18PHC304-THERMAL AND STATISTICAL PHYSICS

UNIT-III : LOW TEMPERATURE

Joule-Thomson's effect - Porous plug experiment - Liquefaction of gases (air, H_2 and He) Adiabatic expansion process - Adiabatic demagnetization - Practical application of low temperature - Refrigerating machanism - Electrolux refrigerator - Air Conditioning machine.

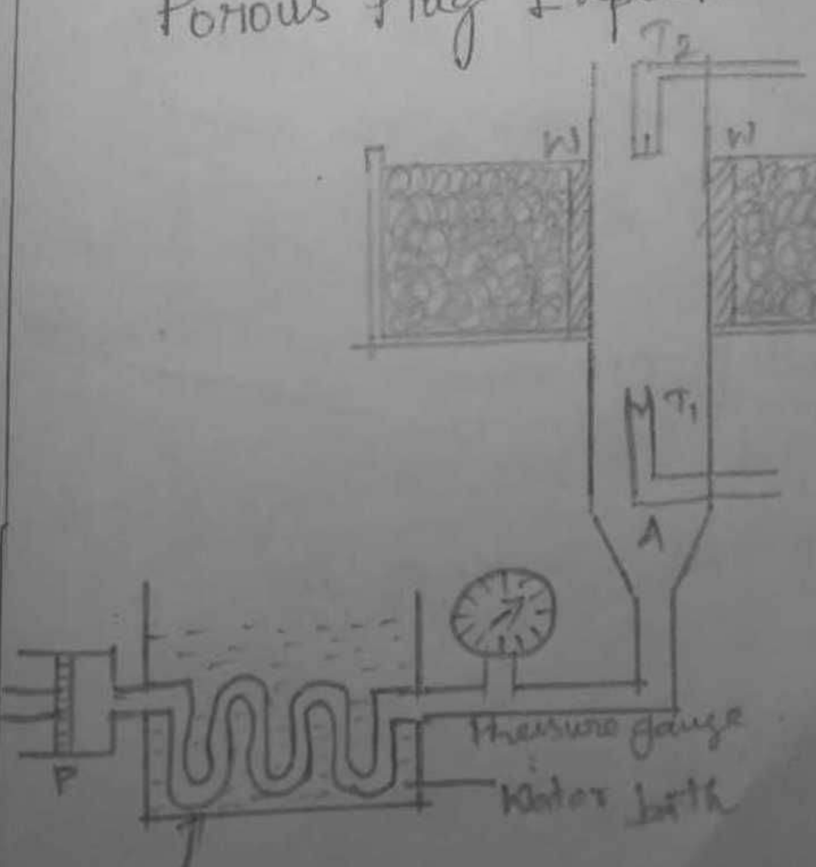
Joule - Thomson Effect:

When a gas under a constant high pressure passes adiabatically through a porous plug to a region of constant low pressure, its temperature changes. This effect is called 'Joule Thomson effect' or Joule Kelvin effect.

The change in temperature of the gas depends upon the nature of the gas and the initial temp.

At ordinary temp. all gases except hydrogen and helium, exhibit a cooling effect.

Porous Plug Experiment:



The porous plug (G) consists of a porous material like silk or cotton wool kept in position by two perforated brass disc.

The plug is enclosed in a box-wood tube W. The tube W is surrounded by a vessel I containing cotton wool.

This is done to avoid loss or gain of heat from the surroundings.

The experimental gas is compressed to the required high pressure.

The heat of compression is removed by passing the gas through a spiral tube S immersed in a constant temperature water bath.

The compressed gas is then passed through the porous plug.

The gas gets throttled due to cotton wool.

Work is done by the gas in overcoming intermolecular attraction.

The temperatures of the incoming and outgoing gas are measured by the ~~pressure gauge~~. ~~The pressure~~ platinum resistance thermometers T_1 and T_2.

The pressure of the incoming gas is measured by the pressure gauge.

The pressure of the outgoing gas is equal to the atmospheric pressure.

The behaviour of a large no. of gases was studied over different ranges of initial temperatures.

The following results were obtained by Joule Kelvin.

1. All gases show a change in temperature on passing through the porous plug.

At ordinary temps, all gases except hydrogen and helium show a cooling effect.

Hydrogen and helium show a heating effect at room temp.

However at sufficiently low temp. all gases show a cooling effect.

2. The fall in temp. is directly proportional to the difference of pressure on the two sides of the porous plug.

3. The fall in temp. per atmosphere difference of pressure decreases as the initial temp. of the gas increases.

4. The fall in temp. becomes zero at a particular temp. called the temperature of inversion (T_i).

At temps. above the temp. of inversion, the gases show heating effect. The temp. of inversion is different for different gases.

The important conclusion of the experiment is,

Any gas below its temperature of inversion will cool on suffering Joule-Thomson expansion.

Theory of Porous Plug Experiment:

The arrangement of the porous plug experiment is shown in Fig. The gas passes through the porous plug from the high pressure side to the low pressure side.

Consider one mole of the gas. Let P_1, V_1 and P_2, V_2 represent the pressure and volume on the two sides of the porous plug.

Let dx be the distance through which each piston moves to the right.

The work done on the gas by the piston $A = P_1 A_1 \; dx = P_1 V_1$

The workdone by the gas on the piston $B = P_2 A_2 \; dx = P_2 V_2$

$\therefore$ Net external work done by the gas $= P_2 V_2 - P_1 V_1$ — (1)

Let w be the work done by the gas in separating the molecules against their inter-molecular attraction

Total amount of workdone by the gas $= (P_2 V_2 - P_1 V_1) + w$ — (2)

There are three cases depending upon the initial temp. of gas.

