac{(2)(2394)}{(4.186)(98)} = 11.67°\text{C}$$

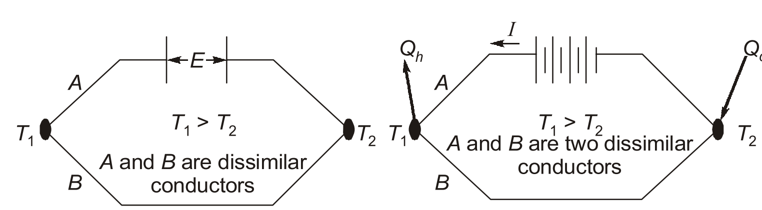
On evaporation of a definite quantity of water, the temperature of the remaining water in the chamber may reach even 0°C. In that case the ice formed is pumped out. Steam from the boiler is expanded through a nozzle (above figure), this helps to keep away the vapour that is formed due to flashing of water in the flash chamber.

The condensate formed flows through the ejector along with the steam into the condenser and the collected condensate is supplied back to the boiler. One would be required to supply the make-up water.

1.3.6 Thermoelectric Refrigeration

It is one of the non-conventional refrigeration methods used for producing low temperature on the basis of the reverse Seebeck effect. When the junctions of two dissimilar conductors are maintained at two different temperatures T_1 and T_2, an electromotive force (emf) E is generated. This phenomenon is called Seebeck effect. This principle is used in thermocouples for measuring temperatures. When a battery is connected between the junctions of two dissimilar conductors which are initially maintained at the same temperature and a current is made to flow through the circuit, it is observed that the junction temperatures are different, one junction becoming hot (T_1) and the other becoming cold (T_2).

This principle is reverse of the Seebeck effect and called Peltier effect. In this case the refrigeration effect is obtained at the cold junction and heat is rejected to the surrounding at the hot junction. This principle is the basis for thermoelectric refrigeration systems.



(b) Peltier effect

Fig. *Principle of thermoelectric refrigeration*

The position of cold and hot junctions can be reversed by reversing the direction of current through the conductor. The principles of Seebeck effect and Peltier effect are illustrated in Fig. (a) and (b), respectively.

The heat transfer rate at each junction is given by

$$Q = \Phi I$$

where Φ is the Peltier coefficient in volts and I is the current in amperes.

1.3.7 Vortex Tube

The vortex tube was invented by a French physicist named Georges J. Ranque in 1931, when he was studying processes in a dust separated cyclone. The vortex tube, also known as the Ranque-Hilsch vortex tube, is a mechanical device that separates a compressed gas into hot and cold streams. It has no moving parts. It is one of the non-conventional types of refrigerating systems for the production of refrigeration. The schematic diagram of the vortex tube is shown in figure. It consists of a nozzle, a diaphragm, a valve, a hot-air side, and a cold-air side. The nozzle is of converging or diverging type or of converging-diverging type as per the design. An efficient nozzle is the one, which is designed to have higher velocity, greater mass flow and minimum inlet losses. The chamber is a portion of the nozzle and provides facility for the tangential entry of high velocity air-stream into the hot side.

Generally the chambers are not of circular form, but of the gradually converted spiral form. The hot-side is cylindrical in cross section and is of different lengths as per design. A throttle valve obstructs the flow of air through the hot-side and it also controls the quantity of hot air passing through the vortex tube. The diaphragm is a cylindrical piece of small thickness and has a small hole of specific diameter at its centre. The air stream travelling through the core of the hot-side is emitted through the diaphragm hole. The cold-side is a cylindrical portion through which the cold air passes.

