UNIT-I

PRODUCTION OF LOW TEMPERATURE

ESSAY QUESTIONS

its sign .

Q. 2. What is Joule-Kelvin effect ? Derive an expression for Joule-Kelvin coefficient.

Joule-Kelvin Effect : Definition :

When a gas under a constant high pressure is passed through a porous plug to a region of constant low pressure, there will be a change in its temperature. This was first observed by Joule and Kelvin (Thomson) and hence is called the ***Joule-Kelvin (or Joule - Thomson)*** *effect. The process of passing of the gas under such conditions is called a* ***throttling process.***

Expression for Joule-Kelvin Coefficient :

Let us consider a cylinder $EFGH$ that is thermally insulated from the surroundings. The cylinder has got two non conducting pistons P_A and P_B that can be moved inside the cylinder. Initially the piston P_B is just to the right of a porous plug C contained in the region MN and the piston P_A is at A to the left of the porous plug at a distance away from it. Between P_A and C there is a gas at a Pressure P_1 and volume V_1. Since the right side piston P_B is just adjacent to the porous plug C, any gas between P_A and C is prevented from going out into the region right of P_B. Hence the initial state of gas is an equilibrium state. Now let us move both the pistons P_A and P_B simultaneously in such a manner *that a constant high pressure P_1 is maintained on the left side of the porous plug and a constant low pressure P_2 is maintained on the right hand side of the porous plug*. After all the gas (initially to the left of C) has **seeped** through the porous plug (now to the right of C) the final equilibrium state will be as shown in Fig. This is called a **throttling process.**

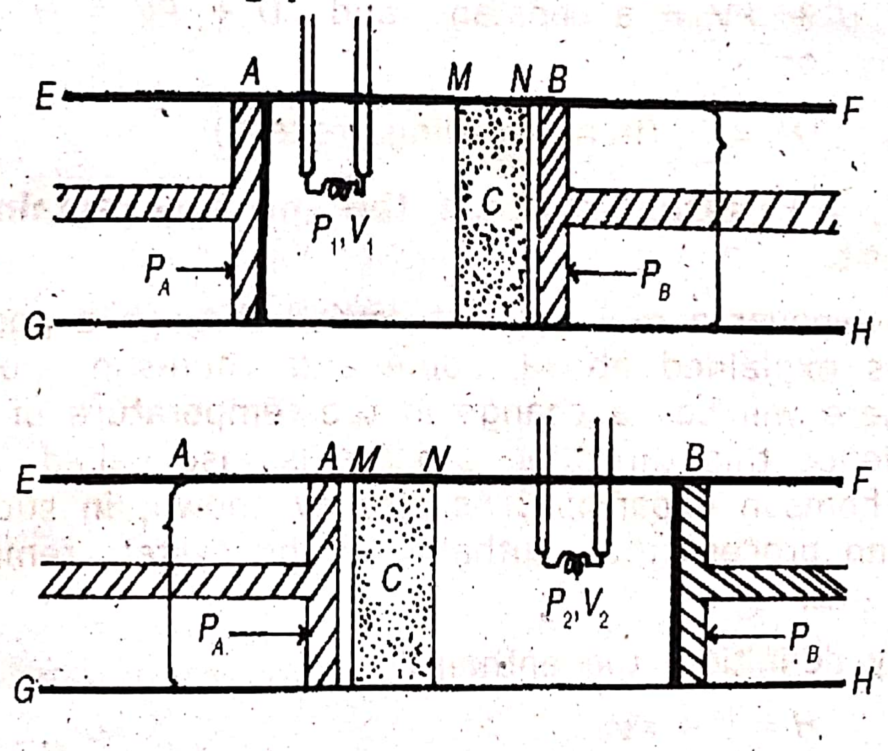

Fig.

This throttling process is an irreversible adiabatic process. Now, we can derive an interesting relation between the final and initial equilibrium states as follows. (Of course, the intermediate states are non equilibrium states).

