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Unit-2 Current Electricity

Book Back Question and Answer

1. **Derive an expression for drift velocity.**

The acceleration $\vec{a}$ experienced by the electron in an electric field $\vec{E}$ is given by,

$$\vec{a} = \frac{-e\vec{E}}{m} \qquad [\because F = -eE]$$

- The drift velocity $\vec{v}_d$ is given by,

$$\vec{v}_d = \vec{a}\tau$$

$$\vec{v}_d = \frac{-e\tau}{m}\vec{E}$$

$$\vec{v}_d = -\mu\vec{E}$$

- Here $\mu = \frac{e\tau}{m}$ is the mobility of the electron.

$$\mu = \frac{|\vec{v}_d|}{|\vec{E}|}$$

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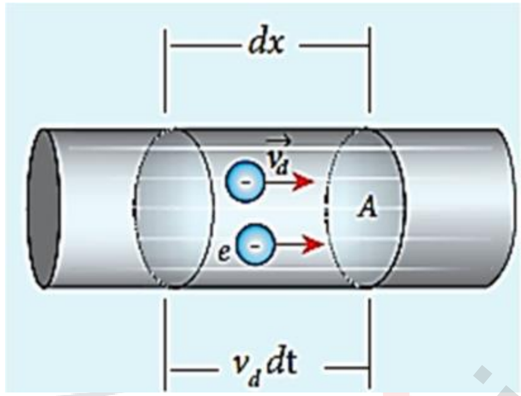
2. **Describe the microscopic model of current and obtain general form of Ohm's law.**

Consider a conductor with area of cross section A and an electric field $\vec{E}$ applied from right to left. Suppose there are n electrons per unit volume in the conductor, each moves with the same drift velocity $\overrightarrow{V_d}$ as shown in Figure.



❖ The distance travelled by the electrons within a small time interval dt,

$$dx = v_d dt \qquad \left[\because \quad v_d = \frac{dx}{dt}\right]$$

❖ No. of electrons available in the volume Adx is,

$$= Adx \times n$$

Substituting dx value,

$$= Av_d dt \times n$$

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- Total charge in volume element(Adx) is,

$$dQ = \begin{pmatrix} electron \\ charge \end{pmatrix} \times \begin{pmatrix} no. of\ electrons\ in \\ the\ volume\ element(Adx) \end{pmatrix}$$

$$dQ = (e) \times Av_d dt\ n$$

- Hence the current,

$$I = \frac{dQ}{dt} = \frac{neAv_d dt}{dt}$$

$$I = neAv_d$$

- Now Current density is defined as,

$$J = \frac{I}{A}$$

- Substituting the value of I, we get,

$$J = \frac{neAv_d}{A}$$

$$J = nev_d$$

- In vector form,

$$\vec{J} = ne\vec{v}_d$$

$$\vec{J} = -\frac{ne^2\tau}{m}\vec{E} \qquad \left[\because\ \vec{v}_d = \frac{-e\tau}{m}\vec{E}\right]$$

$$\vec{J} = -\sigma\vec{E}$$

Where $\sigma = \frac{ne^2\tau}{m}$ is called conductivity.

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- But conventionally, we take direction of $\vec{J}$ is along $\vec{E}$. So that,

$$\vec{J} = \sigma \vec{E}$$

- This equation is called microscopic form of Ohm's law.

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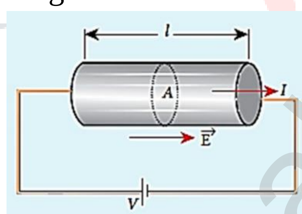
3. Obtain the macroscopic form of Ohm's law from its microscopic form and discuss its limitation.

Consider a segment of wire of length *l* and cross sectional area A as shown in Figure.