(i) Below the Boyle temp. $P_1 V_1 = P_2 V_2$

$$P_2 V_2 - P_1 V_1 = 0$$

The total work done by the gas in this case is w.

$\therefore$ cooling effect at this temp is only due to the work done by the gas in overcoming inter-molecular attractions

(i) Below the Boyle temp. $P_1V_1 < P_2V_2$.

$P_2V_2 - P_1V_1$ is +ve. w must be either positive or zero.

Thus a net +ve work is done by the gas.

Hence there must be a cooling effect.

(ii) At the Boyle temp. $P_1V_1 = P_2V_2$

$\therefore \quad P_2V_2 - P_1V_1 = 0$

The total work done by the gas in this case is w. Therefore, cooling effect at this temp is only due to the work done by the gas in over-coming inter-molecular attractions.

(iii) Above the Boyle temp. $P_1V_1 > P_2V_2$.

$P_2V_2 - P_1V_1$ is $-$ve.

Thus, the observed effect will depend upon whether $(P_2V_2 - P_1V_1)$ is greater or less than w.

If $w > (P_1V_1 - P_2V_2)$, cooling will be observed.

If $w < (P_1V_1 - P_2V_2)$, heating will be observed

Thus, the cooling or heating of a gas depends on

(i) The deviation from Boyle's law, and

(ii) Work done in overcoming inter-molecular attractions

Define: Temperature of inversion:

The temp. at which the Joule-Thomson effect changes sign (i.e., the cooling effect becomes the heating effect) is called the temp of inversion (T_i)

At this temp (T_i) there is neither heating or cooling.

Relation between temp. of inversion (T_i) and critical temp (T_c).

Let T_c be the critical temp of a gas. Then, its temp. of inversion $T_i = 6.75\ T_c$. Thus the temp. of inversion of a gas is much higher than its critical temp.

Liquefaction of Gases:

A gas goes into liquid and solid forms as the temp. is reduced. Thus the processes of liquefaction of gases and solidification of liquids are intimately involved in the production of low temperatures.

Joule-Thomson expansion is a very important technique to liquefy gases. The cooling produced in J-T expansion of a gas depends on the difference of pressure on the two sides of the porous plug and the initial temp. For most of the gases, the J-T cooling is very small. However, the cooling effect can be intensified by employing the process called regenerative cooling.

Liquefaction of Air - Linde's process:

Linde liquefied air using Joule-Thomson effect and the principle of regenerative cooling.

Air is compressed to a pressure of about 25 atmospheres by the pump P_1.

It is then cooled by passing it through the cold water bath.

This compressed air is passed through KOH solution to remove CO_2 and water vapour.

The air then enters the second pump P_2. Here it is compressed to a pressure of about 200 atmospheres.

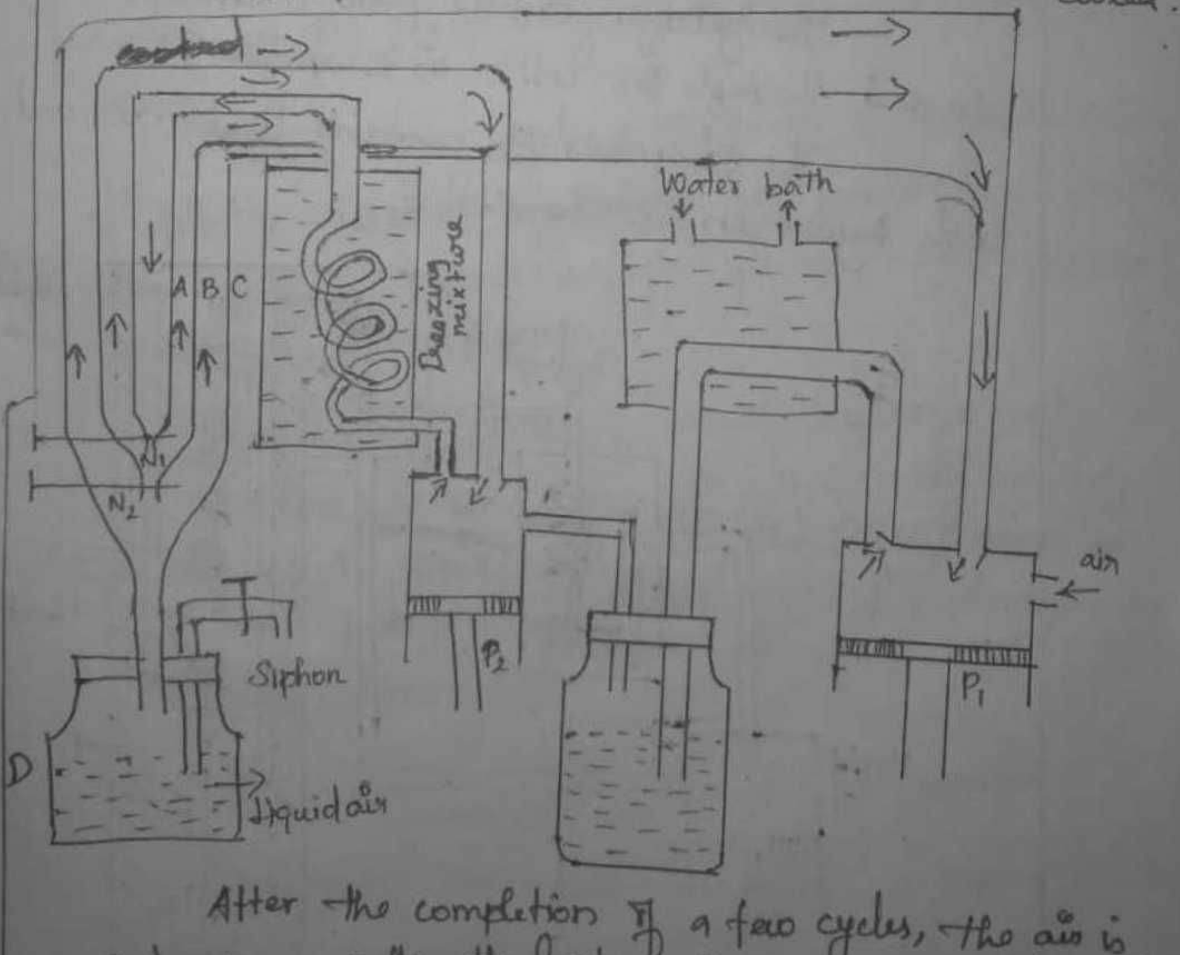
The compressed air next passes through a cooling spiral immersed in a freezing mixture, where its temp. falls to about $-20^{\circ}C$.