From the first law of thermodynamics,

$$Q = (U_2 - U_1) + W \quad \text{.... (1)}$$

As no heat enters or leaves the system,

$$Q = 0 \quad \text{.... (2)}$$

and $$W = \int_0^{V_2} P\,dV + \int_{V_1}^{0} P\,dV \quad \text{.... (3)}$$

As we have ensured that P_1 and P_2 are maintained at constant values, $W = P_2 V_2 - P_1 V_1$ .... (4)

This is the amount of work required (in moving the two pistons) to keep the gas through the porous plug.

$$\therefore\ O = (U_2 - U_1) + P_2V_2 - P_1V_1 \quad \text{.... (5)}$$

or $$U_1 + P_1V_1 = U_2 + P_2V_2 \quad \text{.... (6)}$$

(*i.e.,*) $U + PV$ = a constant, and $U + PV = H$, the enthalpy. or

$$\boxed{H_i = H_f \text{ (in a throttling process)}} \quad \text{... (7)}$$

Thus, **in a throttling process, the enthalpy remains a constant.**

Whenever a real gas is throttled through a porous plug as explained above, Joule and Thomson found that there will be a change in the temperature of the gas. Hence this throttling process is also called the Joule-Thomson expansion. As already shown, in such a throttling process the enthalpy of the system remains a constant.

By definition, the enthalpy

$$H = U + PV \quad \text{.... (1)}$$

and, $$dH = Tds + VdP \quad \text{.... (2)}$$

Now, from the second TdS equation, we have

$$TdS = C_p dT - T\left(\frac{\partial V}{\partial T}\right)_P dP \quad \text{.... (3)}$$

$$\therefore\ dH = C_p dT - T\left(\frac{\partial V}{\partial T}\right)_P dP + VdP \quad \text{.... (4)}$$

$$= C_p dT - \left[T \left(\frac{\partial V}{\partial T} \right)_P - V \right] dP$$

or $$C_p dT = dH + \left[T \left(\frac{\partial V}{\partial T} \right)_P - V \right] dP \qquad .... (5)$$

But, dH = 0 in a throttling process (Joule - Kelvin expansion)

$$\therefore \ dT = \frac{1}{C_p} \left[T \left(\frac{\partial V}{\partial T} \right)_P - V \right] dP \qquad .... (6)$$

But $$dT = \left(\frac{\partial T}{\partial P} \right)_H dP + \left(\frac{\partial T}{\partial H} \right)_P dH \qquad .... (7)$$

But $dH = 0$

$$\therefore \left(\frac{\partial T}{\partial P} \right)_H dP = \frac{1}{C_p} \left[T \left(\frac{\partial V}{\partial T} \right)_P - V \right] dP \qquad .... (8)$$

or $$\boxed{\left(\frac{\partial T}{\partial P} \right)_H = \frac{1}{C_p} \left[T \left(\frac{\partial V}{\partial T} \right)_P - V \right]} \qquad .... (9)$$

The ratio of the change of temperature of a gas to the change of pressure during a throttling process at constant enthalpy is defined as the **Joule - Kelvin coefficient** and is denoted by μ.

$$\therefore \mu = \left(\frac{\partial T}{\partial P} \right)_H \qquad .... (10)$$

Hence, $$\boxed{\mu = \frac{1}{C_p} \left[T \left(\frac{\partial V}{\partial T} \right)_P - V \right]} \qquad .... (11)$$

With $$\mu = \left(\frac{\partial T}{\partial P} \right)_H$$

Cases :

From the definition of μ it is clear that from Eqn. (10)

(a) If μ is negative; $\left(\frac{\partial T}{\partial P} \right)_H$ is negative and hence the temperature increases as **pressure is decreased.** Thus a **heating** *effect* is produced in Joule Thomson expansion where pressure is decreased.

(b) If μ is positive, $\left(\frac{\partial T}{\partial P}\right)_H$ is positive and hence the temperature also decreases when **pressure is decreased**. Thus a *cooling effect* is produced in Joule Kelvin expansion where **pressure is decreased**.