For simplicity, When a potential difference V is applied across the wire, a net uniform electric field is created in the wire which constitutes the current.

$$V = El$$

$$E = \frac{V}{l}$$

We know the magnitude of current density,

$$J = \sigma E = \sigma \frac{V}{l}$$

But $J = \frac{I}{A}$. Thus,

$$\frac{I}{A} = \sigma \frac{V}{l}$$

$$V = I\left(\frac{l}{\sigma A}\right)$$

$$V = IR$$

Where $R = \frac{l}{\sigma A}$ is called resistance of the conductor.

Therefore, the macroscopic form of ohm's law can be stated as,

V = IR

Limitations of Ohm's law:

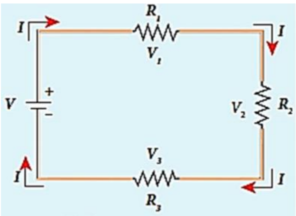
According to Ohm's law V/I = Constant. This constant is R. But when temperature varies, R is not constant. Hence Ohm's law is not valid here.

In some materials like diode, V is not not directly proportional to I. They are called non-ohmic devices. Here also Ohm's law is invalid.

4. Explain the equivalent resistance of a series and parallel resistor network.

(a) Resistors in series:

Consider three resistors R1, R2 and R3 are connected end to end to form series connection as shown in figure



(a) Three resistors in series

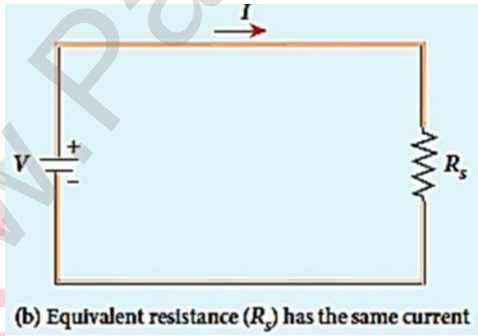
The amount of charge passing through R1, R2 and R3 are same. But the total voltage V given from the battery is divided in each resistor as,

$V_1 = IR_1$, $V_2 = IR_2$ and $V_3 = IR_3$

Now the total voltage V can written as,

$$V = V_1 + V_2 + V_3$$
$$V = IR_1 + IR_2 + IR_3$$
$$V = I(R_1 + R_2 + R_3)$$
$$V = IR_S$$

Where $R_S = R_1 + R_2 + R_3$ is the equivalent resistance.

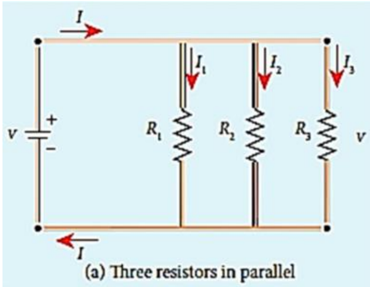


(b) Equivalent resistance (R_s) has the same current

Thus, when several resistances are connected in series, the total or equivalent resistance is the sum of the individual resistances as shown in the figure above.

(b) Resistors in parallel:

Consider three resistors R_1, R_2 and R_3 are connected across the same potential to form parallel connection as shown in figure.



(a) Three resistors in parallel

The total current I leaves from the battery is divided in each resistor as,

$$I_1 = \frac{V}{R_1}, I_2 = \frac{V}{R_2} \text{ and } I_3 = \frac{V}{R_3}$$

Now the total current I can written as,

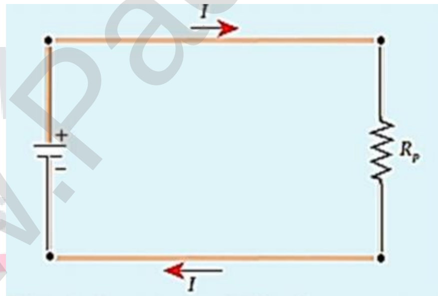
$$I = I_1 + I_2 + I_3$$
$$I = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$
$$I = V\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$
$$I = \frac{V}{R_P}$$

Here,

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Where R_P is the equivalent resistance of parallel connection.