This cooled air at high pressure passes down through the tube A and is allowed to come out of the nozzle N_1.

The temp. falls to about $-70^{\circ}C$. This cooled air flows upwards through the tube B, cools the incoming air through A and returns to P_2.

The pump P_2 again compresses the air to 200 atmospheres. and puts it into circulation one more.

It passes through the nozzle N_1 and is further cooled.



After the completion of a few cycles, the air is cooled to a sufficiently low temp. At this stage, the second nozzle N_2 is opened. The already much cooled air is allowed to expand to a pressure of one atmosphere when it is liquefied. The liquid air is collected in a Dewar flask D. The unliquefied air is led back through the tube C to the pump P_1 and the process is repeated. The entire arrangement is packed in cotton wool to avoid any conduction or radiation

Liquefaction of Hydrogen:

Temperature of inversion for hydrogen is -80°C. But for practical purposes, it has to be pre-cooled to -177°C to obtain appreciable cooling due to J-T effect. The entire apparatus, is enclosed in an outer Dewar flask 1 for complete insulation.

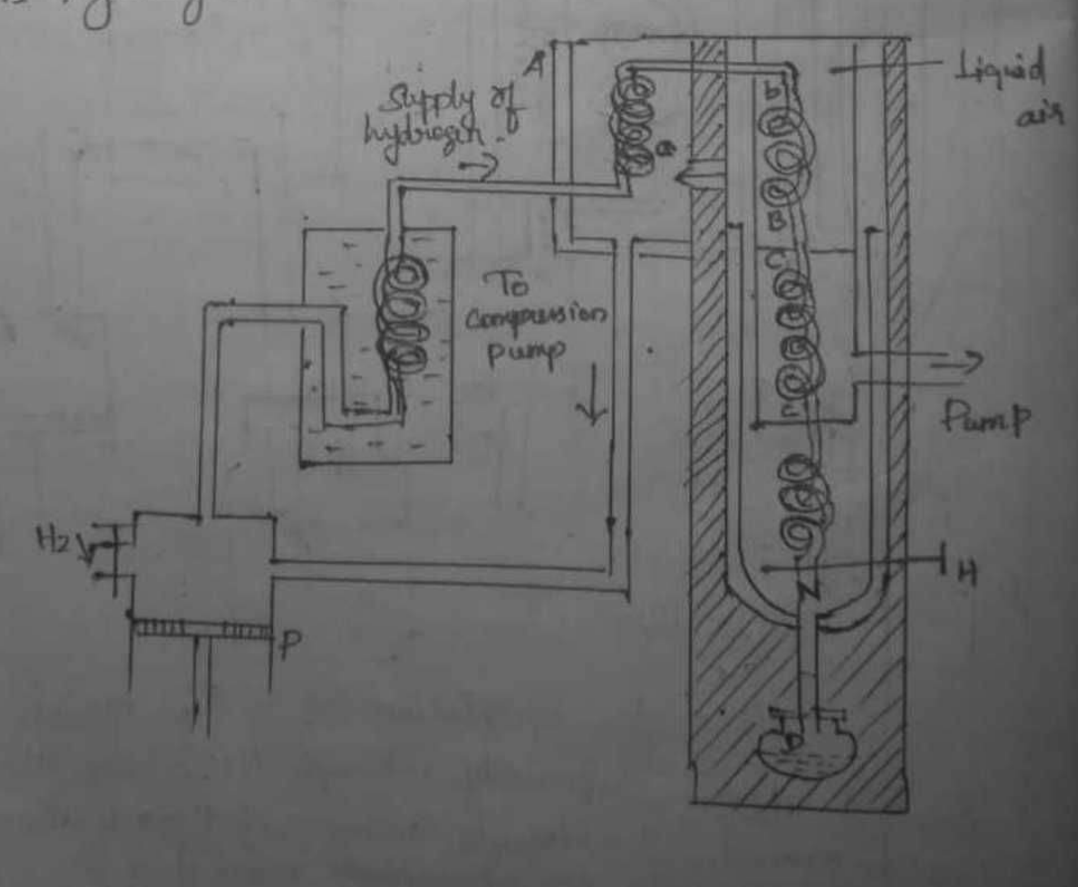
Hydrogen is compressed to a pressure of about 200 atmospheres by the pump P.