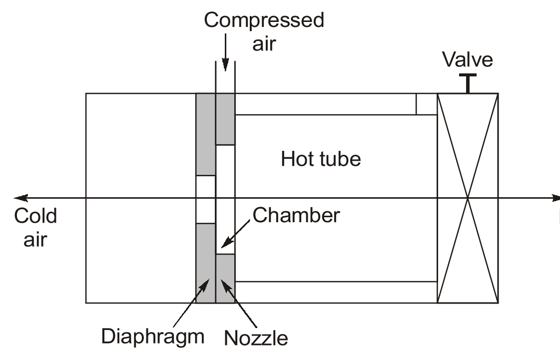


Fig. *Vortex Tube*

In this vortex tube, compressed air is passed through the nozzle as shown in the figure. Air expands and acquires a high velocity due to the particular shape of the nozzle. A vortex flow is created in the chamber and air travels in a spiral like motion along the periphery of the hot-side. This flow is restricted by the valve. When the pressure of the air near the valve is made more than the outside pressure by partly closing the valve, a reversed axial flow through the core of the hot-side starts from the high-pressure region to the low-pressure region.

During this process, heat transfer takes place between the reversed stream and the forward stream. Therefore, the air stream through the core gets cooled below the inlet temperature of the air in the vortex tube, while the air stream in the forward direction gets heated up. The cold stream escapes through the diaphragm hole into the cold-side, while the hot stream is passed through the opening of the valve. By controlling the opening of the valve, the quantity of the cold air and its temperature can be varied. The vortex tube has the following advantages:

- It uses air as refrigerant, so there is no leakage problem.
- It is simple in design and does not require any control system to operate it.
- There are no moving parts in the vortex tube.
- It is light in weight and occupies much less space.
- The initial cost is low and its working expenses are also less, whereas compressed air is readily available.
- Maintenance is simple and no skilled labour is required.

On the disadvantage side, the vortex tube has low COP, limited capacity and only a small portion of the compressed air appearing as the cold air limits its wide use in practice.

1.4 Refrigerating Machines and Second Law of Thermodynamics

A refrigerating machine is a mechanical device that fulfills the purpose of refrigeration i.e. maintains a temperature below that of surroundings. This requires heat to be transferred from a low temperature refrigerated space to high temperature surroundings.

But according to interpretation of Clausius statement of second law of thermodynamics, the above process is not possible on its own. For such heat transfer external work is to be supplied.

Clausius statement of Second Law

It is impossible to construct a device which will operate in cycle and produce no effect other than transfer of heat from a low temperature body to high temperature body.

Hence all the refrigerating machines are work consuming devices.

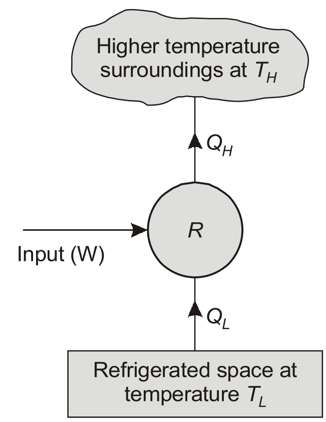


Fig. *Schematic diagram of a Refrigerator (Refrigerating Machine)*

1.4.1 Refrigerating Effect

It is the amount of heat that is required to be extracted from storage space in order to maintain a temperature less than surroundings.

In figure representing a schematic diagram of refrigerator (refrigerating machine), Q_L i.e. extracted heat is the refrigeration effect.

1.4.1.1 Refrigeration Load

The cooling load on refrigerating equipment results from several different sources. Some of the common sources of heat that contribute to the cooling load on the refrigerating equipment are as follows:

1. Ingress of heat into the refrigerated space from outside by conduction through the insulated walls.
2 Solar radiations that enter the refrigerated space through transparent glass or other transparent materials.
3. Heat on account of warm outside air entering the refrigerated space through open doors or through cracks around windows and doors.
4. Heat emitted by warm products whose temperature is to be lowered to the refrigerated space temperature.
5. Heat emitted by people occupying the refrigerated space. For example, people present in an air-conditioned space or the people working in the cold storages during loading and unloading the goods.
6. Heat emitted by any heat generating equipment installed in the refrigerated space such as lamps, motors, electronic devices, etc.

It is to be noted here that all these sources of heat are not present in every application. The significance of any one heat source with relation to the total cooling load will vary considerably with each application.

