

1 ELECTRIC CHARGE AND CURRENT

Electric charges in motion constitute electric current. Metals such as gold, silver, copper, aluminum etc., called **conductors**, have large number of free electrons. These free electrons move around in all directions from atom to atom under normal conditions but when a potential difference is applied between two points (two ends preferably), the electrons move only in one direction. The electrons are negatively charged particles and the conventional current is considered as the flow of positive charges. Hence the direction of flow of electrons is opposite to the direction of conventional current, which takes place in a direction from a point of higher potential to a point of lower potential.

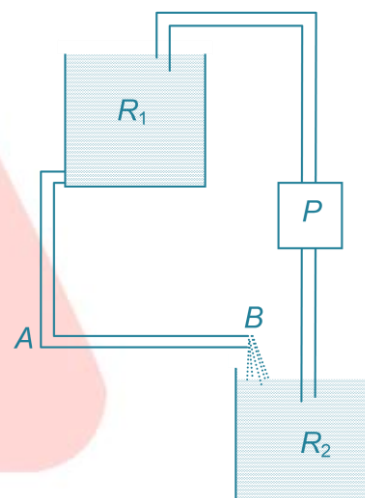
The strength of the current is the rate at which the electric charges are flowing. If a charge Q coulomb passes through a given cross-section of the conductor in t second, the current I through the conductor is given by

$$I = \frac{Q \text{ coulomb}}{t \text{ second}} = \frac{Q}{t} \quad \dots (1)$$

The SI unit of current is 'ampere'(A)

2 ELECTROMOTIVE FORCE AND VOLTAGE

Let us consider a water flow system as shown in the figure. Suppose in the horizontal tube AB we wish to maintain a steady flow of water. This requires a steady pressure difference between A and B . This is accomplished by maintaining the levels of water in the two reservoirs R_1 and R_2 . An external source of energy (the pump P) serves the purpose. Water flows spontaneously from higher to lower pressure. The pump is meant to do the opposite –take water from lower pressure to higher pressure. For this, the pump will need to work at a steady rate. Water cannot flow at a constant rate in an isolated tube.



A steady electric current in a conductor is maintained in an analogous way. In a conductor, positive charge will flow from higher potential (A) to lower potential (B) i.e. in the direction of electric field. To maintain a steady electric current, the conductor cannot be isolated to transport the positive charge from B back to A i.e. from lower to higher potential and thus maintain a potential difference between A and B . The external device will need to do work for transporting positive charge from lower to higher potential.

Electromotive force is the maximum work done in taking a unit charge once around the closed circuit. The external device may be a cell, a battery, a generator or dynamo.

Emf of a cell is defined as the maximum potential difference between the two electrodes of the cell when no current is drawn from the cell.

The SI unit of emf of a cell is volt (V) or joule per coulomb. The emf of the cell is said to be 1 volt, if 1 Joule of energy is supplied by the cell to drive 1 coulomb of charge once around the whole circuit.

In **current electricity**, dry cells or secondary cells or generators are employed to create a potential difference

in order to cause an electric current flow in closed circuits just as a water pump is used to create pressure difference in order to drive water in water pipes.

The unit of **potential difference** is **volt**. The volt is defined as that potential difference between two points of a conductor carrying a current of one ampere when the power dissipated between these points is equal to one watt.

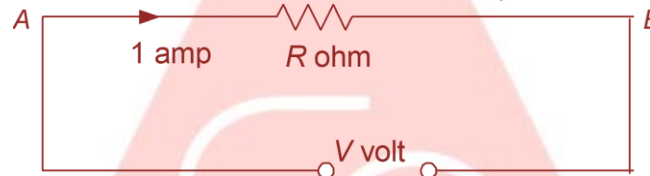
3 RESISTANCE

Electrical resistance may be defined as the property of a substance, which opposes the flow of an electric current through it.

The unit of resistance is **ohm**. Symbol is Ω . Ohm is that resistance between two points of a conductor when a potential difference of one volt is applied between these points produces in this conductor a current of one ampere.

4 OHM'S LAW

Ohm's law is the most fundamental of all the laws in electricity.



Statement: The current which flows in a conductor is proportional to the potential difference which causes its flow provided the temperature of the conductor is constant.

If a potential difference of V volt exists between the ends A and B of a conductor AB current of I ampere flows through the conductor and

$$V \propto I \quad \text{or} \quad V = IR \quad \dots (2)$$

where the constant R is the resistance of the conductor. In this Ohm's law relation, V is in volts, I is in amperes and R is in ohms.

5 RESISTIVITY AND ORIGIN OF RESISTIVITY

The resistance of a resistor depends on its geometrical factors as also on the nature of the substance of which the resistor is made. For a conductor of length l and cross sectional area A , the resistance R is proportional to both l and R .

$$R \propto \frac{l}{A}$$

$$R = \rho \frac{l}{A} \quad \dots (3)$$

where ρ is a constant of proportionality called resistivity. It depends only on the nature of the material of the resistor and its physical conditions such as temperature and pressure. The unit of resistivity is ohm m (Ωm). The inverse of ρ is called conductivity and is denoted by σ . The unit of σ is $(\Omega\text{m})^{-1}$ or mho m^{-1} or siemen m^{-1} .

ORIGIN OF RESISTIVITY

At any temperature, the electrons in a metal have a certain distribution of velocities. When there is no external field, velocities in all directions are equally likely and there is no overall drift. In the presence of an external field each electron experiences an acceleration of $\frac{eE}{m}$ opposite to the field direction. The electrons are accelerated and they start gaining speed. In the motion of the electron they suffer frequent

collisions against the metal ions. After a collision each electron makes a fresh start, accelerates only to be deflected randomly. The net result is that, in addition to their random motion, the electrons acquire a small velocity towards the end of the conductor. This average velocity is called drift velocity. Thus drift velocity is defined as the average velocity with which free electrons get drifted towards the positive electric field. If τ is the average time between two collisions the average drift speed of the electrons is given by

$$v_d = \frac{eE}{m} \tau \quad \dots (4)$$

Resistivity is also the resistance of a cube of 1 m side measured between opposite faces of the cube.

6 RELATION BETWEEN CURRENT AND DRIFT VELOCITY

Let us consider a conductor of length l and of uniform area of cross section A . If n is the number of free electrons per unit volume of the conductor, then total number of free electrons in the conductor = Aln . Thus charge on all the free electrons in the conductor is $q = Alne$. If a constant potential difference V be applied across the ends of the conductor with the help of a battery, then electric field set up across the conductor is given by $E = \frac{V}{l}$, let v_d be the drift speed of the electrons.

Therefore the time taken by the free electrons to cross the conductor, $t = \frac{l}{v_d}$

$$\text{Hence current} \Rightarrow I = \frac{q}{t} = \frac{Alne}{l/v_d} = neAv_d$$

$$\text{or } I = \frac{ne^2Av\tau}{lm} \quad \text{or } v = \frac{m}{ne^2\tau} \frac{I}{A} = RI$$

$$\therefore R = \frac{m}{ne^2\tau} \frac{l}{A}$$

$$\text{Resistivity of the material } \rho = \frac{m}{ne^2\tau}$$

MOBILITY OF ELECTRON

Mobility of electron (μ_e) is defined as the drift velocity of electron per unit electric field applied.

$$\mu_e = \frac{v_d}{E} \Rightarrow v_d = \mu_e E$$

$$\text{So, } I = neA\mu_e E$$

TEMPERATURE DEPENDENCE OF RESISTIVITY

In most metals an increase in temperature increases the amplitude of vibration of lattices ions of the metal. Due to it, the collision of free electrons with ions/atoms while drifting, becomes more frequent, resulting in a decreases in relaxation time τ .

The resistivity of all metallic conductors increases with temperature.

$$\text{Resistivity of the material } \rho = \frac{m}{ne^2\tau}$$

Over a limited temperature range that is not too large, the resistivity of a metallic conductor can often be represented approximately by a linear relation

$$\rho_T = \rho_0 [1 + \alpha(T - T_0)]$$

Where ρ_0 is the resistivity at a reference temperature T_0 and ρ_T its value at temperature T . The factor α is called the temperature coefficient of resistivity.

7 TEMPERATURE DEPENDENCE OF RESISTANCE

If R_0 and R be the resistances of a conductor at 0°C and $\theta^\circ\text{C}$, then it is found that

$$R = R_0 (1 + \alpha\theta) \quad \dots (6)$$

where α is a constant called the **temperature coefficient of resistance**.

$$\alpha = \frac{R - R_0}{R_0 \cdot \theta} \quad \text{and the unit of } \alpha \text{ is } K^{-1} \text{ or } ^\circ\text{C}^{-1}.$$

If R_1 and R_2 be the resistances of a conductor at temperatures $\theta_1^\circ\text{C}$ and $\theta_2^\circ\text{C}$, then

$$R_1 = R_0 (1 + \alpha\theta_1)$$

$$R_2 = R_0 (1 + \alpha\theta_2) \quad \text{and} \quad \alpha = \frac{R_2 - R_1}{R_1\theta_2 - R_2\theta_1}$$

8 COLOUR CODE FOR CARBON RESISTORS

The resistance of a carbon resistance is indicated by means of colour code printed on it. There are two types of colour codes.

(a) In the first code, there is always a set of co-axial rings or strips printed on the resistor. In order to understand the significance of these rings, let us first understand the resistor colour code given in the following table.

Colour	Number	Multiplier	Colour	Tolerance
Black	0	10^0	Gold	$\pm 5\%$
Brown	1	10^1	Silver	$\pm 10\%$
Red	2	10^2	No colour	$\pm 20\%$
Orange	3	10^3		
Yellow	4	10^4		
Green	5	10^5		
Blue	6	10^6		
Violet	7	10^7		
Grey	8	10^8		
White	9	10^9		

The multipliers in the case of gold and silver are 10^{-1} and 10^{-2} respectively.

The first two rings or strips from the end give the first two significant figures or resistance in ohm. While the colour of the first ring on the extreme left represents the first significant figure, the second ring represents the second significant figure.

The third ring indicates the decimal multiplier i.e. the number of zeros that will follow the two significant figures.

The last ring indicates the tolerance in percentage about the indicated value i.e. it represent the percentage accuracy.

(b) In the second code the body of the resistor one, end of a resistor and a dot on the body of the resistor carry specific colours.