Then it is passed through a coil immersed in solid CO_2 and alcohol.

It enters the coil a in the chamber A where it is further cooled by the outgoing hydrogen.

The hydrogen coming from chamber A is passed through the coil b in chamber B.

The chamber B contains liquid air and cools hydrogen in the coil b.



This hydrogen is then passed through coil c in the chamber C.

In Chamber C, liquid air is allowed to boil under reduced pressure.

Hence in this chamber hydrogen is cooled to a temp. of $-200^{\circ}C$. After the pre-coding, the hydrogen passes through the coil D.

It suffers throttle expansion at the nozzle valve N which is operated by the handle H.

Hence hydrogen is cooled further due to J-T effect. The cooled hydrogen passes up through the chambers C, A and B, cooling the gas coming through the coils in those chambers.

Thus the incoming gas from the compressor is cooled by the gas flowing up the chambers after expansion.

After a few cycles, the temp. of the gas reaching N falls to $-250^{\circ}C$. Hydrogen gas under these condition suffering J-T expansion is liquefied and collected in the Dewar flask D.

The boiling point of liquid hydrogen at atmospheric pressure is $-252.8^{\circ}C$. By making it boil at a lower pressure, the liquid can be made to freeze into a solid. Solid hydrogen is white in colour.

Liquefaction of helium :

Helium was the last gas to be liquefied because of its extremly low critical temp ($T_c = 5.25k$). The temp. of inversion (T_i) for helium is 33 k.

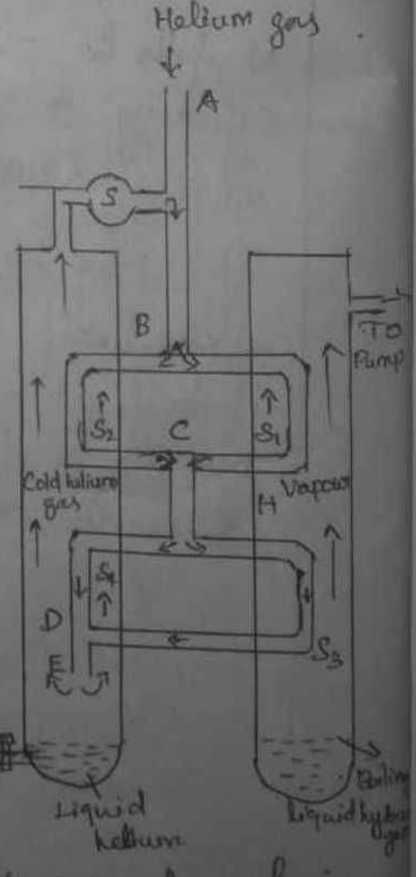
Helium gas at a pressure of about 36 atmospheres enters a tube at A. It is divided into two portions at B. Helium passing through the spiral S_1 is cooled because it is surrounded by hydrogen boiling under reduced pressure.

The other portion of the helium gas passing through the spiral S_2 is cooled due to outgoing cooled helium gas.

The two portions reunite at C, and then, again split into two portions. As in the previous case, cooling takes place in the spirals S_3 and S_4.

The two portion reunite at D. Then the gas suffers J-T expansion at the nozzle E and undergoes further cooling.

The cooled helium gas thereupon rises up and further cools down the incoming gas through the spirals S_2 and S_4. The rising gas is compressed at S. It is again made to pass through the spirals. After a few such cycles when the temp. of helium is sufficiently low, it gets liquefied on suffering J-T expansion at E. Liquid helium is collected in the Dewar flask.



Solid helium was obtained by Keesom by applying an external pressure at 4 k to liquid helium.

Adiabatic Dimagnetisation:

Principle:

When a paramagnetic substance is magnetised, external work is done on it and its temp rises. When the substance is demagnetised, work is done by the substance. Hence, if the substance is demagnetised adiabatically, its temp. falls. This is called magneto-caloric effect.

Curie's law: According to Curie law, the paramagnetic susceptibility χ of a substance is inversely proportional to the absolute temp. T, i.e.,

$$\chi \propto \frac{1}{T}$$

or $$\chi = \frac{C}{T}.$$

Here, C is a constant.

Thus, the susceptibility of a paramagnetic substance is higher, the lower the temp is.

Hence, a paramagnetic substance is powerfully magnetized at very low-temp. When this substance is adiabatically demagnetized, a large cooling is produced.

Giauque's method.

The paramagnetic salt (gadolinium sulphate) is suspended inside a glass bulb B. Bulb B is surrounded by Dewar flasks D_1 and D_2 containing liquid helium and liquid hydrogen respectively.

The whole arrangement is placed between the poles of a strong electromagnet.