1.4.1.2 Heating Load

In those regions where the atmospheric temperature falls considerably (below 10°C), especially during winters, heating is needed to keep the rooms warm. The rate of heat to be supplied to such a conditioned space is known as heating load. In Western countries, the houses are facilitated with solar heating systems.

1.4.2 Unit of Refrigeration

Standard Refrigeration unit is 'ton of refrigeration' or simply 'ton' represented by 'TR'.

1TR is defined as heat required to be extracted from one US tonne (2000 pounds) of water at 0°C (32°F) to form ice at 0°C (32°F) in one day (24 hours).

$$1\text{TR} = \frac{0.454 \times 2000 \times 334}{24 \times 60 \times 60} = 3.51 \text{ kJ/s} \approx 3.5 \text{ kW} = 210 \text{ kJ/min}$$

[1 pound = 0.454 kg, latent head of fusion of ice = 334 kJ/kg (at 0°C)]

1.4.3 Concept of Heat Engine, Refrigerator and Heat Pump

It is a well-known fact that heat flows in the direction of decreasing temperature, i.e. from a high temperature body to a low temperature body. Such heat transfer occurs in nature without any external aid or device.

(i) Heat Engine:

It is a prime mover that generates heat from the fossil fuel. It works according to the second law of thermodynamics stated by Kelvin and Planck–It is impossible to construct a device that operates continuously in a cycle and produces no effect other than the withdrawal of heat energy from a single reservoir and converts all the heat into useful work. This means that the heat engine (HE) rejects part of the heat available from the heat source while converting it to useful work. This is shown in Fig. (a). It takes heat at the rate of Q_1 from the heat source and generates the work at the rate of W while rejecting heat at the rate of Q_2 to the heat sink. The performance of a heat engine is known as 'thermal efficiency' or 'Carnot efficiency' and is mathematically represented as

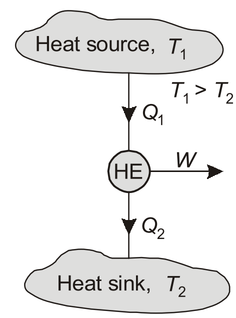


Fig. (a) *Heat engine*

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

(ii) Refrigerator:

As discussed refrigerators are cyclic devices having working substances called refrigerants used in refrigeration cycles. The working principle of the refrigerator (R) is shown in Fig. (b).

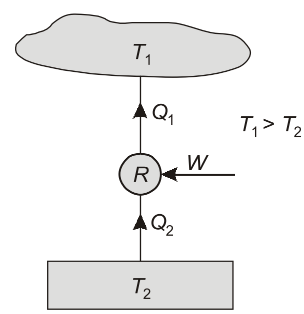


Fig. (b) *Refrigerator*

(iii) Heat Pump:

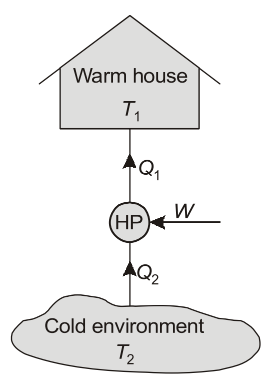


Fig. (c): *Heat pump*

A heat pump (HP) transfers heat from a low temperature space to a higher temperature space. The objective of a heat pump is to supply heat Q_1 to warm a space as shown in Fig. (c).

1.4.4 Coefficient of Performance (COP)

Coefficient of performance is defined as the ratio of desired output to the work input.

i.e.
$$\text{COP} = \frac{\text{Desired effect}}{\text{Work input}}$$

$$\text{COP of refrigerator} = \frac{\text{Amount of heat extracted from cooled space}}{\text{Work input}} = \frac{Q_L}{W}$$

NOTE

- From 1st law of thermodynamics, $W = Q_H - Q_L$. This can be substituted to find out COP_{HP} or COP_R, where Q_H = heat exchanged at higher temperature T_H and Q_L = heat exchanged at lower temperature T_L.
- COP_{HP} varies from 1 to ∞, and COP_R varies from 0 to ∞.
- For a reversible refrigerator or heat pump, $\frac{Q_H}{Q_L} = \frac{T_H}{T_L}$
- Using this equation, $COP_{rev\ HP} = \frac{T_H}{T_L - T_L}$ and $COP_{rev.R} = \frac{T_L}{T_H - T_L}$
- T_H and T_L to be used in kelvin only.