The colour of the body gives the first significant figure.

The colour of the end gives the second significant figure.

The colour of the dot on the body of the resistor gives the decimal multiplier i.e., the number of zeros that will follow the two significant figures.

The colour of the ring R indicates the percentage accuracy of resistance or tolerance limits of the value of resistance.

9 NON - OHMIC CONDUCTORS

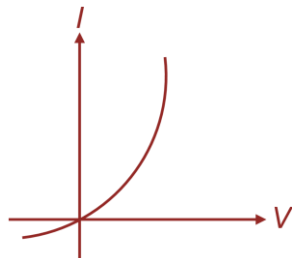
The conductor which do not obey Ohm's Law called **non-ohmic conductors**. In such conductors the relation of voltage to current may not be a direct proportion and it may be different for the two directions of current. One common semi conductivity device that has non linear. I versus V characteristics is the diode. The resistance of this device is small for currents in one direction and large for currents in the reverse direction. There are a number of commonly used circuit elements with one or more of the following prosperities;

- (a) V depends on I non-linearly
- (b) The relation between V and I depends on the sign of V for the same absolute value of V .
- (c) The relation between V and I is non unique, i.e. for the same current I , there is more than one value of voltage V .

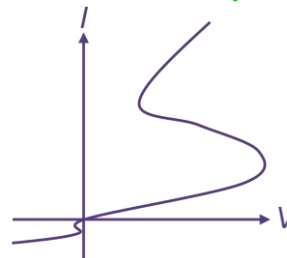
For example,

Vacuum tubes, semiconductor diodes liquid electrolyte, thyristor are all non-ohmic conductors

Characteristics of diode



Characteristics of thyristor



10 SUPER CONDUCTIVITY

The electrical resistivity of many metals and alloys drops suddenly to zero when their specimen are cooled to a sufficiently low temperature called the critical temperature. This phenomenon is called superconductivity and the material showing such a behaviour is called super conductor. The phenomenon was first discovered by H. Kamerlingh Onnes in 1911 in mercury and the critical temperature of mercury was found out to be 4.2K

10.1 MEISSNER EFFECT

In 1933, **Meissner and Ochsenfeld** in 1933, found that if conductor is cooled in a magnetic field to below the transition temperature, then at the transition the lines of induction B are pushed out of the conductor.

The **Meissner effect** shows that a bulk superconductor behaves as if inside the specimen, the magnetic field is zero.

10.2 SOME SUPER CONDUCTORS

It was later found that lead, tin and indium also become superconductors at 7.2 K, 3.7 K and 3.4 K respectively. Certain alloys become super conductors at rather high temperatures. As an example, the compound Nb_3Sn becomes superconducting at 17.9 K

Critical temperature T_c (K) of some superconducting materials

Hg	4.2
Au_2Bi	1.7
$YBa_2Cu_3O_7$	90
$Tl_2Ba_2Ca_2Cu_3O_{10}$	120

Application of superconductor

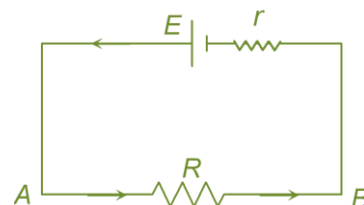
1. Superconductor are used in making large electromagnets. This is because no heat is generated when a current flows through a superconductor.
2. Superconductor may be used for transmission of electric power without power losses.
3. Super conductors can be used for making high speed computers.

11 EMF OF A CELL AND ITS INTERNAL RESISTANCE

If a cell of emf E and internal resistance r be connected with a resistance R the total resistance in the circuit is $(R+r)$.

The current through the circuit $I = \frac{E}{R+r}$

Potential difference across the ends A and B



$$=IR = \frac{ER}{R+r}$$

Thus, although the emf of the cell is E , the effective potential difference it can deliver is less than E and it is given by

$$V_{AB} = E - Ir$$

The quantity V_{AB} is called the terminal potential difference of the cell and this is also the potential difference across the external resistance R .

If $R \rightarrow \infty$, $V_{AB} \rightarrow E$, the emf of the cell.

12 GROUPING OF RESISTANCES

12.1 RESISTORS IN SERIES

The series circuit is one in which the same current flows in all the components of the circuit. If resistors R_1 , R_2 , R_3 , ... are connected in series, the equivalent (or effective) resistance of the combination is the sum of the resistances so connected.

$$R = R_1 + R_2 + R_3 + \dots \quad \dots (7)$$



In a series combination of resistors

- (i) the equivalent resistance is equal to the sum of the individual resistances,
- (ii) the same current flows through all the components and
- (iii) the sum of the separate voltage drops (IR drop) is equal to the applied voltage across the combination. If V be the applied voltage, V_1 , V_2 , V_3 , be the IR drops across resistances R_1 , R_2 , R_3 , respectively.

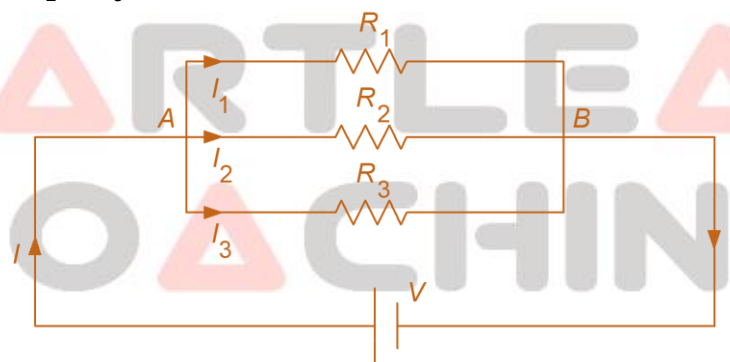
$$V = IR_1 + IR_2 + IR_3 + \dots = V_1 + V_2 + V_3 + \dots$$

12.2 RESISTORS IN PARALLEL

A parallel circuit of resistors is one in which the same voltage is applied across all the components.

If resistors R_1 , R_2 , R_3 , are connected in parallel then reciprocal of the equivalent resistance is the sum of the reciprocals of the resistance of separate components.

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots \quad \dots (8)$$



- (i) the total current taken from the supply is equal to the sum of the currents in separate branches.
- (ii) the potential difference across each resistor is the same V volt which is the applied voltage.
- (iii) the branch currents I_1 , I_2 , I_3 , ... are in the ratio,

$$\frac{1}{R_1} : \frac{1}{R_2} : \frac{1}{R_3} : \dots$$

- (iv) the equivalent resistance is smaller than the smallest of the resistances in parallel.

12.3 SERIES-PARALLEL GROUPINGS

A **series-parallel circuit** is a combination of resistors in series as well as parallel connections. The following

examples will illustrate the solutions of such problems.

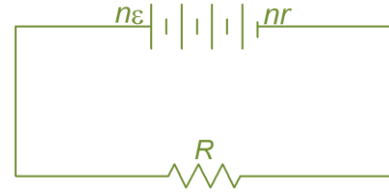
13 GROUPING OF CELLS

13.1 CELLS IN SERIES

Let there be n cells each of emf ϵ , arranged in series. Let r be the internal resistance of each cell.

The total emf is $n\epsilon$ and the total internal resistance is nr . If R be the external load, the current I through the circuit $I = \frac{n\epsilon}{R+nr}$

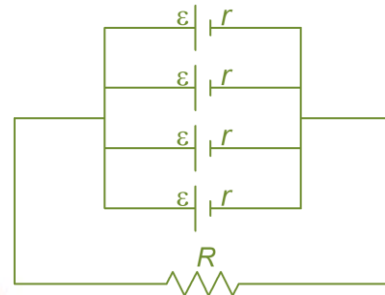
... (9)



13.2 CELLS IN PARALLEL

If m cells each of emf ϵ and internal resistance r be connected in parallel and if this combination be connected to an external resistance R , then the emf of the circuit = ϵ .

The internal resistance of the circuit = the resistance due to m resistances each of r in parallel $= \frac{r}{m}$.



... (10)

Now the current through the external resistor $R = \frac{\epsilon}{R + \frac{r}{m}} = \frac{m\epsilon}{mR + r}$.

13.3 MIXED GROUPING OF CELLS

Let n identical cells be arranged in series and let m such rows be connected in parallel. Obviously the total number of cells is nm .

The emf of the system = $n\epsilon$

The internal resistance of the system $= \frac{nr}{m}$

The current through the external resistance R

$$I = \frac{n\epsilon}{R + \frac{nr}{m}} = \frac{mn\epsilon}{mR + nr} \quad \dots (11)$$

14 ARRANGEMENT OF CELLS FOR MAXIMUM CURRENT

Considering the above case it is required to find the condition for maximum current if the product mn is given.

In this case the product mn , ϵ , r and R are constants and m and n alone can be varied to get I maximum.

For I_{\max} denominator $(mR + nr)$ should be minimum in equation (9). This happens when $mR = nr$ or $R =$

$$\frac{nr}{m}$$

Hence the current through the external resistance R is a maximum when it is equal to internal resistance of the battery $\frac{nr}{m}$.

If cells of different emf and internal resistance are in parallel there is no simple formula to give the total emf and the internal resistance and any calculations involving circuits in such cases can be done with the help of Kirchhoff's laws which will be discussed later.

15 KIRCHHOFF'S LAW

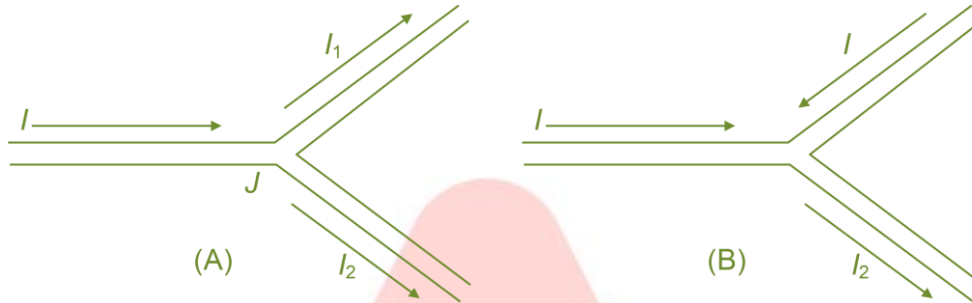
KIRCHHOFF'S LAWS: If several resistors and cells are connected such that they cannot be reduced to simple series and parallel arrangements, Ohm's law becomes insufficient to solve the problem.