Thus, when a number of resistors are connected in parallel, the sum of the reciprocal of the values of resistance of the individual resistor is equal to the reciprocal of the effective resistance of the combination as shown in figure below.



(b) Equivalent resistance (R_p) has the same current

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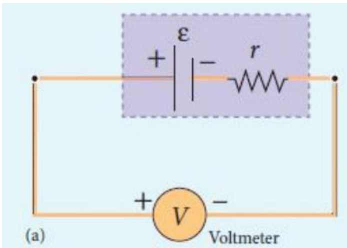
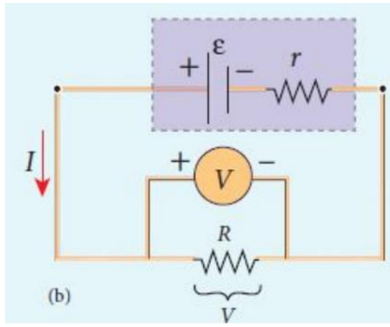
5. **Explain the determination of the internal resistance of a cell using voltmeter.**

The emf of cell ε is measured by connecting a high resistance voltmeter across it without connecting the external resistance R as shown in Figure(a).



Then, external resistance R is included in the circuit and current I is established in the circuit. The potential difference across R is equal to the potential difference across the cell (V) as shown in Figure(b).



The potential drop across the resistor R is, V = IR ------------------------(1)

Due to internal resistance r of the cell, the voltmeter reads a value V, which is less than the emf of cell ε. It is because, certain amount of voltage (Ir) has dropped across the internal resistance r.

$$V = \varepsilon - Ir$$

$$Ir = \varepsilon - V \longrightarrow (2)$$

Dividing equation(2) by(1),we get,

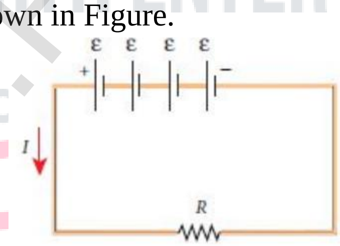
$$\frac{Ir}{IR} = \frac{\varepsilon - V}{V}$$

$$r = \left(\frac{\varepsilon - V}{V}\right) R$$

Since ε, V and R are known, internal resistance r can be determined. We can also find the total current that flows in the circuit.

6. Explain about cells in series.

Suppose n cells, each of emf ε volts and internal resistance r ohms are connected in series with an external resistance R as shown in Figure.



The total emf of the battery = nε

The total resistance in the circuit = nr + R

By Ohm's law, the current in the circuit is

$$I = \frac{Total\ emf}{Total\ resistance} = \frac{n\varepsilon}{nr + R}$$

Case(a) : If r << R, then,

$$I = \frac{n\varepsilon}{R} \approx nI_1$$

Where I_1 is the current due to single cell.

$$I_1 = \frac{\varepsilon}{R}$$

Thus, if r is negligible when compared to R the current supplied by the battery is n times that supplied by a single cell.

Case (b) : If r >> R, then,

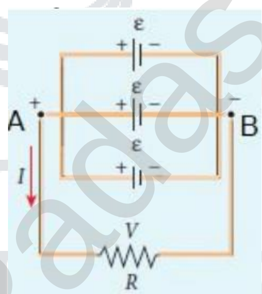
$$I = \frac{n\varepsilon}{nr} \approx \frac{\varepsilon}{r}$$

It is the current due to a single cell. That is, current due to the whole battery is the same as that due to a single cell and hence there is no advantage in connecting several cells.

Thus, series connection of cells is advantageous only when the effective internal resistance of the cells is negligibly small compared with R.

7. Explain about cells in parallel.

Suppose n cells, each of emf ε volts and internal resistance r ohms are connected in parallel. An external resistance R is connected between A and B as shown in Figure.