1.4.5 Heat Pump v/s Refrigerator

As a refrigerator maintains a space colder than atmospheric i.e. a lower temperature than ambient, heat pump is a mechanical device used to maintain a hotter space i.e. a temperature higher than ambient. The main difference is the operating temperature.

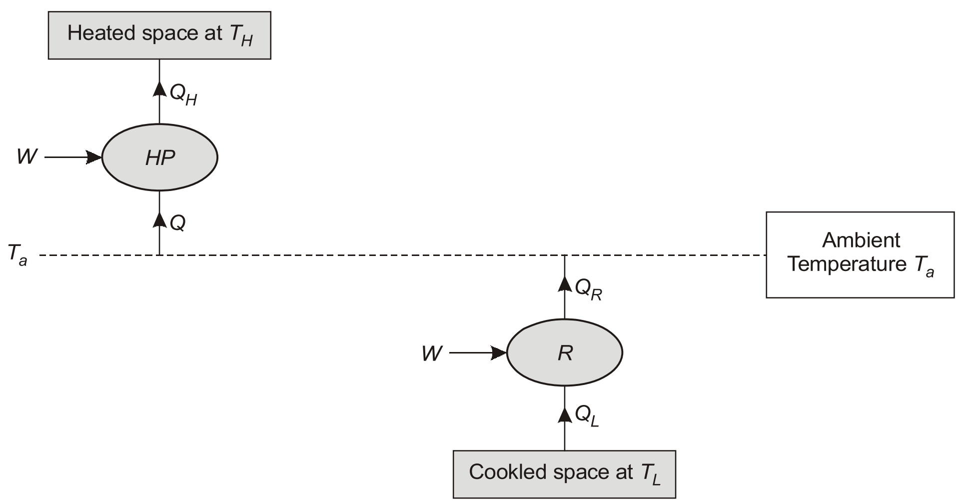


Fig. *Schematic illustration showing the working temperature of Heat Pump and Refrigerator*

1.4.5.1 Relations between COP of heat pump & refrigerator working under same temperature limits.

Consider a heat pump and refrigerator working under same temperature limits.

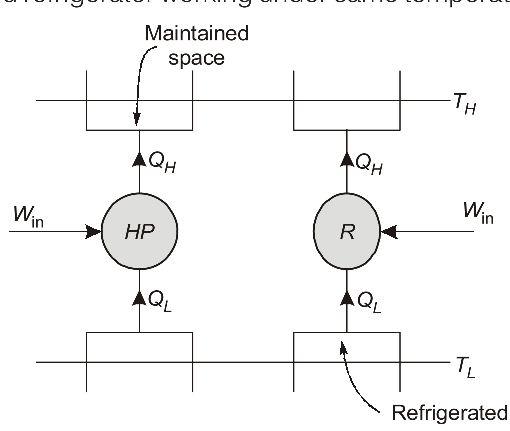


Fig. *Refrigerator and heat pump working between same temperature limits*

$$\text{COP of refrigerator, } COP_R = \frac{Q_L}{W}$$

$$\text{COP of Heat pump, } COP_{HP} = \frac{Q_H}{W} = \frac{Q_L + W}{W} \qquad \text{(From energy balance } Q_H = Q_L + W\text{)}$$

$$COP_{HP} = 1 + \frac{Q_L}{W}$$

$$COP_{HP} = 1 + COP_R$$

This relation is applicable only between same temperature limits.

1.4.6 Heat pump v/s Electric Resistance heater

In previous section we had derived a relationship between COP of heat pump and COP of refrigerator.

$$COP_{HP} = 1 + COP_{refrigerator}$$

This is a very significant relationship which states that COP of heat pump is always greater than one.