1. FIRST LAW

According to it, "The algebraic sum of currents meeting at a junction is zero"

$$\text{i.e. } \sum I = 0$$

... (12)



Treating the current to be positive if it is reaching a junction and negative if leaving it, we have

$$I - I_1 - I_2 = 0$$

$$\text{or } I = I_1 + I_2 \quad (\text{for figure A})$$

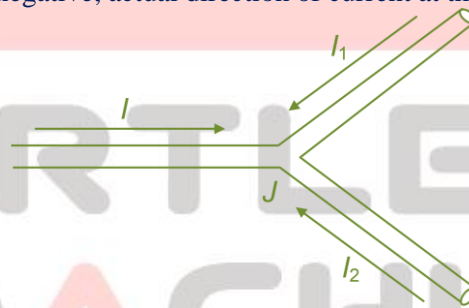
For the figure (B), we have

$$I + I_1 - I_2 = 0$$

$$\text{or } I + I_1 = I_2$$

IMPORTANT POINTS REGARDING FIRST LAW

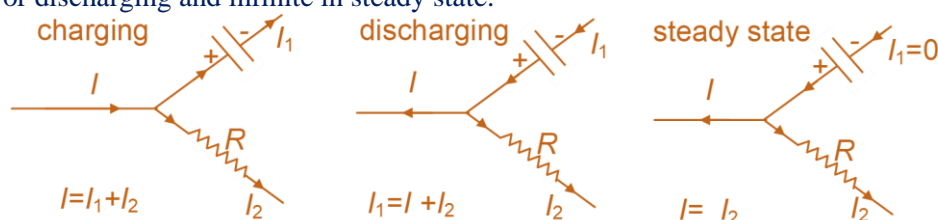
- (i) This law implies that current reaching a junction is equal to the current leaving the junction
- (ii) If a current comes out to be negative, actual direction of current at the junction is opposite to that assumed.



In the above diagram, $I + I_1 + I_2 = 0$ can be satisfied only if at least one current is negative i.e. leaving the junction.

(iii) This law is simply a statement of "conservation of charge". If current reaching a junction is not equal to the current leaving, charge will not be conserved.

(iv) This law is also applicable to a capacitor treating the resistance of capacitor to be zero during charging or discharging and infinite in steady state.



(v) This law is also known as junction rule or current law (KCL) or node theorem.

2. SECOND LAW

According to it “ The algebraic sum of all potential differences in closed loop is zero” i.e

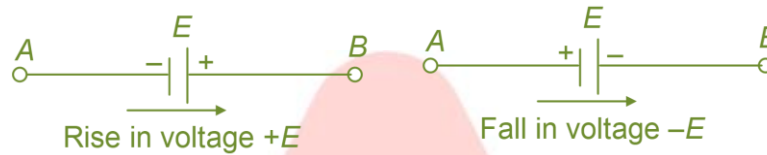
$$\sum v = 0 \quad \dots (13)$$

IMPORTANT POINTS REGARDING SECOND LAW

1. Determination of sign

(a) Sign of Battery E.M.F

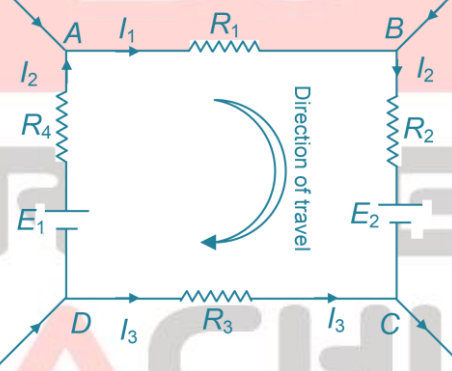
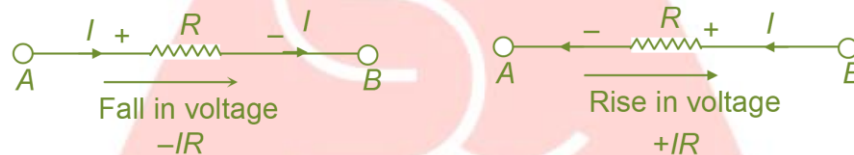
A rise in voltage should be given a +ve sign and a fall in voltage a –ve sign. Keeping this in mind, it is clear that as we go from the negative terminal of a battery to its positive terminal, there is a rise in potential, hence this voltage should be given a +ve sign. If, on the other hand, we go from +ve terminal to the –ve terminal, then there is a fall in potential, hence this voltage should be preceded by a negative sign.



It is important to note that the sign of the battery emf is independent of the direction of the current through that branch.

(b) Sign of IR drop

If we go through a resistor in the same direction as the current, then there is a fall in potential because current flows from a higher to a lower potential. Hence, this voltage fall should be taken as negative. However, if we go in a direction opposite to that of the current, then there is a rise in voltage. Hence, this voltage rise should be given a positive sign.



Consider the closed path ABCDA (as shown in the above figure). As we travel around the mesh in the clockwise direction, different voltage drops will have the following signs.

- $I_1 R_1$ is –ve (fall in potential)
- $I_2 R_2$ is –ve (fall in potential)
- $I_3 R_3$ is +ve (rise in potential)
- $I_4 R_4$ is –ve (fall in potential)
- E_2 is –ve (fall in potential)
- E_1 is +ve (rise in potential)

Using Kirchoff's voltage law, we get

$$-I_1 R_1 - I_2 R_2 + I_3 R_3 - I_4 R_4 - E_2 + E_1 = 0$$

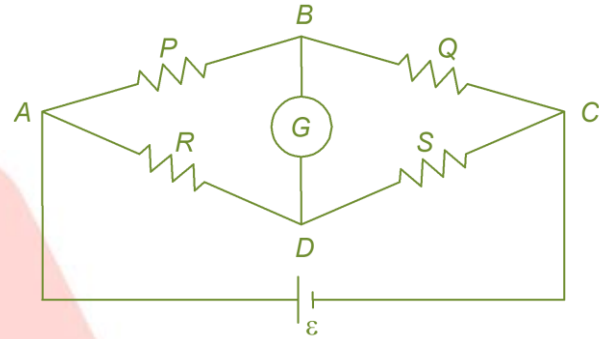
or $I_1R_1 + I_2R_2 - I_3R_3 + I_4R_4 = E_1 - E_2$

- This law represents “conservation of energy”. If the sum of potential changes around a closed loop is not zero, unlimited energy could be gained by repeatedly carrying a charge around a loop.

16 ELECTRICAL DEVICES

16.1 WHEATSTONE'S BRIDGE

For measurement of a resistance, a network made up of four resistance arms P , Q , R and S is arranged as shown. Arms AB and BC having resistances P and Q respectively are known as ratio arms.



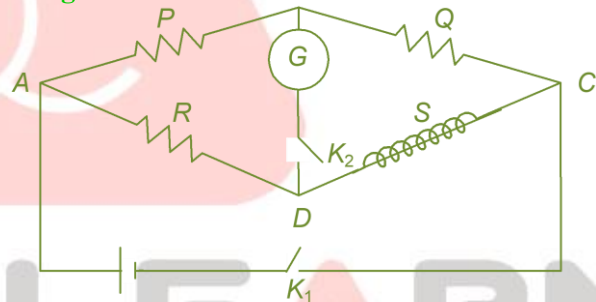
A galvanometer G is connected across B and D . A battery is connected across A and C . When the values of resistances P , Q , R and S are such that no current flows through the galvanometer G the bridge is said to be balanced. In that case B and D are at the same potential and we have the condition

$$\frac{P}{Q} = \frac{R}{S}$$

Usually S is an unknown resistance and P , Q and R are known.

Temperature measurement using wheatstone's bridge

A platinum wire about 50 cm in length is wound on a non-conducting rod with a non inductive winding. This platinum wire is connected in the arm CD of wheatstone bridge circuit as shown in the figure.



Working and Theory

- Keeping the platinum wire S is ice at 0°C the arms P and Q are made equal. The value of R is adjusted so that on closing key K_1 and K_2 the galvanometer shown no deflection. If R_0 is the resistance of platinum wire at 0°C , then

$$R_0 = \frac{RQ}{P} \quad \dots \text{(i)}$$

- Keeping the platinum wire into steam at 100°C and repeating the same procedure as in step 1, we get

$$R_{100} = \frac{R'Q}{P} \quad \dots \text{(ii)} \quad [R' = \text{resistance of arm } R]$$

- Keeping the platinum wire into the bath whose temperature $t^\circ\text{C}$ is to be determined and repeating the step - 1, we get

$$R_t = \frac{R''Q}{P} \quad \dots \text{(iii)} \quad [R'' = \text{resistance of arm } R]$$

If α is the temperature coefficient of resistance of platinum wire at $t^\circ\text{C}$, then

$$R_{100} = R_0(1 + \alpha \times 100)$$

$$\alpha = \frac{R_{100} - R_0}{R_0 \times 100} \quad \dots \text{(iv)}$$

Also $R_t = R_0(1 + \alpha t)$

$$\alpha = \frac{R_t - R_0}{R_0 \times t} \quad \dots \text{(v)}$$

From (iv) and (v)

$$\frac{R_t - R_0}{R_0 \times t} = \frac{R_{100} - R_0}{R_0 \times 100}$$

$$t = \frac{R_t - R_0}{R_{100} - R_0} \times 100 = \frac{R' - R}{R' - R} \times 100$$

16.2 METER BRIDGE

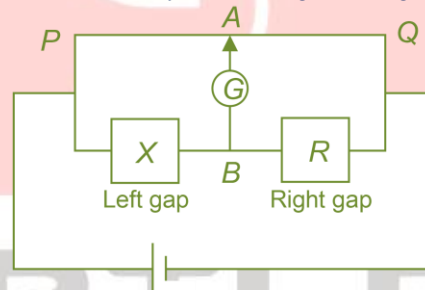
The wheatstone network is used to determine unknown resistances. The meter bridge is an instrument based on the balancing condition of wheatstone network.

The resistances R_1 and R_2 are two parts of a long wire PQ (usually 1 m long). The portion PA of the wire offers resistance R_1 and the portion QA offers resistance R_2 . The sliding contact at A is adjusted so that galvanometer reads zero.