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The equivalent internal resistance of the battery is,

$$\frac{1}{r_{eq}} = \frac{n}{r}$$

$$r_{eq} = \frac{r}{n}$$

The total resistance = $r_{eq} + R = \frac{r}{n} + R$

By Ohm's law, the current in the circuit is

$$I = \frac{Total\ emf}{Total\ resistance} = \frac{\varepsilon}{\frac{r}{n} + R}$$

$$I = \frac{n\varepsilon}{r + nR}$$

Case(a) : If r << R, then,

$$I = \frac{\varepsilon}{R}$$

The above equation implies that current due to the whole battery is the same as that due to a single cell.

Case (b) : If r >> R, then,

$$I = \frac{n\varepsilon}{r} = nI_1$$

Where $I_1 = \frac{\xi}{r}$ is the current due to single cell.

Thus, the current through the external resistance due to the whole battery is n times the current due to a single cell.

Hence it is advantageous to connect cells in parallel when the external resistance is very small compared to the internal resistance of the cells.

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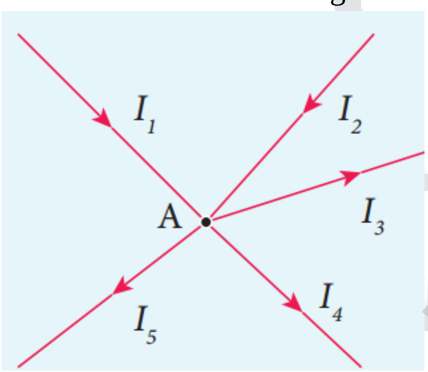
8. State and explain Kirchhoff's rules.

(i) Kirchhoff's first rule : (Current or Junction rule)

It states that the algebraic sum of the currents at any junction of a circuit is zero.



It is a statement of conservation of electric charge. All charges that enter a given junction in a circuit must leave that junction since charge cannot build up or disappear at a junction.

Current entering the junction is taken as positive and current leaving the junction is taken as negative.

Applying this law to the junction A in Figure.

$$I_1 + I_2 - I_3 - I_4 - I_5 = 0$$

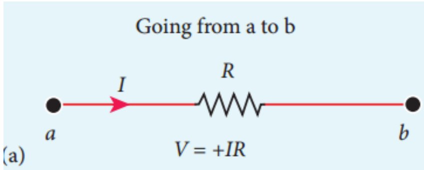
$$I_1 + I_2 = I_3 + I_4 + I_5$$

(i) Kirchhoff's Second rule :(Voltage or Loop rule)

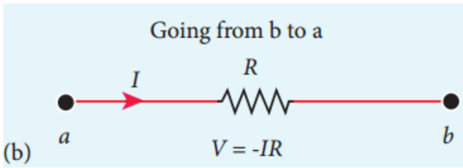
It states that in a closed circuit the algebraic sum of the products of the current and resistance of each part of the circuit is equal to the total emf included in the circuit.

This rule follows from the law of conservation of energy for an isolated system (The energy supplied by the emf sources is equal to the sum of the energy delivered to all resistors).

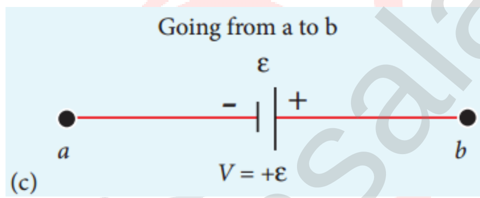
The product of current and resistance is taken as positive when the direction of the current is followed. (Figure (a))



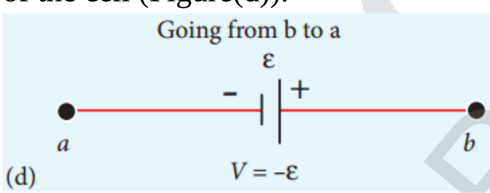
Suppose if the direction of current is opposite to the direction of the loop, then product of current and voltage across the resistor is negative. (Figure (b))



The emf is considered positive when proceeding from the negative to the positive terminal of the cell
(Figure(c)).