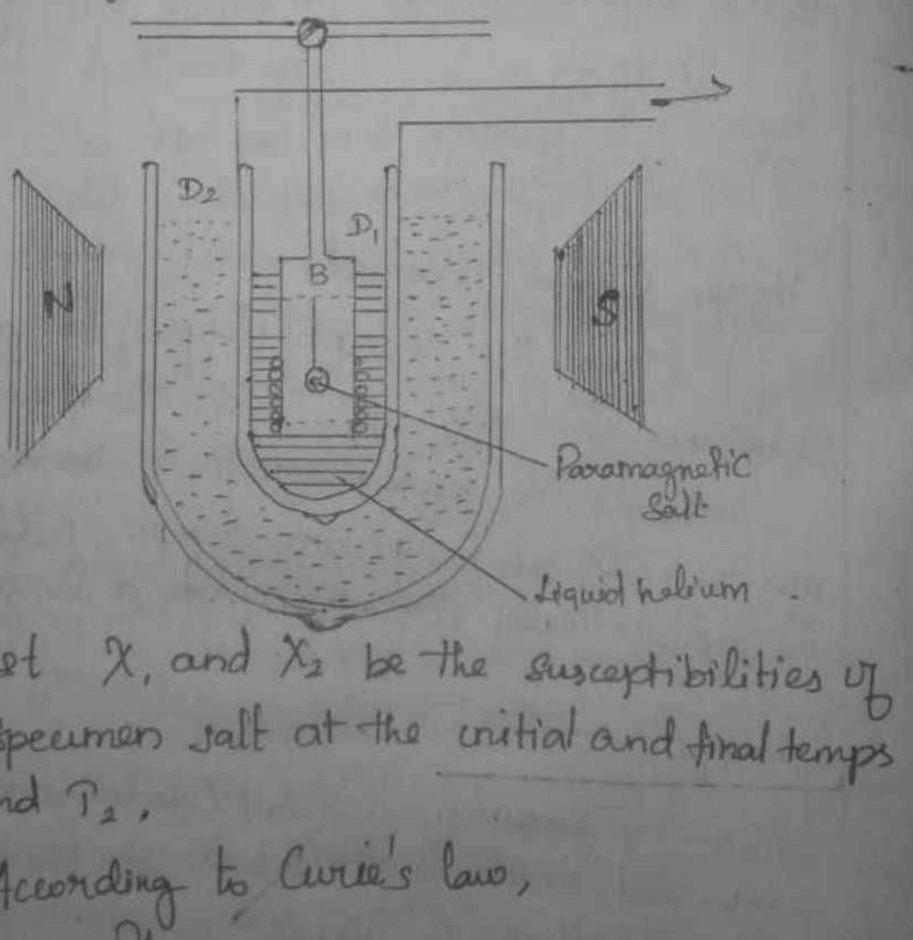
(i) The magnetic field is switched on, so that the specimen is magnetised.

(ii) The heat due to magnetisation is removed by first introducing hydrogen gas into B and then pumping it off with a high vacuum pump. Now the cold magnetised specimen is thermally isolated from D_1 and D_2.

(iii) The magnetic field is now switched off.

Adiabatic demagnetisation of the specimen takes place and its temp. falls.

The final temp. of the specimen (T_2) is determined by measuring the susceptibility of the substance at the beginning and at the end of the experiment by using a solenoid coil CC.



Let χ_1 and χ_2 be the susceptibilities of the specimen salt at the initial and final temps T_1 and T_2,

According to Curie's law,

$$\frac{\chi_1}{\chi_2} = \frac{T_2}{T_1}$$

$$T_2 = \frac{\chi_1}{\chi_2} T_1$$

Using this method with the salt gadolinium sulphate, Giauque and Macdougall reached a temp 0.25K

Practical application of low temperatures:

Applications in pure Science:

1. Seperation of the constituents of air.

A very important application of low temp. is in the separation of the constituents of air.

The atmospheric air contains 21% of oxygen, 78% of nitrogen and 1% of the rare gases like helium, neon, krypton, etc.,

Liquid oxygen and liquid nitrogen are obtained by subjecting liquid air fractional distillation. Liquid nitrogen has a lower boiling point (-196°C) than liquid oxygen (-183°C). On evaporating liquid air, nitrogen first seperates out and the residue gets richer in oxygen. Thus after subjecting liquid air to a few distillations, oxygen and nitrogen can be completely separated in the liquid form.

By a similar process, the rare gases can also be separated. Liquid air is first separated into two parts, the more volatile part containing hydrogen, helium and neon and the less volatile part containing oxygen, nitrogen, argon, krypton, xenon and carbon-dioxide.

By cooling the more volatile portion with liquid hydrogen, all other components except hydrogen are removed. Hydrogen is subsequently removed by sparking with oxygen. Thus liquid helium is obtained.

2. Production of high Vacua.
3. Calorimetric Work
4. Study of the properties of the upper atmosphere.
5. Study of properties of substance at low temperatures.

Applications in industry:

(1) Liquid oxygen stored up in cylinders are used in hospitals for artificial respiration.

Liquid oxygen is used in the manufacture of explosives. Liquid air is kept in coal mines in order to supply large quantities of oxygen in the event of an explosion.

Nitrogen is used for the production of synthetic ammonia and for the manufacture of fertilisers.

Inert gases like argon, neon, krypton and xenon separated from liquid air, have good commercial value. Argon is used in "gas filled" electric lamps.

Neon is employed in discharge tubes required for illumination and advertising sign boards.

Liquid air is of considerable importance in chemical industry, for separation and purification of gases. It is extensively used in high vacuum technique and also for calorimetric observations.

(2) The most important application of liquefied gases is in the working of refrigerating and air-conditioning machines.

REFRIGERATION:

Definition:

Refrigeration is defined as the production of temp. lower than those of the surroundings and maintaining the lower temp. within the boundary of a given space.