For purpose of heating it is more economical to use heat pump rather than electric resistance heaters. Electric resistance heaters have a COP of unity while heat pumps will always have COP greater than one. Hence for same work input, heat pump will supply higher heat to the heated space than electric resistance heaters.

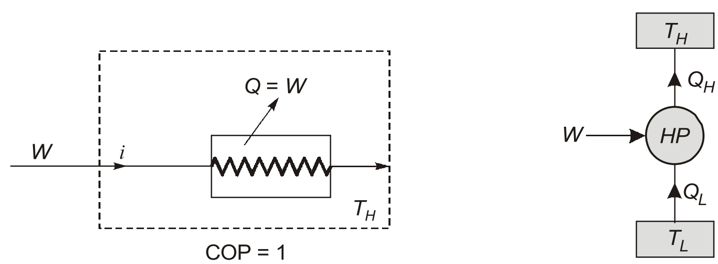


Fig. *Heat pump and electrical resistance heater*

$$Q_H = W + Q_L$$

Hence, $Q_H > W$

$$COP > 1$$

A heat pump (HP) transfers heat from a low temperature space to a higher temperature space. The objective of a heat pump is to supply heat Q_H to warm a space as shown in figure.

1.5 Reversed Carnot Cycle : Best Refrigeration Cycle

It is possible to show that reversed Carnot cycle is the best refrigeration cycle which requires minimum work for same refrigeration effect working between same temperature limits. i.e. COP of reversible carnot refrigerating machine is always greater than other machines working between same temperature limits.

To prove this, let us on contrary assume that irreversible machine is having higher COP than reversible Carnot machine.

$$(COP)_I > (COP)_R$$

$$\frac{Q}{W_I} > \frac{Q}{W_R}$$

$$W_R > W_I$$

Since, $Q_H = W_R + Q$

and $Q'_H = W_I + Q$

$\Rightarrow$ $Q_H > Q'_H$

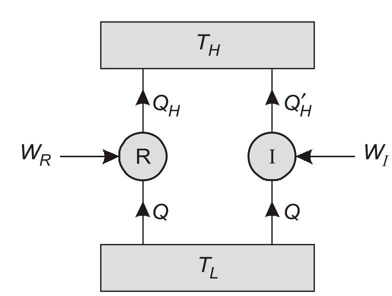


Fig.

Now reversing the direction of reversible Carnot machine.

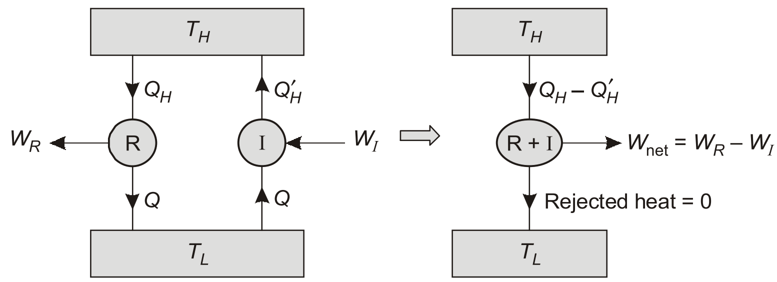


Fig.

The resultant combination of reversed Carnot refrigerator and irreversible refrigerator is leading to violation of Kelvin-Plank's statement of second law of thermodynamics i.e. work is developed in cycle exchanging heat only with one thermal reservoir.

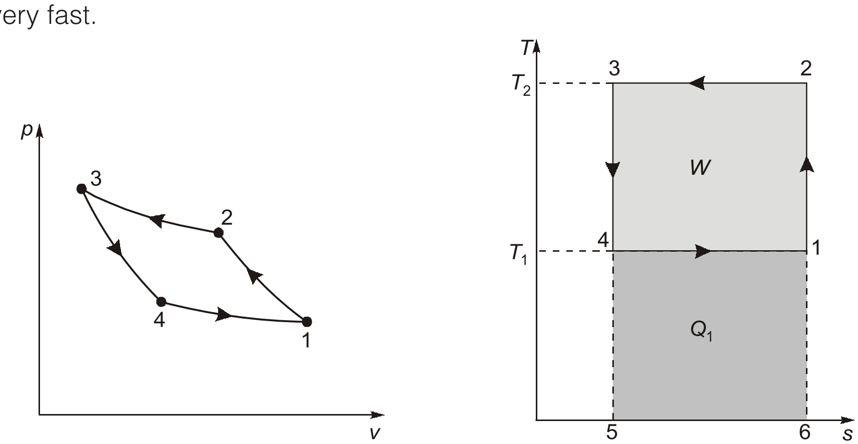
This is due to our wrong assumption that irreversible refrigerator is having higher COP than reversible Carnot refrigerator.