(c) If μ is Zero, $\left(\frac{\partial T}{\partial P}\right)_H = 0$ and hence there will be neither cooling (decrease of temperature with decrease of pressure) nor heating (increase of temperature with decrease of pressure). The corresponding transition temperature at which the cooling changes into heating is called the **Inversion Temperature** and is a characteristic of the given gas. Below the inversion temperature we can have the cooling effect for a gas — and this phenomenon is of quite significance in liquification of gases.

Q. 4. What is Joule - Thomson effect (or) Joule - Kelvin effect ? Describe the porous plug experiment and indicate the results ? Obtain an expression for the cooling produced when a gas suffers Joule - Thomson effect ?

Joule - Thomson effect : *Definition* : *When a gas under a constant high pressure, passes through a porous* plug to a region of constant low pressure, its temperature changes. This is called **Joule-Thomson effect.** The magnitude and sign of the effect depends on the initial temperature of the gas. It is also called ***"Joule-Kelvin effect"***.

At ordinary temperatures most gases show a cooling effect, while hydrogen and helium show a heating effect.

Porous Plug Experiment :

Description : The apparatus consists of a *porous plug* *G* of cotton wool or silk fibres arranged in a wide tube. The porous plug is held between two perforated brass discs *D* and *D*. To prevent conduction of heat into the plug, the portion of the tube is made of box wood cylinder and ensures good thermal insulation of the porous plug. The lower portion of the tube is connected to the compression pump *P*. through a long spiral tube *S*. The whole apparatus is immeresed in a water bath *W* to have a steady constant temperature.

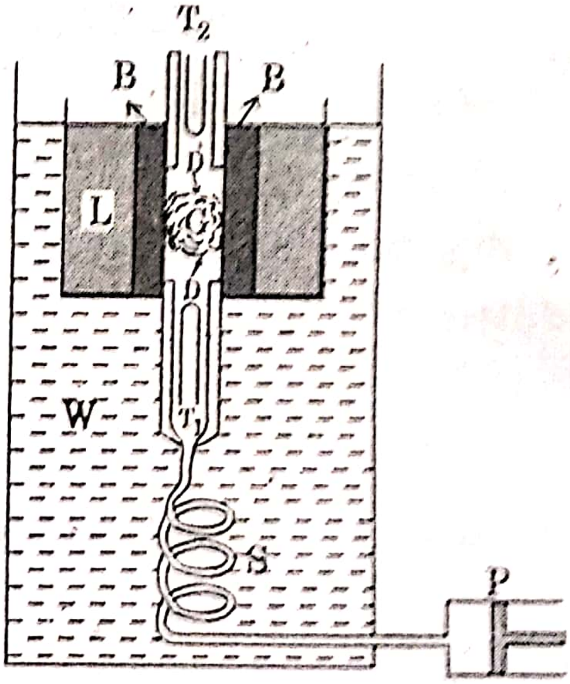

Fig.

Procedure : The gas under investigation is compressed and its temperature consequently rises. As it slowly passes through the spiral *S* cools down to the temperature of the bath. Now it is allowed to suffer *throttle expansion* through the porous plug and escapes into the atmosphere. The temperature on the two sides of the plug are measured with two platinum resistance thermometers T_1 and T_2. Care should be taken that *no sound is produced when the gas escapes through the plug,* since this would also produce a cooling. The gas is allowed to flow very slowly for about an hour in order that the temperatures at various parts in the side tube may become constant.

Results :

(1) *At fairly low temperatures, all gases show cooling effect on passing through the plug.* But at *ordinary temperatures most gases* show a *cooling effect* (+ *ve J – K* effect) *while hydrogen* and *helium* show a *heating effect* (– *ve J – K* effect).

(2) The *fall in temperature* is proportional to the *difference of pressure* on the two sides of the porous plug.