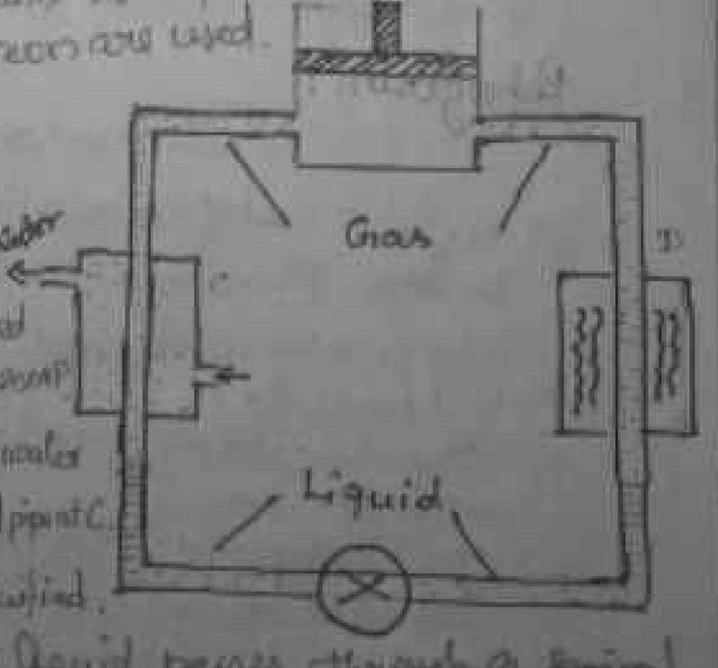
A machine used for producting low temp. below surroundings and maintaining an enclosure at that temp. is called refrigerator.

Actually, a refrigerator is a Carnot engine working in backward direction. In this case, certain amount of work is done on the engine which transfer heat from insulated chamber to the environment.

Principle:

The principle used in refrigeration is the production of low temp. by evaporation of a suitable liquid under reduced pressure.

The liquid used for the purpose is called a refrigerant. Some of the common refrigerant in use are ammonia, sulphur dioxide, carbon dioxide, freon (CCl_2F_2) and methyl chloride. In large refrigerating plants ammonia is used while in small plants used for domestic purposes sulphur dioxide and freon are used.



The principle of working of a refrigerator is shown in fig.

=) The gas is compressed to a high pressure by the compressor P.

=) It is cooled down by water circulating through a spiral pipe C.

=) The gas then gets liquified.

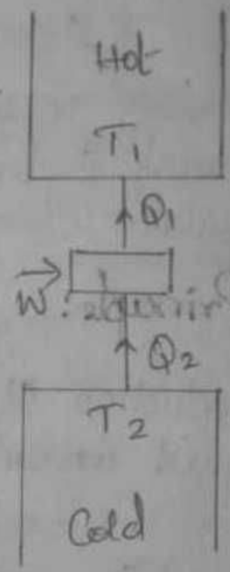
=) This high pressure liquid passes through a spiral pipe throttle valve T towards a low pressure side.

=) It comes out as a mixture of liquid and vapour and its temp. gets lowered.

⇒ At D this liquid - vapour mixture of liquid and vapour mixture takes heat from its surrounding materials thus cooling this stuff.

In this process, the remaining liquid also turns into vapour. This vapour is finally sucked by the pump P.

Carnot's cycle as refrigerator:



When the Carnot's engine work as a refrigerator, it absorbs heat Q_2 from the sink at temp. T_2.

W amount of work is done on it by some external means and rejects heat Q_1 to the source at a temp. T_1

Coefficient of performance

$$\frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

The coefficient of performance (K) is defined as the ratio of the heat taken in from the cold body to the work needed to run the refrigerator.

Refrigerant:

A refrigerant must fulfil the following requirements.

⇒ The latent heat of vaporisation of the refrigerant liquid must be large. When a small quantity of liquid evaporates, a large amount of heat is removed. So the cooling will be more.

⇒ The refrigerant must be a vapour at normal temp. and pressure.

⇒ The refrigerant should have low boiling point and low freezing point.

⇒ The specific volume (Volume occupied by 1 gm of refrigerant) should be small in order to reduce the size of compressors.

⇒ It should have high thermal conductivity.

=) It should be non-flammable, non-explosive and should not have bad effect on the stored foodmaterial.

=) The pressure necessary to liquefy the vapour in condenser coils must not be very large otherwise the apparatus will have to be very robust and heavy.

Types of refrigerating machines:

Refregerating machines are of two types.

1. Vapour compression machine, and
2. Vapour adsorption machine.

Here we shall discuss both the refrigerating machine.

Electrolux refrigerator [Vapour absorption machine]

Principle:

The principle involved is the production of low temp by making a liquid evaporate rapidly under reduced pressure. The liquid ammonia is made to evaporate under reduced pressure in an atmosphere of hydrogen.

The electrolux refrigerator is a modern form of Vapour Absorption Machine.

Construction:

=) Four essential parts.

(1) Generator: Here ammonia gas is generated by heating the strong aqueous solution of ammonia in it by means of a heater H.

(2) Condenser: It is cooled by water circulating round it. So the gaseous ammonia condenses to the liquid form.

(3) Evaporator: The evaporator is inside the space desired to be cooled. Here, the liquid ammonia gets evaporated.

(4) Absorber: The absorber is surrounded by a cold water jacket. Here, the gasous ammonia from the evaporator gets absorbed by the weak aqueous solution from the generator.

Working:

The weak ammonia solution in the boiler is forced into the absorber.