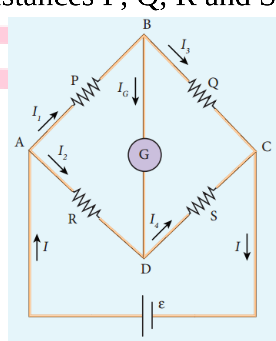
The emf is considered negative when proceeding from the positive to the negative terminal of the cell (Figure(d)).



Kirchhoff voltage rule has to be applied only when all currents in the circuit reach a steady state condition (the current in various branches are constant).

9. Obtain the condition for bridge balance in Wheatstone's bridge.

The bridge consists of four resistances P, Q, R and S are connected as shown in Figure.



A galvanometer G is connected between the points B and D. The battery is connected between the points A and C. The current through the galvanometer is IG and its resistance is G.

Applying Kirchhoff 's current rule to junction B

$$I_1 - I_G - I_3 = 0 \longrightarrow (1)$$

Applying Kirchhoff 's current rule to junction D

$$I_2 + I_G - I_4 = 0 \longrightarrow (2)$$

Applying Kirchhoff 's voltage rule to loop ABDA,

$$I_1P + I_GG - I_2R = 0 \longrightarrow (3)$$

Applying Kirchhoff 's voltage rule to loop ABCDA,

$$I_1P + I_3Q - I_4S - I_2R = 0 \longrightarrow (4)$$

When the points B and D are at the same potential, the bridge is said to be balanced. In this condition $I_G = 0$. Substituting this in equations(1),(2) &(3), we get,

$$I_1 = I_3 \longrightarrow (5)$$
$$I_2 = I_4 \longrightarrow (6)$$
$$I_1P = I_2R \longrightarrow (7)$$

Substituting the equations(5) &(6) in equation(4) we get,

$$I_1P + I_1Q - I_2S - I_2R = 0$$

$$I_1(P + Q) = I_2(R + S) \longrightarrow (8)$$

Dividing equation(8) by equation(7), we have,

$$\frac{P+Q}{P} = \frac{R+S}{R}$$
$$1 + \frac{Q}{P} = 1 + \frac{S}{R}$$
$$\frac{Q}{P} = \frac{S}{R}$$
$$\boxed{\frac{P}{Q} = \frac{R}{S}}$$

This is the bridge balance condition. If three of the resistances are known, the value of unknown resistance (fourth one) can be determined.

10. Explain the determination of unknown resistance using meter bridge.

The meter bridge is another form of Wheatstone's bridge. It consists of a uniform manganin wire AB of one meter length.

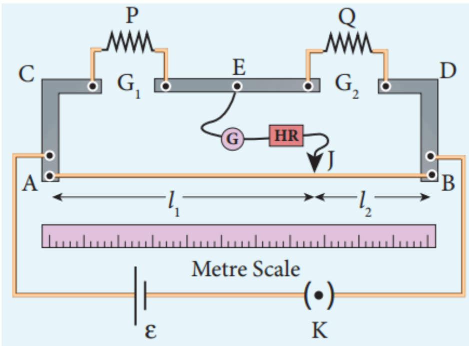
This wire is stretched along a meter scale on a wooden board between two copper strips C and D.

Between these two copper strips another copper strip E is mounted to enclose two gaps G_1 and G_2 as shown in Figure.

An unknown resistance P is connected in G1 and a standard resistance Q is connected in G_2.

A jockey (conducting wire) is connected to the terminal E on the central copper strip through a galvanometer (G) and a high resistance (HR).

The exact position of jockey on the wire can be read on the scale. A Lechlanche cell and a key (K) are connected across the ends of the bridge wire.



The position of the jockey on the wire is adjusted so that the galvanometer shows zero deflection. Let the point be J.