(3) The *fall in temperature* for a given difference of pressure *decreases with rise in initial temperature of the gas and becomes zero at a certain temperature,* called the **temperature of inversion**, which is different for each gas. *If the initial temperature of the gas is above this temperature, a heating effect is observed instead of cooling.*

Expression for cooling produced when a gas suffers Joule-Thomson effect :

Consider a *thermally insulated cylinder AB* divided into two compartments by a *porous plug G.* Let V_1 and V_2 be the volumes of a *gram molecule* of a gas on the high pressure (P_1) and low pressure (P_2) sides of the porous plug respectively. During expansion the gas has to do external as well as internal work.

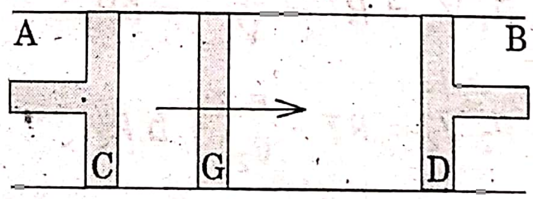

Fig.

External work done on the gas ..... = $P_1 V_1$

and external work done by the gas ...... = $P_2 V_2$

∴ Net external work done by the gas = $(P_2 V_2 - P_1 V_1)$

In Vander Waals' equation, it is assumed that he molecules of a gas attract one another and the attraction is equal to an *internal pressure* a/V^2, where (a) is constant. Hence when the gas expands from V_1 to V_2, the work done against the internal forces of attraction is given by,

$$\int_{V_1}^{V_2} \frac{a}{V^2} \cdot dV = a\left(\frac{1}{V_1} - \frac{1}{V_2}\right)$$

$$\therefore \left.\begin{array}{r}\text{Total work done}\\ \text{by the gas } W\end{array}\right\} = P_2 V_2 - P_1 V_1 + a\left(\frac{1}{V_1} - \frac{1}{V_2}\right) \quad ....(1)$$

[If the temperature on either side of the plug is to be the same (say T), the amount of energy given by Eq. (1) should be supplied to the system].

According to Vander Waals' equation, we have

$$\left(P + \frac{a}{V^2}\right)(V - b) = RT$$

$$\text{or } PV + \frac{a}{V} - Pb - \frac{ab}{V^2} = RT$$

As a and b are small quantities, ab/V^2 can be neglected.

$$\therefore PV + \frac{a}{V} - Pb = RT$$

$$\text{or} \qquad PV = RT - \frac{a}{V} + bP$$

$$\text{Hence} \qquad P_1 V_1 = RT - \frac{a}{V_1} + bP_1$$

$$\text{and} \qquad P_2 V_2 = RT - \frac{a}{V_2} + b P_2$$

$$\therefore \qquad P_2 V_2 - P_1 V_1 = a\left(\frac{1}{V_1} - \frac{1}{V_2}\right) - b\ (P_1 - P_2)$$

Substituting this value in Eq. (1), we have

$$W = 2a\left(\frac{1}{V_1} - \frac{1}{V_2} - b\ (P_1 - P_2)\right) \quad .... (2)$$

As a and b are *very small quantities*, Van derWaals' equation can be approximately written as,

$$PV = RT \text{ or } \frac{1}{V} = \frac{P}{RT}$$

$$\therefore \quad \frac{1}{V_1} = \frac{P_1}{RT} \text{ and } \frac{1}{V_2} = \frac{P_2}{RT}$$

Substituting these values in Eq. (2), we have

$$W = 2a\left(\frac{P_1}{RT} - \frac{P_2}{RT}\right) - b\,(P_1 - P_2)$$

$$= \frac{2a}{RT}\,(P_1 - P_2) - b\,(P_1 - P_2)$$

$$= (P_1 - P_2)\left[\frac{2a}{RT} - b\right] \text{ ergs} \qquad \text{.... (3)}$$

As the system is *thermally insulated, this work is drawn from the K.E. of the molecules of the gas, which therefore decreases and the gas cools.* Let dT be the fall in temperature.