For no deflection $\frac{R_1}{R_2} = \frac{X}{R}$

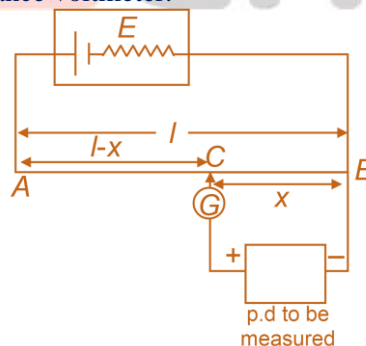
$$\Rightarrow X = R \left[\frac{R_1}{R_2} \right] = R \frac{l_1}{l_2} \quad \dots \text{(14)}$$

If R is a known resistance, then X can be measured by measuring the length l_1 and l_2



16.3 POTENTIOMETER

We already know that when a voltmeter is used to measure potential difference, its finite resistance causes it to draw a current from the circuit. Hence the p.d. which was to be measured is changed due to the presence of the instrument. Potentiometer is an instrument which allows the measurement of p.d. without drawing current from the circuit. Hence it acts as an infinite-resistance voltmeter.



The resistance between A and B is a uniform wire of length l , with a sliding contact C at a distance x from B . The sliding contact is adjusted until the galvanometer G reads zero. The no deflection condition of galvanometer

ensures that there is no current through the branch containing G and the p.d. to be measured. The length x for no deflection is called as the balancing length.

$$V_{CB} = V \text{ p.d. to be measured.}$$

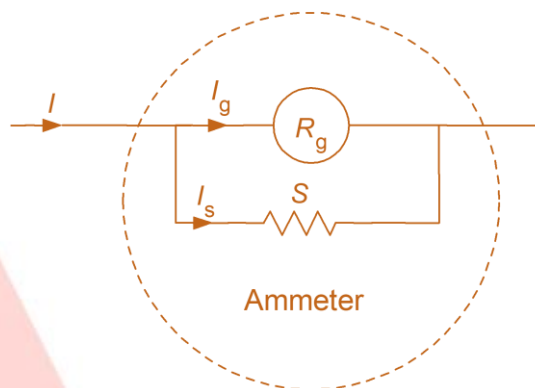
If λ is the resistance per unit length of AB .

$$V = V_{CB} = \frac{x}{l} V_{AB} = \left(\frac{V_{AB}}{l} \right) x \quad \dots (15)$$

16.4 AMMETER

An ammeter is a modified form of suspended coil galvanometer. While galvanometers can permit only very small currents to pass through them, ammeters can allow, depending upon their construction, much heavy currents to flow through them.

A suitable shunt resistance S (of very small value compared to R_g) in parallel with that of galvanometer of resistance R_g achieves this objective.



If the ammeter is designed to measure a maximum current I (full scale deflection current), then the shunt S required for the purpose is given by $I_g \cdot R_g = (I - I_g) S$

where I_g is the maximum permissible current through the galvanometer.

The resistance of ammeter is small (smaller than that of the shunt S) and for current measuring purposes it is included in series in a circuit. An ideal ammeter has zero resistance.

16.5 VOLTMETER

Voltmeter is also a modified form of a galvanometer. It is used to measure potential differences.

A suitable high resistance R is included in series with the galvanometer of resistance R_g to enable the instrument to measure voltages. If the maximum range of the voltmeter is V_0 and the maximum permissible current through the galvanometer is I_g , then the value of R is given by

$$I_g = \frac{V_0}{R + R_g} \quad \dots (17)$$



To measure the potential difference across two points in a circuit the voltmeter is connected in parallel with it. An ideal voltmeter has infinite resistance.

17 HEATING EFFECT OF CURRENT

17.1 JOULE'S LAW OF ELECTRICAL HEATING

When an electric current flows through a conductor electrical energy is used in overcoming the resistance of the wire. If the potential difference across a conductor of resistance R is V volt and if a current of I ampere flows the energy expended in time t seconds is given by

$$W = VIt \text{ joule} = I^2 R t \text{ joule} = \frac{V^2}{R} t \text{ joule}$$

The electrical energy so expended is converted into heat energy and this conversion is called the heating effect of electric current.

The heat generated in joules when a current of I ampere flows through a resistance of R ohm for t seconds is given by

$$H = I^2 R t \text{ joule} \quad \dots (17)$$

This relation is known as Joule's law of electrical heating.

17.2 ELECTRICAL POWER

The energy liberated per second in a device is called its power. The electrical power P delivered by an electrical device is given by

$$\left. \begin{aligned} P &= VI \text{ watt} \\ &= I^2 R \text{ watt} \\ &= \frac{V^2}{R} \text{ watt} \end{aligned} \right\}$$

The power P is in watts when I is in amperes, R is in ohms and V is in volts.

The practical unit of power is 1 kW = 1000 W.

The formula for power $P = I^2 R = VI = \frac{V^2}{R}$ is true only when all the electrical power is dissipated as heat and not converted into mechanical work, etc., simultaneously.

17.3 UNIT OF ELECTRICAL ENERGY CONSUMPTION

1 unit of electrical energy = 1 kilowatt-hour = 1 kWh = 36×10^5 J

Number of units consumed = $\frac{\text{watt} \times \text{hour}}{1000} = \text{kWh}$

18 CHEMICAL EFFECT OF CURRENT

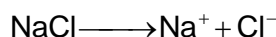
The chemical effect current is one of the earliest effects of electric current known to mankind. The chemical effect of current was first studied by Faraday in 1833.

Pure metals do not decompose when an electric current is passed through them. Substances which decompose and show chemical reaction when an electric current is passed through them are known as electrolytes. Solutions of inorganic salts in water, dilute acids and bases are examples of electrolytes. An electrolyte in solution separates into free ions, positive and negative. This process of breaking up of molecules of electrolyte (salt) is called dissociation. When an electric field is applied between the two electrodes dipped in the solution, the positively charged ions called cations move toward the negative electrode called cathode while the negatively charged ions called anions move towards the positive electrode called anode and get discharged there.

This process of decomposition of a compound by the application of an electric field is called electrolysis or chemical effect of current. The vessel in which electrolysis is carried out is called **voltmeter or electrolytic cell**.

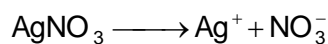
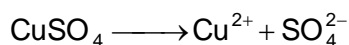
18.1 THEORY OF IONIC DISSOCIATION

In 1887 **Arrhenius** explained the phenomenon of electrolysis by an ionic dissociation theory. The molecules of an electrolyte, say NaCl, are compounds of equally charged positive and negative ions, Na^+ and Cl^- . In crystalline NaCl the ions are bound together under strong electrostatic attraction. When NaCl is dissolved in water (where dielectric constant is 81) its ionic binding reduces by a factor of 1/81. The ions, therefore dissociate from each other due to thermal agitation



and move purely at random in the solution. Because at any instant, both the positive and negative ions are present every where in the solution, the solution remains electrically neutral.

Like NaCl, the substance like CuSO_4 and AgNO_3 , when dissolved in water dissociate in the following way.

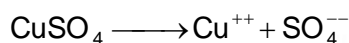


18.2 COPPER VOLTAMETER

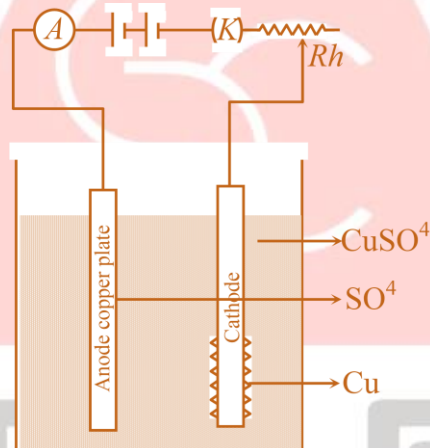
It consists of a glass vessel containing CuSO_4 solution as the electrolyte, and two copper plates as cathode and anode. The electrodes are connected across a battery along, with an ammeter (A) key (K) and rheostat (Rh) as shown in figure.

When the current is passed through the electrolyte, the Cu^{++} ions move to the cathode and get deposited on it. The SO_4^{--} ions are attracted by the anode and remove copper from the anode. The process continues but the concentration of the CuSO_4 in the solution remains constant.

Explanation: Before passing the current, some CuSO_4 molecules in the solution dissociate into its positive end negative ions, i.e.



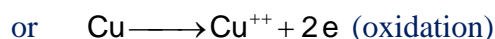
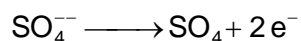
When the current is passed through CuSO_4 solution, Cu^{++} ions are attracted by the cathode and SO_4^{--} move towards the anode.



At the cathode: Each Cu^{++} ions takes two electrons and becomes neutral and gets deposited on the cathode.



At anode: Each SO_4^{--} ion loses its two electrons at the anode and becomes neutral. The electrons so released move towards the positive terminal of the battery through the external circuit. The neutral SO_4 ion combines with one copper atom of the anode and forms CuSO_4 when comes in the solution and gets dissolved.

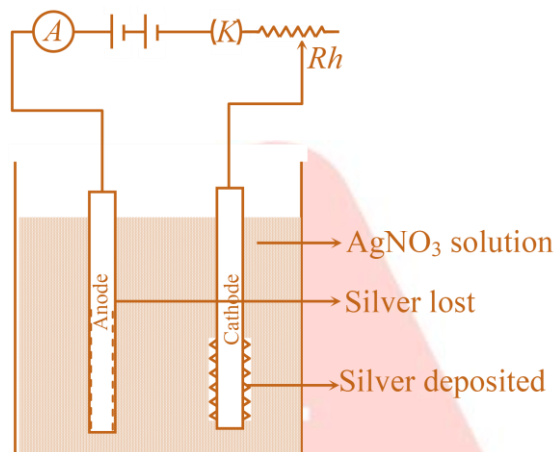


Thus, during electrolysis of CuSO_4 , copper is lost by the anode and an equal amount of copper is deposited on the cathode. The concentration of the solution remains constant.

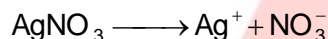
18.3 SILVER VOLTAMETER

It consists of a glass vessel containing an aqueous solution of AgNO_3 as the electrolyte and two silver plates as the electrodes. A battery along with an ammeter, key (K) and a rheostat (Rh), are connected as shown in the figure.