Hence reversible Carnot refrigerator has highest COP working between same temperature limits than any other refrigerating machine or Carnot cycle is the best refrigerating cycle.

1.5.1 Carnot Refrigerator

The following processes are imagined to take place in a reciprocating compressor:

Process (1-2) reversible adiabatic compression process: Air is compressed from initial pressure p_1 to pressure p_2 till the temperature rises from T_1 to T_2 in a reversible adiabatic compression process. The piston is assumed to move very fast.



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

Fig. *Reversed Carnot cycle*

Process (2-3) isothermal compression process: Air is compressed isothermally till its pressure rises from p_2 to p_3. It is assumed that at point 2, a body at temperature T_2 is brought in contact with cylinder. Heat Q_2 is rejected at constant temperature T_2 during isothermal compression. The piston is assumed to move at dead slow speed.

Process (3-4) reversible adiabatic expansion process: Reversible adiabatic expansion of air takes place till its pressure and volume change from p_3 and v_3 to p_4 and v_4 during which the temperature falls to T_4. The piston is assumed to move at a fast speed.

Process (4-1) isothermal expansion process: Air from p_4 and v_4 expands isothermally till the pressure and volume reach p_1 and v_1. It is assumed that when a cold body at temperature T_1 is brought in contact with the

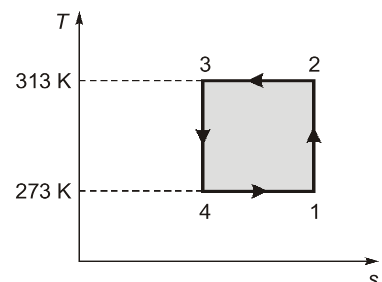
(iii) During the reversible adiabatic compression process (1-2), the piston is supposed to move very fast and for the isothermal compression process, the piston has to move at a very slow speed. It means that the piston has to move at very high speed in the first part of its compression stroke and for the remaining part of the stroke, it has to move at very slow speed, which are both practically impossible situations.

1.6 Actual Refrigeration Systems

Reversed Carnot cycle, even though being the best theoretical cycle, having highest COP for same temperature limits has practical limitations.

The practical conventional refrigeration system is **Vapour Compression Refrigeration System (VCRS)** which has highest COP amongst all practical systems. In air-crafts, air-refrigeration systems are used based on reversed Brayton cycle (Bell-Colemann cycle). Another practical system is **Vapour Absorption Refrigeration System (VARS)** which is heat operated and is less used.

Example 1.1 The overall pressure ratio of a reversed Carnot cycle working with air as a refrigerant is 7. The temperature limits of the cycle are 40°C and 0°C. Determine: (i) the pressure and temperature at each point of the cycle, (ii) the work done in the cycle, (iii) the refrigerating effect, and (iv) COP of the cycle.



Solution:

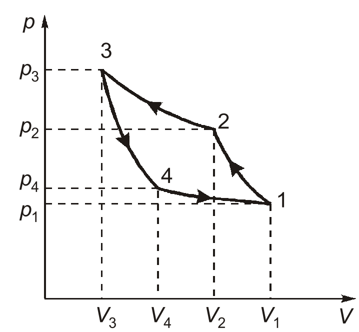
(i) Working temperature $T_L = 0 + 273 = 273$ K

$T_H = 40 + 273 = 313$ K

Overall pressure ratio = 7

Air as refrigerant

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{313}{273}\right)^{\frac{1.4}{1.4-1}} = 1.61 \quad ...(1)$$