If C_p be the specific heat at constant pressure then the amount of heat that must be supplied to restore the original temperature.

$$= C_p.dT \text{ cal.}$$

$$= C_p.dT\,.J \text{ ergs}$$

$$\text{Hence } C_p.dT\;J = (P_1 - P_2)\left[\frac{2a}{RT} - b\right]$$

$$\text{or} \quad \boxed{dT = \frac{(P_1 - P_2)}{C_p.J}\left[\frac{2a}{RT} - b\right]} \qquad \text{.... (4)}$$

Equation (4) represents, *"The expression for the cooling produced"*, When a gas suffers Joule-Thomson effect.

As $P_1 > P_2$, $(P_1 - P_2)$ is $+ve$. Hence $[2a/RT - b]$ determines the sign of dT.

Cases :

(1) If $\frac{2a}{RT} > b$, then dT is $+$ *ve* and hence there will a be *cooling effect*, since dT represents a fall in temperature.

(2) If $\frac{2a}{RT} < b$, then dT is $-$ *ve* and hence there will be a heating effect.

and (3) If $\frac{2a}{RT} = b$, then $dT = 0$ *i.e.*, there will be no change in temperature.

SHORT ANSWER QUESTIONS

Q. 2. Explain Joule-Kelvin effect.

Joule - Kelvin effect : *Explanation* : The Joule-Thomson effect depends upon two aspects. The first one is the internal work done by the gas in overcoming the intermolecular forces of attraction. (This will be zero for an ideal gas, but for all real gases it will be present). The second one is the external work done by the gas or done on the gas. The first one produces a cooling effect where as the second one may produce either a heating effect or a cooling effect. If the work done by the gas in the former process (in expanding itself against inter molecular forces) is more than the external work done *on the gas* then the kinetic energy of the gas molecules decreases and as a result the temperature of the gas decreases and there is a cooling effect.

On the other hand, if the work done by the (external agency) *on the gas* is more than the work done by the gas (in expanding itself against internal molecular forces) then there will be an increase in the kinetic energy of the gas molecules and as a result the temperature of the gas increases and there will be a heating effect.

Q. 7. What is superconductivity.

Superconductivity, complete disappearance of electrical resistance in various solids when they are cooled below a characteristic temperature. This temperature, called the transition temperature, varies for different materials but generally is below 20 K (−253 °C).The use of superconductors in magnets is limited by the fact that strong magnetic fields above a certain critical value, depending upon the material, cause a superconductor to revert to its normal, or non-superconducting, state, even though the material is kept well below the transition temperature. Suggested uses for superconducting materials include medical magnetic-imaging devices, magnetic energy-storage systems, motors, generators, transformers, computer parts and very sensitive devices for measuring magnetic fields, voltages or currents. The main advantages of devices made from superconductors are low power dissipation, high-speed operation and high sensitivity.

temperature considerably.

Q. 9. What are the Applications of super conductor?

Films of the new materials can carry currents in the superconducting state that are large enough to be of importance in making many devices. Possible applications of the high-temperature superconductors in thin-film or bulk form include the construction of computer parts (logic devices, memory elements, switches and interconnects), oscillators, amplifiers, particle accelerators, highly sensitive devices for measuring magnetic fields, voltages or currents, magnets for medical magnetic-imaging devices, magnetic energy-storage systems, levitated passenger trains for high-speed travel, motors, generators, transformers and transmission lines. The principal advantages of these super-conducting devices would be their low power dissipation, high operating speed and extreme sensitivity. Equipment made with the high-temperature superconductors would also be more economical to operate because such materials can be cooled with inexpensive liquid nitrogen (boiling point, 77 K) rather than with costly liquid helium (boiling

VERY SHORT ANSWER QUESTIONS

Q. 5. Why is adiabatic demagnetization ?

Adiabatic demagnetization comes under magnetic cooling, exploiting paramagnetic properties to cool some materials down. It is based on the fact that the entropy of paramagnetic materials is lower in the magnetic field. The magnetic regions aligned in the paramagnetic field originate lower entropy.

Q. 6. What is superconductivity explain ?

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