When a steady electric current is passed through the electrolyte, silver is deposited at the cathode and an equal amount of silver is lost by the anode. The amount of silver lost by the anode goes into the solution. Thus the concentration of the solution remains the same.

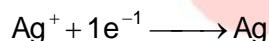


Explanation: Before passing the current AgNO_3 dissociates into Ag^+ and NO_3^- ions i.e.



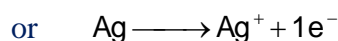
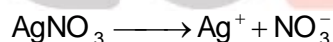
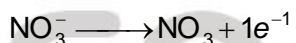
On passing the current through the electrolytes, Ag^+ ions move to the cathode and NO_3^- ions to the anode.

At cathode: Each Ag^+ ion take one electron from the cathode end becomes neutral and gets deposited around the cathode.



At anode: Each incoming NO_3^- ion loses its electron and becomes neutral. The electron so released moves to the positive terminal of the battery through the external circuit and maintains the continuity of current.

The neutral NO_3 ion combines with a silver atom and forms AgNO_3 which then goes into the solution.



Thus, during the electrolysis of AgNO_3 , silver is lost by the anode and equal amount of silver gets deposited on the cathode.

18.4 FARADAY'S LAWS OF ELECTROLYSIS

On the basis of his experimental study, Faraday gave two laws to explain the quantitative aspects of electrolysis. These are

First law: It states that the mass of the substance liberated or deposited at the cathode during electrolysis is directly proportional to the amount of charge passed through the electrolyte.

Let m be the mass of the substance liberated at the cathode when a charge q is passed through the electrolyte. Then according to Faraday's first law.

$$m \propto q$$

$$\text{or } m = Zq \quad \dots \text{ (i)}$$

when Z is a constant of proportionality and is called electro-chemical equivalent (ECE) of that substance.

Let charge q be the amount of charge that flows through the electrolyte due to the flow of a steady current I for time t seconds.

$$\therefore q = It \quad \dots \text{ (ii)}$$

$$\therefore m = ZIt$$

\therefore From equation (i) and (ii), we get

$$Z = \frac{m}{q} = \frac{m}{It}$$

$$\text{If } q = 1 \text{ C or } I = 1 \text{ A and } t = 1 \text{ sec}$$

$$\text{Then, } Z = m$$

Hence, the **electro-chemical equivalent of a substance** may be defined as the mass of the substance liberated during electrolysis when one coulomb of charge is passed through the electrolyte (or when a steady current of 1A flows through it for 1sec)

Electro-chemical equivalent of substance is generally expressed in gm/coulomb (gC^{-1}) and different substances have different values of ECE. For example, -

$$\text{ECE of hydrogen} = 1.05 \times 10^{-5} \text{ gc}^{-1} \text{ and ECE of copper} = 3.2945 \times 10^{-5} \text{ gc}^{-1}.$$

Second law: If the same amount of charge is passed through different electrolytes (or same current is passed through them for the same time interval), the masses of the substances liberated are directly proportional to their chemical equivalents.

Let m_1 and m_2 be the masses of the two substances liberated when the same current is passed through the two electrolytes for the same time let E_1 and E_2 are the chemical equivalents of the substances. Therefore, according to Faraday's second law.

$$\frac{m_1}{m_2} = \frac{E_1}{E_2}$$

Chemical equivalent of an element (E)

is defined as atomic mass per unit valency of the element, i.e.

$$E = \frac{\text{Atomic Mass}}{\text{Valency}} = \frac{M}{p}$$

Relationship between Electro-chemical Equivalent (Z) and Chemical Equivalent (E)

Suppose a steady current I flows for time t through two different voltmeters connected in series. Let the masses of the substance liberated at their cathodes be m_1 and m_2 and E_1 and E_2 be their chemical equivalents.

Then, from Faraday's second law.

$$\frac{m_1}{m_2} = \frac{E_1}{E_2} \quad \dots \text{ (i)}$$

From Faraday's law

$$\frac{m_1}{m_2} = \frac{Z_1 I t}{Z_2 I t} = \frac{Z_1}{Z_2} \quad \dots \text{(ii)}$$

From equation (i) and (ii) we get

$$\frac{E_1}{E_2} = \frac{Z_1}{Z_2} \quad \text{or} \quad \frac{E_1}{Z_1} = \frac{E_2}{Z_2} = \text{constant}$$

$$\therefore \frac{E}{Z} = \text{constant}$$

This is called Faraday constant and is denoted by F

$$\therefore \frac{E}{Z} = F$$

$$\text{or} \quad E = ZF \quad \dots \text{(18)}$$

18.5 FARADAY CONSTANT (F)

Consider one mole of an element liberated during electrolysis

\therefore Let M be its atomic mass and p be the valency of the element.

\therefore Charge required to liberate one atom of the element at the cathode = pe

\therefore Charge required to liberate 1 mole, i.e., $q = Npe$

where N is Avogadro number

\therefore From Faraday's first law,

$$m = Zq$$

$$\text{or} \quad M = Z \cdot pNe$$

$$\text{or} \quad \frac{M}{p} = Z \cdot Ne \quad \text{but} \quad \frac{M}{p} = E$$

$$\text{or} \quad E = Z \cdot (Ne)$$

$$\text{But} \quad Ne = 6.023 \times 10^{23} \times 1.6 \times 10^{-19} = 96500 \text{ c mole}^{-1}$$

Comparing equation, we conclude

$$F = Ne = 96500 \text{ c mole}^{-1}$$

Thus **Faraday constant (F)** may be defined as the amount of charge required to liberate 1 mole of a substance during electrolysis.

18.6 APPLICATION OF ELECTROLYSIS

It finds a variety of applications in industry. Some of them are as under

(i) Electroplating: It is the process in which a thin layer of a superior metal is coated over the surface of an inferior metal.

For example, gold coating over a silver ornament or silver coating over a copper vessel. The article to be coated is made the cathode and the metal to be coated is made the anode. The solution of a soluble salt of the superior metal is used as the electrolyte. When the current is passed, electrolysis takes place and the layer of the metal is deposited on the article. Apart from giving an attractive look, it helps to protect the articles from corrosion.

(ii) Electrotyping: The process of obtaining the exact copy of a page composed of metallic type used in printing work by using electrolysis is called electrotyping.

The impression of the page is first obtained on a sheet of wax. It is, then, coated with graphite powder to make it conducting. It is, then, electroplated with copper in a copper voltameter. This is how we obtain the exact copy of the metallic typed page. Gramophone records are also manufactured using the same technique.

(iii) **Purification of Metals:** Metals can be extracted from their ore or an impure sheet by electrolysis. The ore or the impure sheet is made the anode and a pure sheet of that metal is the cathode. The solution of a salt of that metal is taken as the electrolyte.

When a steady current is passed through the electrolyte, the atoms of the metal from the anode come into the electrolyte and then deposit on the cathode. Thus, the metal gets purified.

(iv) **Manufacturing Chemicals:** Caustic soda is manufactured by the electrolysis of sodium chloride solution. It is also used for commercially preparing hydrogen and oxygen. It is also employed for chemical analysis of compounds.

(v) **Medical Applications:** Electrolysis is used for local anaesthesia, nerve stimulation (especially for polio) and for removing unwanted hair from any part of the body.

18.7 ELECTRO-CHEMICAL CELLS

An electro-chemical cell is a device in which a chemical reaction proceeding at a steady rate converts chemical energy into electrical energy.

Electro-chemical cells are of the two types

- (i) Primary cells
- (ii) Secondary cells

Primary cell: The cell in which the chemical energy is converted into electrical energy due to an irreversible chemical reaction is called a primary cell.

Voltaic cell, Leclanche cell and Daniel cell are the examples of primary cells.

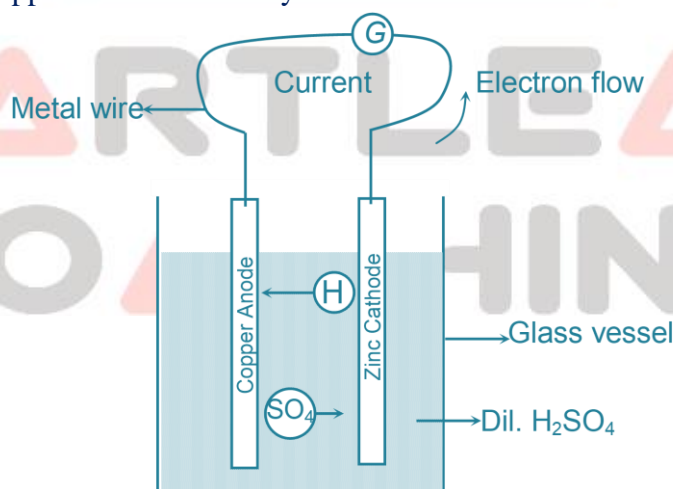
Secondary cell: The cell in which the chemical energy is converted into electrical energy due to a reversible chemical reaction is called a secondary cell. Such cells are therefore, rechargeable. They are also known as storage cell or accumulators. Edison's alkali cell, and lead acid cell are the two commonly used secondary cells.

18.8 PRIMARY CELLS

Simple Voltaic Cells

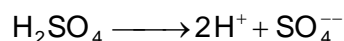
This cell was developed by Volta in 1800

It consists of a glass vessel containing dil H_2SO_4 which acts as electrolyte. Two rods, one of copper and the other of zinc are dipped in the acid. They act as the anode and cathode respectively.



Chemical Action of the Cell

Dil H_2SO_4 dissociates into positive hydrogen ions and negative sulphate ions. i.e

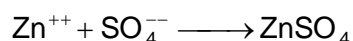


Some H^+ ions from the acid go to the copper plate, take free electrons from the copper rod and become neutral H atoms. The copper electrode on losing its free electrons becomes positively charged till it attains a potential of 0.46 V w.r.t. the acid.

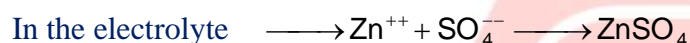
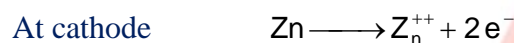
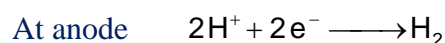
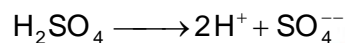
Some zinc ions (Zn^{++}) from the zinc electrode go into the acid and in the process, gives up two electrons each on the electrode. Thus, the zinc electrode becomes negatively charged till it attains a potential of -0.62 V w.r.t. the acid.

$$\begin{aligned} \therefore \text{Potential difference between the two electrodes i.e. the emf of the cell} \\ &= 0.46 - (-0.62) \\ &= 1.08 \text{ V} \end{aligned}$$

Inside the electrolyte Zn^{++} ions combine with SO_4^{--} and form $ZnSO_4$. i.e.