The lengths AJ and JB of the bridge wire now replace the resistance R and S of the Wheatstone's bridge. Then,

$$\frac{P}{Q} = \frac{R}{S} = \frac{R'.AJ}{R'.JB}$$

where R′ is the resistance per unit length of wire.

$$\frac{P}{Q} = \frac{AJ}{JB} = \frac{l_1}{l_2}$$

$$P = Q\frac{l_1}{l_2}$$

The end resistance is created at the ends of the copper strips due to soldering. To eliminate this, another set of readings are taken with P and Q interchanged. From this the average value of P is found.

To find the specific resistance of the material of the wire in the coil P, the radius r and length *l* of the wire are measured.

The specific resistance or resistivity ρ can be calculated using the relation,

$$\rho = P \times \frac{A}{l}$$

$$\rho = P \times \frac{\pi r^2}{l} \qquad [\because A = \pi r^2]$$

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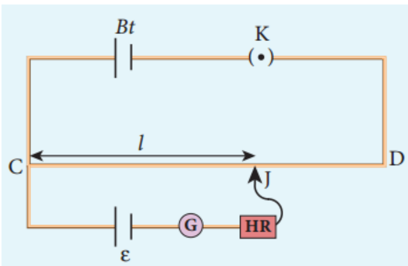
11. Explain the potentiometer and its principle.

Potentiometer is used for the accurate measurement of potential differences, current and resistances.

It consists of 10 m long uniform wire of manganin or constantan stretched in parallel rows each of 1 meter length, on a wooden board.

The two free ends A and B are brought to the same side and fixed to copper strips with binding screws. A meter scale is fixed parallel to the wire.

The principle of the potentiometer is illustrated in Figure.



A steady current is maintained across the wire CD by a battery Bt. The battery, key and the potentiometer wire are connected in series forms the primary circuit.

The positive terminal of a primary cell of emf ε is connected to the point C and negative terminal is connected to the jockey through a galvanometer G and a high resistance HR. This forms the secondary circuit.

Let contact be made at any point J on the wire by jockey where galvanometer shows zero.

$$\begin{pmatrix}\text{The emf of} \\ \text{the cell}\end{pmatrix} = \begin{pmatrix}\text{potential difference} \\ \text{across CJ}\end{pmatrix}$$

$$\varepsilon = Irl$$

Since l and r are constants,

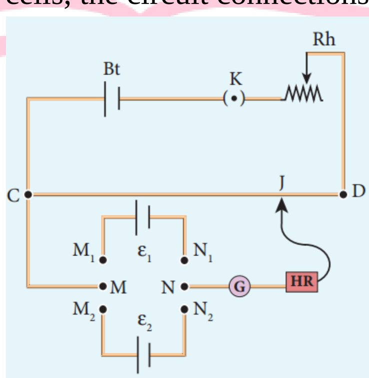
$$\varepsilon \propto l$$

Now CJ is the balancing length *l*. In this position,

The emf of the cell is directly proportional to the balancing length.

12. How the emf of two cells are compared using potentiometer?

To compare the emf of two cells, the circuit connections are made as shown in Figure.



Potentiometer wire CD is connected to a battery Bt and a key K in series. This is the primary circuit.

The end C of the wire is connected to the terminal M of a DPDT (Double Pole Double Throw) switch and the other terminal N is connected to a jockey through a galvanometer G and a high resistance HR.

The cells whose emf ε1 and ε2 to be compared are connected to the terminals M1,N1 and M2,N2 of the DPDT switch. The positive terminals of Bt, ε1 and ε2 should be connected to the same end C.

The DPDT switch is pressed towards M1, N1 so that cell ε1 is included in the secondary circuit and the balancing length *l1* is found by adjusting the jockey for zero deflection.

Then the second cell ε2 is included in the circuit and the balancing length *l2* is determined.

Let r be the resistance per unit length of the potentiometer wire and I be the current flowing through the wire. we have,

$$\varepsilon_1 = Irl_1 \longrightarrow (1)$$

$$\varepsilon = Irl_2 \longrightarrow (2)$$

Dividing equation (1) by (2), we get,

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{l_1}{l_2}$$

By including a rheostat (Rh) in the primary circuit, the experiment can be repeated several times by changing the current flowing through it.