Assuming, p_1 to be atmospheric i.e. 1.01325 bar

$\therefore \quad p_2 = 1.61p_1 = 1.01325$ bar

Also overall pressure ratio = 7

i.e. $$\frac{p_3}{p_1} = 7 \quad ...(2)$$

$p_3 = 7.09$ bar

Dividing Eq. (2) by Eq. (1), we get,

$$\frac{p_3}{p_2} = 4.3$$

$$\frac{p_3}{p_4} = \left(\frac{T_3}{T_4}\right)^{\frac{\gamma}{\gamma-1}} = 1.61$$

$$\therefore \quad p_4 = \frac{7.09}{1.61} = 4.4 \text{ bar}$$

Point as in figure	Pressure (bar)	Temperature (K)
1	1.01325	273
2	1.63	313
3	7.09	313
4	4.4	273

(ii) Work done in cycle $= W_{1-2} + W_{2-3} + W_{3-4} + W_{4-1}$

$$= \frac{R(T_1 - T_2)}{\gamma - 1} + RT_2 \ln\left(\frac{p_2}{p_3}\right) + \frac{R(T_3 - T_4)}{\gamma - 1} + RT_4 \ln\left(\frac{p_4}{p_1}\right)$$

Since $T_1 = T_4$

and $T_2 = T_3$

$$T_1 - T_2 = T_4 - T_3$$

$$(T_1 - T_2) + (T_3 - T_4) = 0$$

Therefore, $\frac{R(T_1 - T_2)}{\gamma - 1} + \frac{R(T_3 - T_4)}{\gamma - 1} = 0$

$\therefore$

$$W = RT_2 \ln\left(\frac{p_2}{p_3}\right) + RT_4 \ln\left(\frac{p_4}{p_1}\right)$$

$$= 0.287 \times 313 \times \ln\left(\frac{1.63}{7.09}\right) + 0.287 \times 273 \times \ln\left(\frac{4.4}{1.01325}\right)$$

$$= -17 \text{ kJ/kg}$$

Negative sign indicates that work is absorbed in cycle.

(iii) Refrigerating effect $= Q_{4\text{-}1}$

From 1st law of thermodynamics

$$Q_{4\text{-}1} = c_v(T_1 - T_4) + W_{4\text{-}1}$$

$$= 0 + RT_4 \ln\left(\frac{p_4}{p_1}\right) = 0.287 \times 273 \times \ln(4.34) = 115 \text{ kJ/kg}$$

Alternative:

(i)

$$\Delta s = s_2 - s_3 = s_1 - s_4$$

$$\Delta s = c_p \ln\left(\frac{T_1}{T_4}\right) - R \ln\left(\frac{P_1}{P_4}\right) = 1.005 \ln\left(\frac{273}{273}\right) - 0.287 \ln\left(\frac{1.01325}{4.4}\right)$$

$$= 0.421 \text{ kJ/kgK}$$

(ii) Work done = Area enclosed by cycle

$$= (T_H - T_L)\Delta s = 40 \times 0.421 = 16.84 \text{ kJ/kg}$$

(iii) Refrigerating effect $= T_L(\Delta s) = 273 \times 0.421 = 114.93$ kJ/kg

(iv) Coefficient of performance,

$$\text{COP} = \frac{\text{Refrigerating effect}}{\text{Work supplied}} = \frac{115}{17} = 6.764$$

Also, COP of reversed Carnot cycle as refrigerator

$$= \frac{T_L}{T_H - T_L} = \frac{273}{40} = 6.8$$

Example 1.2 A refrigerating machine has to maintain a temperature of – 5°C, operating in ambient of 45°C. If the capacity of refrigerator is 1/6 TR and actual COP is 0.75 times the ideal COP. Find (i) Power input to the machine, (ii) Heat rejected to ambient. Assume that a temperature difference of 3°C is required for heat transfer.

Solution:

Given: Ambient temperature = 45°C, Maintained temperature = – 5°C