The chemical reactions which occur in the voltaic cell can be summarised as under



Hydrogen gas liberated is bubbled out

18.9 DEFECTS OF A VOLTAIC CELL

Voltaic cell suffers from the following two defects

(i) Local action

The zinc plate used in the cell contains the impurities such as iron, lead, carbon etc. The atoms of these impurities along with zinc come in contact with the electrolyte i.e. dil H_2SO_4 and constitute minute voltaic cells. As a consequence, a small local currents are set up in the zinc electrode. These local currents not only reduce the current in the external circuit but cause the wastage of zinc even when the cell is not used. This is called local action. This defect can be avoided by coating the zinc plate with mercury, i.e. by amalgamating it. The layer of mercury does not allow the impurities to come in contact with acid. Hence local action is eliminated.

(ii) Polarisation

In a voltaic cell (even in other primary cells) the positive hydrogen ions move to copper electrode from the electrolyte and give off their positive charges i.e. gain electron from copper rod and become neutral. These neutral hydrogen atom combine to form free hydrogen molecules and bubble out the electrolyte. But in the process hydrogen gas is partly deposited as a layer around the copper electrode. Due to this the current supplied by the cell falls to very low value. It is because

- (i) Hydrogen being bad conductor increases the internal resistance of the cell.
- (ii) The incoming H^+ ions cannot give up their positive charge to the copper electrode and are repelled back.

A back emf is thus set up in the cell. These two factors reduce the emf of the cell and hence the current supplied by it. This defect can be prevented either by

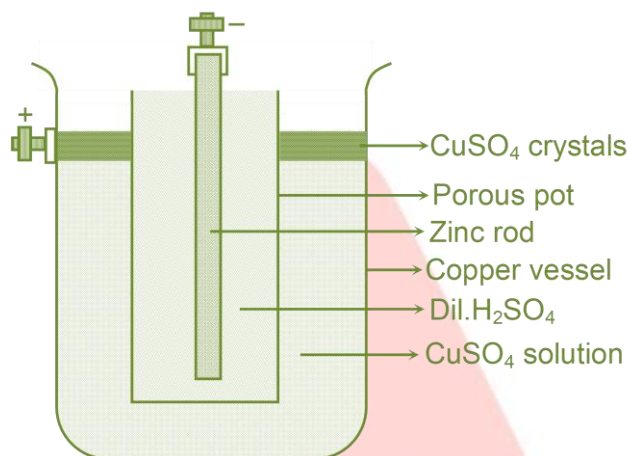
- (a) Talking out the copper electrode from time to time and rub it with a brush to remove the hydrogen layer or

(b) By using depolarisers (oxidizing agents) such as MnO_2 , HNO_3 , CuSO_4 etc. to oxidise the hydrogen into water.

Daniel Cell

It consists of a copper vessel containing CuSO_4 solution. The copper vessel itself acts as anode.

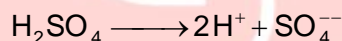
A porous pot containing dil H_2SO_4 is placed in the copper vessel. An amalgamated zinc rod placed inside the porous pot acts as the cathode. Some CuSO_4 crystals are kept in the perforated shell near the top of the vessel. This is done to keep the concentration of CuSO_4 solution constant in the vessel.



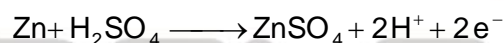
Dil H_2SO_4 acts as the electrolyte and CuSO_4 as the depolariser.

Chemical reactions of the cell: $\text{Zn} \longrightarrow \text{Zn}^{++} + 2\text{e}^-$

In the porous pot:



\therefore The combined reaction is



The electrons released in such reactions are collected by the zinc electrode and thus it attains a negative potential.

The hydrogen ions (H^+) pass through the pores of the porous pot and enter CuSO_4 solution which contains the Cu^{++} and SO_4^{--} ions.

Here H^+ and SO_4^{--} ions combine and form H_2SO_4 . i.e.

Inside copper vessel: $2\text{H}^+ + \text{SO}_4^{--} \longrightarrow \text{H}_2\text{SO}_4$

The positive ions of copper (Cu^{++}) move to the copper vessel where they give up their charge and deposit on the vessel.

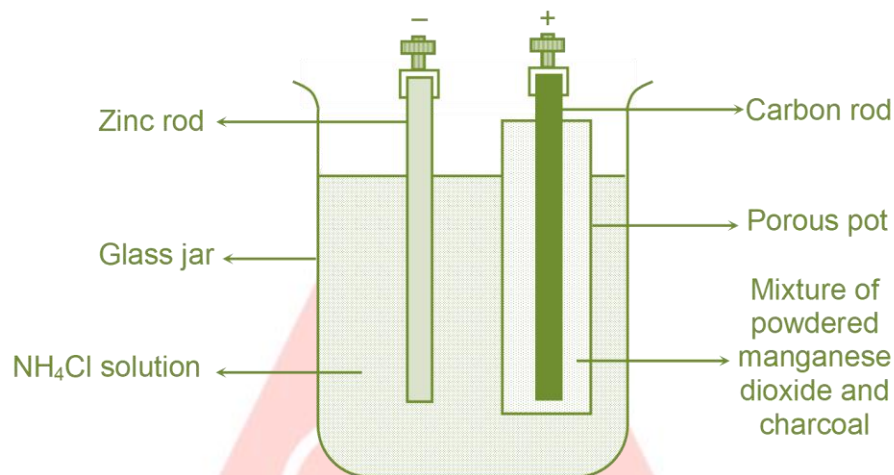
At anode $\text{Cu}^{++} + 2\text{e}^- \longrightarrow \text{Cu}$

The emf of Daniel cell is about 1.09 V and it can supply a steady current for reasonably long durations.

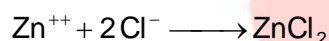
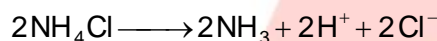
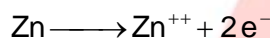
Leclanche Cell

It consists of glass vessel containing the saturated solution of NH_4Cl which acts as the electrolyte. An amalgamated zinc rod dipped in the solution acts as the cathode.

A porous pot consisting of a carbon rod and a mixture of powdered carbon and manganese dioxide is placed in the vessel. The carbon rod in the porous pot acts as the anode and MnO_2 as the depolariser. Powdered carbon (charcoal) reduces the internal resistance of the cell by making MnO_2 conducting.



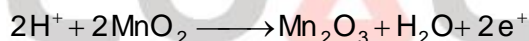
Chemical reactions of the cell



\therefore The combined reaction is

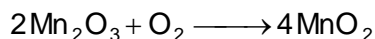


Ammonia gas liberated in the reaction escapes out. The electrons released in the reaction are collected by zinc rod. Due to which it attains a negative potential. H^{+} ions pass through the pores of the porous pot and react with MnO_2 to form water i.e.



Here e^{+} represents one unit of positive charge. The positive charge is given up to the carbon electrode. Due to which it attains positive potential w.r.t. the electrolyte.

The Mn_2O_3 is oxidised to MnO_2 by the atmospheric oxygen i.e.



Leclanche cell has one defect. It cannot supply a steady current for longer time intervals. It is because of slow depolarising action of MnO_2 . It cannot oxidise the hydrogen as fast as it is formed. Hence some hydrogen is deposited around the carbon rod and the cell gets partially polarised. This can be

prevented by allowing the cell to rest for some time. During this period, the deposited hydrogen gets oxidised into water and the cells regains its initial strength of emf.

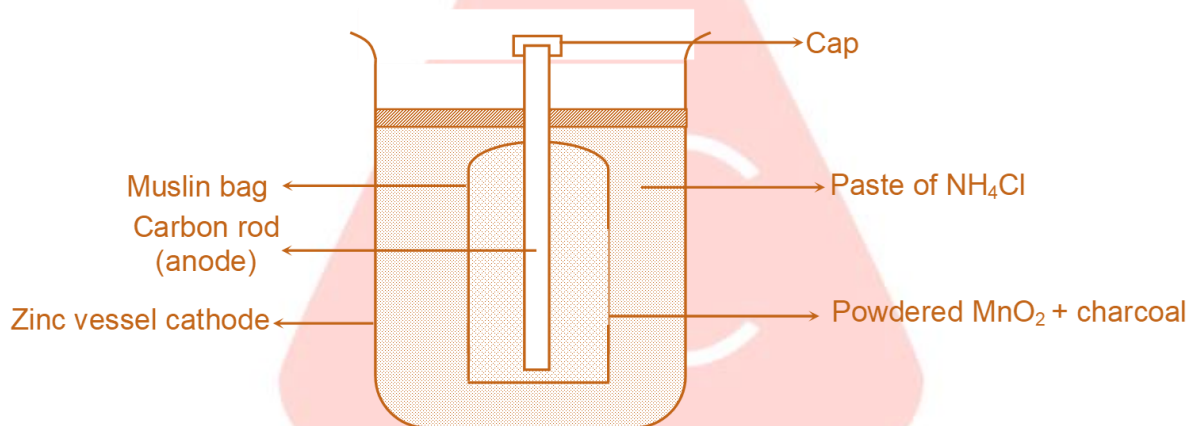
Hence, a Leclanche cell is suitable when intermittent current is required.

The emf of this cell is about 1.5 V.

18.10 DRY CELL

It is a portable form of Leclanche cell. It consists of a small zinc vessel which acts as the cathode. The vessel contains the moist paste of ammonium chloride (NH_4Cl), Zinc chloride (ZnCl_2) and gum. NH_4Cl acts as the electrolyte and ZnCl_2 helps in maintaining the moisture of the paste. A carbon rod with a brass cap is placed at the centre of the vessel and acts as the anode of the cell.

The carbon rod is surrounded by a compressed mixture of MnO_2 and charcoal in powder form in a muslin bag. The vessel is sealed at the top with pitch or shellac to prevent evaporation. A small hole is, however provided at the top for allowing ammonia to escape out shown in the figure. The emf of a dry cell is about 1.5 V.