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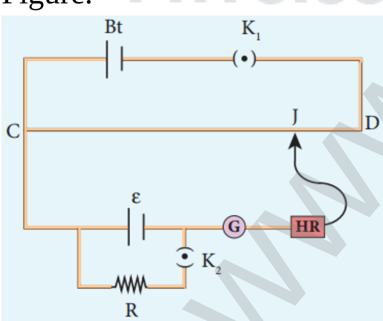
13. Explain the determination of the internal resistance of a cell using potentiometer.

To measure the internal resistance of a cell, the circuit connections are made as shown in Figure.



The end C of the potentiometer wire is connected to the positive terminal of the battery Bt and the negative terminal of the battery is connected to the end D through a key K1. This forms the primary circuit.

The positive terminal of the cell ε whose internal resistance is to be determined is also connected to the end C of the wire.

The negative terminal of the cell ε is connected to a jockey through a galvanometer and a high resistance.

A resistance box R and key K2 are connected across the cell ξ. With K2 open, the balancing point J is obtained and the balancing length CJ = *l1* is measured. Since the cell is in open circuit, its emf is

$$\varepsilon \propto l_1 \longrightarrow (1)$$

A suitable resistance (say, 10 Ω) is included in the resistance box and key K2 is closed. Let r be the internal resistance of the cell.

The current passing through the cell and the resistance R is given by,

$$I = \frac{\varepsilon}{R + r}$$

The potential difference across R is,

$$V = \frac{\varepsilon R}{R + r} \qquad [\because V = IR]$$

When this potential difference is balanced on the potentiometer wire at the balancing length l_2, we can write,

$$\frac{\varepsilon R}{R + r} \propto l_2 \longrightarrow (2)$$

Dividing equation(1) by(2), we get,

$$\frac{R + r}{R} = \frac{l_1}{l_2}$$

$$1 + \frac{r}{R} = \frac{l_1}{l_2}$$

$$r = R\left[\frac{l_1}{l_2} - 1\right]$$

$$r = R\left[\frac{l_1 - l_2}{l_2}\right]$$

Substituting the values of the R, *l1* and *l2*, the internal resistance of the cell is determined. It is found that the internal resistance of the cell is proportional to the external resistance.

14. Elucidate the applications of Joule's heating effect.

Electric heaters

- Electric iron, electric heater, electric toaster are some of the home appliances that utilize the heating effect of current.
- In these appliances, the heating elements are made of nichrome, an alloy of nickel and chromium.
- Nichrome has a high specific resistance and can be heated to very high temperatures without oxidation.

Electric fuses

- Fuses are connected in series in a circuit to protect the electric devices from the heat developed by the passage of excessive current.
- It is a short length of a wire made of a low melting point material.
- It melts and breaks the circuit if current exceeds a certain value.
- An alloy of lead - tin is used for fuses when current rating is below 15 A and when current rating is above 15 A, copper fuse wires are used.
- Now-a-days in houses, circuit breakers (trippers) are also used instead of fuses.
- Whenever there is an excessive current produced due to faulty wire connection, the circuit breaker switch opens. After repairing the faulty connection, we can close the circuit breaker switch.

Electric furnace

- Furnaces are used to manufacture a large number of technologically important materials such as steel, silicon carbide, quartz, gallium arsenide, etc.
- To produce temperatures up to 1500°C, molybdenum-nichrome wire wound on a silica tube is used.
- Carbon arc furnaces produce temperatures up to 3000°C.

Electrical lamp

- It consists of a tungsten filament (melting point 3380^{0}C) kept inside a glass bulb and heated to incandescence by current.
- In incandescent electric lamps only about 5% of electrical energy is converted into light and the rest is wasted as heat.
- Electric discharge lamps, electric welding and electric arc also utilize the heating effect of current.

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