The strong ammonia solution goes into the boiler.

The gaseous ammonia enters the condenser. It is cooled and is condensed.

Liquid ammonia enters the evaporator and is mixed with hydrogen.

Hydrogen reduces the partial pressure of ammonia below its saturation point and causes evaporation.

This evaporator is surrounded by the compartment to be cooled.

When ammonia evaporates under reduced pressure the latent heat of evaporisation is taken from surrounding compartment. In this way the compartment is cooled.

Hydrogen and gaseous ammonia leave the evaporator and enter the absorber.

Here they meet the weak ammonia solution. The ammonia gas is dissolved and hydrogen gas rises through the absorber and enters the evaporator.

The strong ammonia solution is forced up into the boiler again.

The process continues and a sufficiently low temp. is produced in the compartment to be cooled.

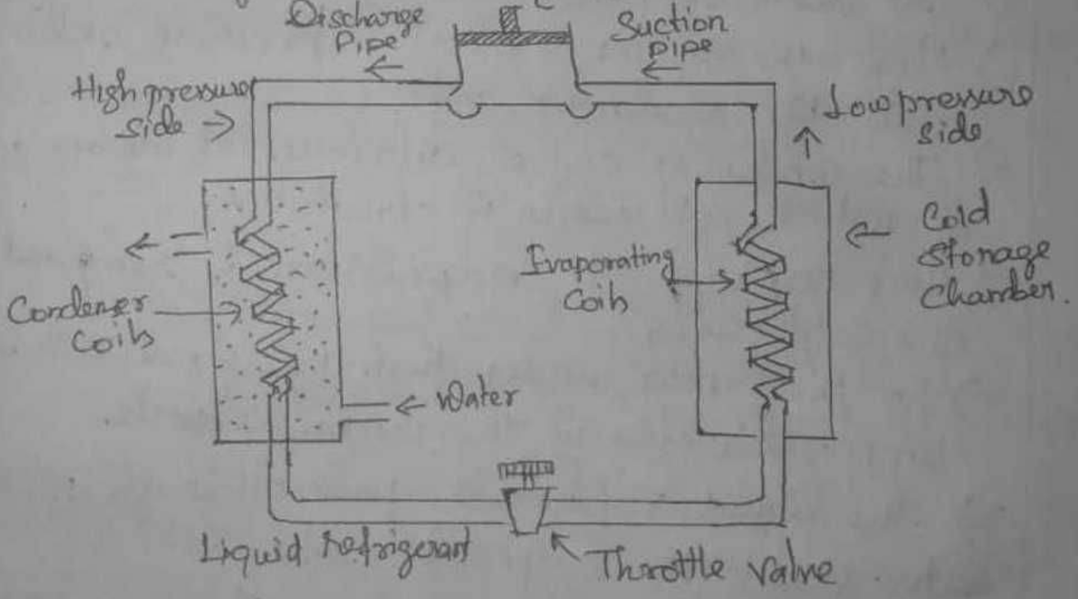
Advantag: No compressor is required and the circulation of the liquid and the gas is automatic.

Frigidaire [Vapour compression machine] :

Principle:

A frigidaire maintains an adiabatic enclosure at a low temp. The principle involved is the production of low temp. by making a liquid evaporate rapidly under reduced pressure and circulating the evaporating liquid around the enclosure.

The refrigerant used is sulphur dioxide. It is now being increasingly replaced by Freon or F_{12}. This refrigerator is generally used for domestic purposes.



Construction:

C is an electric motor-driven compressor.

=> It is fitted with two spring - loaded valves V_1 and V_2 in its bottom.

=> During the downstroke of the piston, when the pressure on the gas or vapour in it increases, V_1 is thrown open, V_2 remaining closed.

A steady stream of cold water is kept circulating round the condenser coils.

The evaporating coils are surrounded by the space or the chamber to be cooled. The throttle valve has a small orifice in it.

The pressure on the liquid, passing through it from the condenser coils on the high pressure side, can be reduced to be equal to that prevailing in the evaporator coils on the low pressure side.

Working:

To start with, some vapour of the refrigerant is introduced into the compressor.

=> The vapour is compressed by the compressor during its downward stroke.

=> The valve V_1 opens while V_2 closed.

=> Now the vapour under high pressure enters into the condenser coils.

=> The condenser coil is surrounded by an enclosure in which cold water is circulating.

=> Here the heat of compression is removed by the cold water.

=> So the vapour, under high pressure and low temp., liquefies in the condenser coils.

=> The liquid refrigerant passes through the regulator valve V into the evaporator coils.

The regulator valve reduces the pressure of liquid from high value (inside condenser) to low value (inside evaporator).

Due to low pressure, the liquid evaporates in the evaporator coils.

Here, when the liquid evaporates, it absorbs latent heat of vapourisation from surrounding cold storage space. The space or the chamber thus gets cooled.

The low pressure vapour from the evaporator coils is then drawn into the compressor during the upstroke of its piston, through valve V_2. Now valve V_1 opens and V_2 remains closed.

The same cycle of operations is repeated again.

After some time, the temp. of the space around the evaporator coils gets cooled to the desired temp.

Uses for refrigeration are:

1. Preservation of perishable products during storage or transportation:
2. The manufacture of ice and solid carbon dioxide
3. The control of air temp. and humidity in air-conditioning systems.

Air Conditioning:

Definition: Air conditioning may be defined as a method of controlling the weather conditions within the limited space of a room, or a hall, so that one may have the maximum comfort.