18.11 SECONDARY CELLS

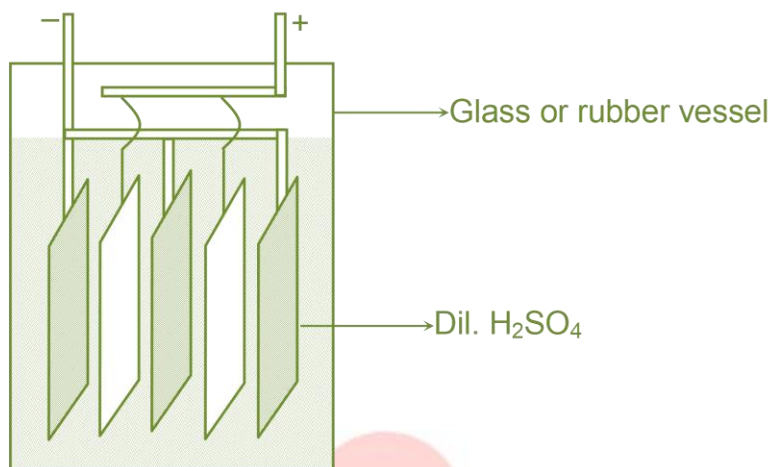
(i) Lead acid accumulator

It consists of two sets of perforated lead Plate arranged alternately parallel to each other and kept separated by thin strips of rubber, plastic or wood.

The perforations or holes in one set of alternative plates shown in the figure are filled with spongy lead (Pb) and connected together to a lead rod which acts as the negative terminal i.e. the cathode of the cell.

The plates of the other set coated with the paste of lead per oxide (PbO_2) are connected to another rod of lead which acts as the anode of the cell.

The entire arrangement is immersed in dil H_2SO_4 (electrolyte) contained in a glass or hard rubber vessel.

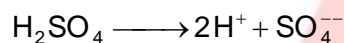


Working

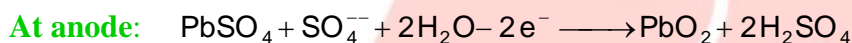
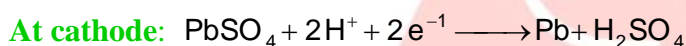
(i) Charging process

The accumulator is first charged with the help of a dc charger battery such that its positive terminal is connected to the anode of the accumulator and the negative terminal to the cathode.

The electrolyte H_2SO_4 dissociates into its positive and negative ions, i.e.

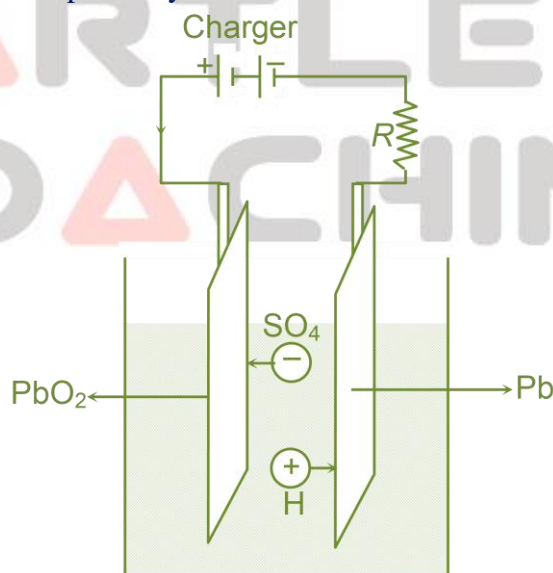


H^+ ions move to the cathode and SO_4^{--} ions to the anode, as shown in figure. Consequently, the following reactions take place.



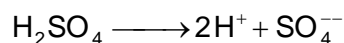
(Actually before charging both, the anode and cathode had the coating of PbSO_4 on them.)

Above reactions show that during the charging, the electrons move from the anode to the cathode and hence the potential difference between the electrodes (emf) of the accumulator increases. We also find that in the process H_2SO_4 is formed and water is consumed and the cathode and anode get deposited with spongy lead (Pb) and PbO_2 respectively.

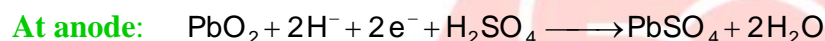
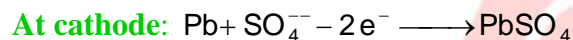
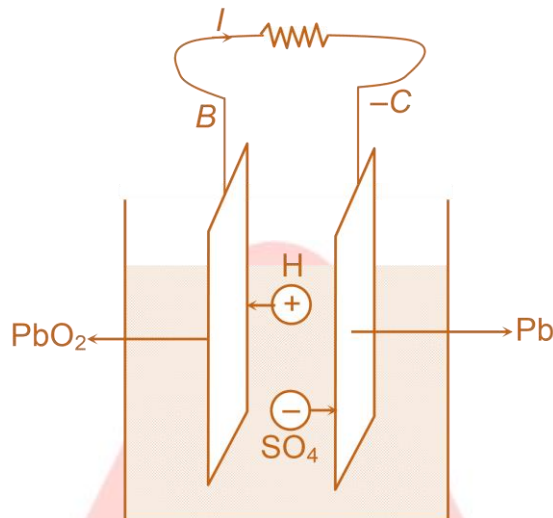


(ii) Discharging: When the two electrodes of the cell are connected to an external resistance, as shown in the figure, a current flows in the external circuit from the anode to the cathode.

The following chemical reaction occurs inside the cell



H^+ ions move to the anode and SO_4^{--} ions to the cathode. On reaching their electrodes, they give up their charges and forms lead sulphate (PbSO_4). Following reactions occur at the two electrodes



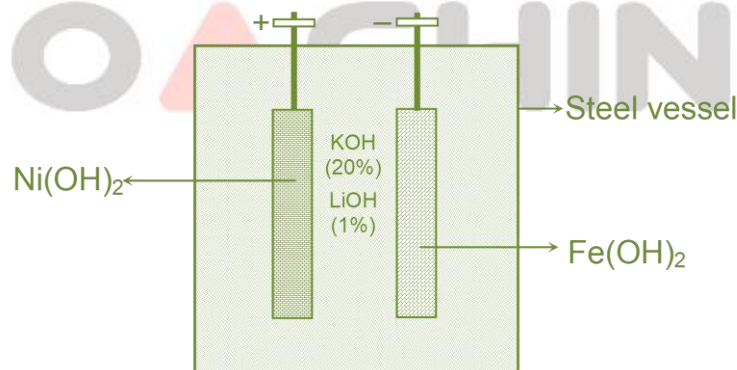
Thus, we find that during the discharging process, the active material of the electrode is converted into PbSO_4 and the sulphuric acid is slowly converted into water. Hence, the density of the acid falls and the emf of the cell falls to about 1.08 V.

The emf of a fully charged lead acid accumulator is about 2.2 V.

(iii) Edison cell or Alkali accumulator (Ni – Fe)

It consists of steel vessel constraining a 20% solution potassium hydroxide (KOH) in distilled water and 1% lithium hydroxide (LiOH). KOH acts as the electrolyte of the cell while LiOH makes it conducting. Two perforated steel grids acts as the electrodes of the cell.

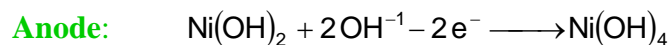
The holes of the anode grid are stuffed with $\text{Ni}(\text{OH})_2$ and traces of nickel to make it conducting. The holes of the cathode grid are stuffed with $\text{Fe}(\text{OH})_2$ and traces of mercury oxide to decrease the internal resistance shown in the figure.



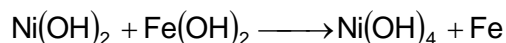
Working: Potassium hydroxide (KOH) dissociates into K^+ ions and OH^- ions.

During charging: The cell is connected to a dc charger battery such that the anode of the cell is connected to the positive terminal of the charger and the cathode to the negative terminal of the charger. A current

flows from the anode to the cathode inside the cell. As a result, OH^- ions are attracted by the anode and K^+ ions by the cathode. On reaching their respective electrodes, the ions lose their charge and react with them. Following reactions occur at the electrodes.



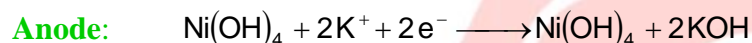
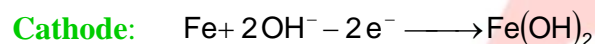
Thus complete reaction occurring inside the cell during charging is



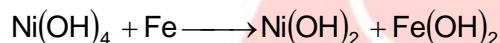
Hence, during charging, the density of electrolyte (KOH) remains the same but electrons move from anode to cathode, raising the potential difference between the two electrodes of the cell. The emf of a fully charged Edison cell is 1.36 V.

During discharging: When the two terminals of the cell are connected to an external resistance, a current flows from the anode to the cathode through the external resistance and from cathode to anode inside the cell. Hence the cell begins to discharge. During the process, K^+ ions are attracted by the anode and OH^- ions by the cathode.

Following reactions occur at the electrodes.



Thus, complete reaction occurring inside the cell during charging is



Hence, during discharging the electrons move from cathode to anode, decreasing the potential difference between the two electrodes. When the emf of the cell becomes less than 1.1 V, it requires recharging.

18.12 SOLID STATE CELL

Solid state cells are very small sized dry cells used in wrist watches, video games, calculators, hearing aids etc. Since they look like a button in shape, they are also known as button cells.

Although different solid state cells used positive and negative electrode of different size and material, they have the same basic structure in their construction.

The basic geometry of a solid state cell is given in the figure (i) using a solid electrolyte with mobile cation M^+ and anion X^- . Either one of these ions or both can move.

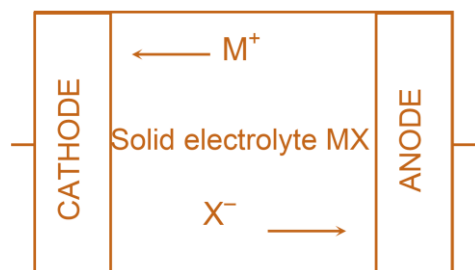
Solid electrolytes are generally available in the form of gels, polymers, composites, polycrystalline solids or thin solid films.

In a lithium solid state cell, the basic electrochemical reaction with the electrode (say I_2) is

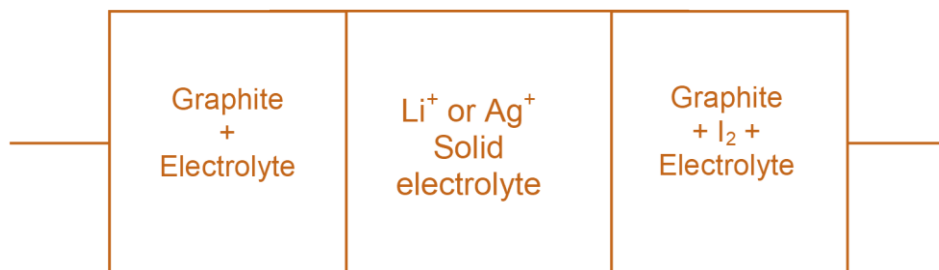


Some electrolyte is also mixed in the cathode or anode to decrease polarisation.

1. Solid state cell



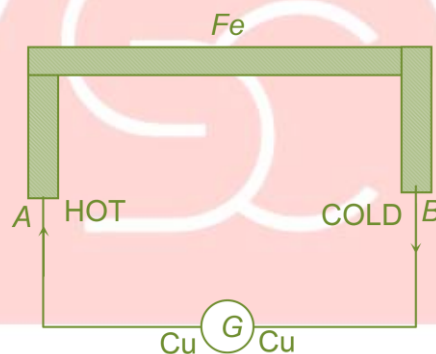
2. Simple lithium/silver solid state cell



19 THERMOELECTRIC EFFECT OF CURRENT

19.1 SEEBECK EFFECT

Seebeck in 1821 found that if two wires of different metals, say copper and iron, are joined at their ends *A* and *B*, through a low resistance galvanometer *G* to form a closed circuit, and if one of the junctions, say *A*, is heated and the other junction *B* is kept cold, the galvanometer shows a deflection shown in the figure. This must be due to a current in the circuit called thermo electric current which must further be due to certain emf called thermo emf. The assembly of two different metals joined at their ends to have two junctions in a circuit, is called a thermocouple. The phenomenon is known as thermo electric effect as electricity has been produced from heat.



Thus Seebeck effect is the phenomenon of generation of an electric current in a thermocouple by keeping its two junctions at different temperature.

Seebeck also found that for a given difference of temperature of two junctions, the larger is the gap in Seebeck series between the metals forming the thermo couple, the greater will be the thermo emf generated.

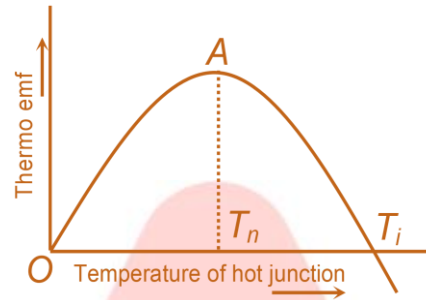
19.2 ORIGIN OF THERMO EMF

We know that number of electrons per unit volume (i.e. electron density) of a conductor depends on material of the conductor. In general, it is different for different conductors.

When two different metals are brought into contact, at the junction, the free electrons tend to diffuse from the metal with greater free electron density to the other with lower free electron density. Due to this diffusion, a potential difference is developed at the junction of the two metals called contact potential. When both the junctions are at the same temperature, the contact potentials at the two junctions will be the same. Hence no current flows in the thermocouple. But if one junction is heated up, the rate of diffusion of free electrons at that junction will change. As a result of it, the contact potentials at the two junctions will become different and there will be an effective potential difference emf in the circuit, called thermo emf.

19.3 EFFECT OF TEMPERATURE ON THERMO EMF

- (i) When the two junctions of the thermocouple are at same temperature (say 0°C), galvanometer shows no deflection i.e. thermo emf is zero.
- (ii) As the temperature of the hot junction increases, keeping the cold junction at constant temperature 0°C , the thermo emf increases with the increase in temperature till it becomes maximum at a certain temperature.



The temperature of the hot junction at which thermo emf. in a thermocouple is maximum is called **neutral temperature**. It is represented by T_n in the graph.

The value of neutral temperature

- (a) is constant for a thermocouple
- (b) depends upon the nature of materials forming the thermocouple
- (c) is independent of the temperature of cold junction

For Cu-Fe thermocouple, neutral temperature is 270°C , whatever may be the temperature of cold junction.

- (iii) when hot junction is heated beyond neutral temperature, thermo emf starts decreasing instead of increasing.
- (vi) At another particular temperature of hot junction, the value of thermo emf becomes zero. On heating slightly further, the direction of thermo emf is reversed. It is due to the number densities and rates of diffusion of electrons in the two metals used are reversed.

The temperature of the hot junction at which the thermo emf in a thermocouple becomes zero and just beyond, it reverses its direction, is called temperature of inversion. It is represented by T_i . The value of temperature of inversion depends upon.

- (a) the temperature of the cold junction and
- (b) the nature of materials forming the thermo-couple.

Thus for a given thermocouple, there will be different values of temperature of inversion corresponding to different values of temperature of cold junction.

19.4 RELATION BETWEEN T_n and T_i

It is found that temperature of inversion (T_i) is as much above the neutral temperature (T_n) as neutral temperature is above the temperature of the cold junction (T_0 , say) i.e.

$$T_i - T_n = T_n - T_0 \text{ or } T_i = 2T_n - T_0$$

$$\text{or } T_n = \frac{T_i + T_0}{2} \quad \dots (19)$$

19.5 THERMO-ELECTRIC POWER

Thermo electric power is defined as the rate of change of thermo emf with temperature. It is also called **Seebeck coefficient** and is denoted by S .

From experimental study, it was concluded that the variation of thermo emf E with the temperature T of the hot junction, when cold junction is at 0°C is a parabolic curve represented by the equation

$$E = \alpha T + \frac{1}{2} \beta T^2 \quad (i)$$

when α and β are constants which depend upon the nature of the metals forming the thermocouple and the temperature difference of the two junctions.

The thermoelectric power (called Seebeck coefficient) is given by

$$S = \frac{dE}{dT} = \alpha + \beta T \quad (ii)$$

It means, $S \propto T$

Hence the graph between $S = \left[\frac{dE}{dT} \right]$ and T will be a straight line. Since neutral temperature (T_n)

is that temperature of the hot junction at which thermo emf in a thermocouple is maximum, therefore at neutral temperature

$$\frac{dE}{dT} = 0 \quad \text{and} \quad T = T_n$$

From (ii), $0 = \alpha + \beta T_n$ or $T_n = -\alpha/\beta$

If cold junction is at 0°C then $T_i = -2\alpha/\beta$.

19.6 PELTIER EFFECT

If a current is passed through a junction of two different metals, the heat is either evolved or absorbed at that junction. This effect is known as Peltier effect. The quantity of heat absorbed or evolved at a junction is proportional to the quantity of charge crossing that junction. If the direction of current is reversed, the heating effect at that junction is also reversed. Thus Peltier effect is reversible effect.

Peltier co-efficient. Peltier co-efficient is defined as the amount of heat energy absorbed or evolved at a junction of two different metals when one coulomb charge passes through that junction. It is denoted by π and is given by

$$\pi = \frac{\text{Peltier heat}}{\text{charge flowing}}$$

S.I. unit of π is J C^{-1}

Peltier co-efficient depends upon (i) the nature of the two metals forming the junction and (ii) temperature of the junction. Peltier effect has different values for hot and cold junctions.

19.7 THOMSON'S EFFECT

If two parts of a single conductor are maintained at different temperatures, an emf is developed between them. The emf so produced is called Thomson's emf. If the steady current is passed through an unequally heated conductor, an absorption or evolution of heat in excess of Joule's heat, takes place in the conductor.

Thus Thomson's effect is the absorption or evolution of heat in excess of Joule heat when current is passed through an unequally heated conductor. Thomson effect is reversible effect.

Thomson's coefficient: Thomson's co-efficient is defined as the emf that exists between the two points of a uniform conductor which has a temperature difference of 1°C (or 1K). It is denoted by σ .

Let dV = potential difference between two points of a metal rod.

dT = temperature difference between the same two points of rod

Then Thomson's co-efficient of the rod is given by

$$\sigma = \frac{dV}{dT} \quad \text{or} \quad dV = \sigma dT$$

Total Thomson's emf between temperature T_1 and T_2 of a metal rod is given by

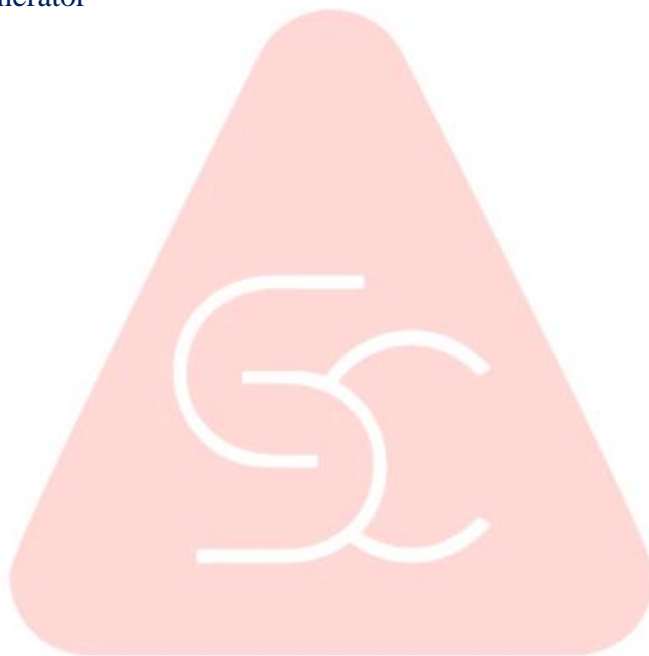
$$V = \int_{T_2}^{T_1} \sigma dT \quad \dots (20)$$

Thomson's co-efficient is also defined as the amount of heat energy evolved or absorbed between the two points of a conductor maintained at a unit temperature difference when unit current is passed for one second through the conductor.

19.8 APPLICATIONS OF THERMOELECTRIC EFFECTS

Important applications of thermoelectric effects are as follows:

- (i) To measure temperature; using thermoelectric thermometers
- (ii) To detect heat radiation; using thermopile
- (iii) Thermoelectric refrigerator
- (iv) Thermoelectric generator



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