The conditions required for a person to have maximum comfort are the following:

(i) The temp. of the air in the room should lie between 65°F and 70°F during summer and 65°F and 75°F during winter.

(ii) Relative humidity should be maintained between 60-65 %.

(iii) Each individual in the room should at least have about $0.85m^3$ of air having a movement of 15 per minute. At least 25 %. of the total air circulating must be fresh air.

(iv) The air in the room should be free from dust, smoke, carbon dioxide etc.

Air Conditioner:

Air conditioner cools the air, removes the dust and controls the humidity of the atmosphere.

Refrigeration is the process of removing heat from the space or materials.

Air conditioners => ① Window air conditioner
② Package air conditioner and
③ Centralised air conditioner.

=> Window air conditioner is used for small rooms.
=> Package air conditioner is used for comparatively larger rooms.
=> Centralised air conditioner is used for theatres and lodges.

The important actions involved in the operation of an air conditioning system are,

1. Temperature control
2. Humidity control
3. Air filtering, cleaning and purification
4. Air movement and circulation.

A complete air conditioning system provides automatic control of these conditions for both winter and summer.

Temp. Control in winter means control of heating source and in summer means control of refrigerating system. Humidity control for winter requires addition of moisture (i.e use of humidifier) and in summer requires removal of moisture i.e., use of a dehumidifier.

=> In general, air filtering is the same for both summer and winter air conditioning.

Window air-conditioner (room air-conditioner)

This is suitable for cooling rooms in summer.

It consists of three basic parts:

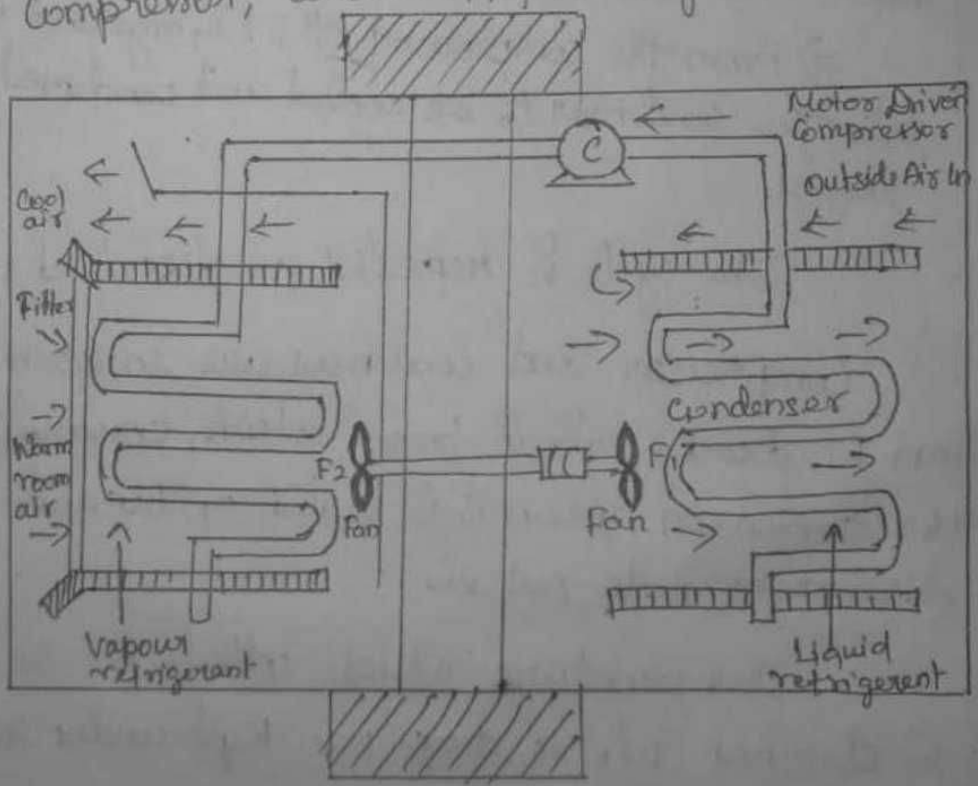
A hermatic compressor, a condenser and an evaporator.

Construction:

It consists of two units ① indoor unit and
② outdoor unit

The indoor unit consists of an evaporator, fan, air filter, control panel, trays etc.

The outdoor unit consists of a motor driven compressor, condenser, fan, trays etc.



Working:

⇒ The condenser and evaporator are connected through a capillary tube.

⇒ The liquid refrigerent collects in the lower coils of the condenser and from there flows via capillary tube (refrigerant control) into the evaporator.

⇒ Pressure inside the evaporator or cooling coil is very low.

⇒ So the liquid refrigerant evaporates rapidly by picking up heat from evaporator surface which is consequently cooled.

⇒ The motor-driven fan F_2 draw air from inside the room through a suitable filter and forces it to flow over the evaporator.

⇒ The air so cooled goes back to the room. An adjustable thermostat mounted on the control panel provides the necessary temp. control.

⇒ The low-pressure refrigerant is sucked back into the compressor.

⇒ From the compressor, the refrigerant is forced into the condenser to be cooled and condensed to a liquid.

The cycle is repeated as described above.

Compressor and condenser are so mounted that fan F_1 draws air is from outside, circulates it over the condenser where it is heated up ~~too~~ and then discharges it to outside.

The moisture which collects on the evaporator is drained into a drip pan kept under the evaporator