D.C. circuits

Direct current (d.c.) : A current whose magnitude and direction does not change with time is called d.c. e.g. current produced by cell or battery. The waveform of d.c. is shown in fig. 1.

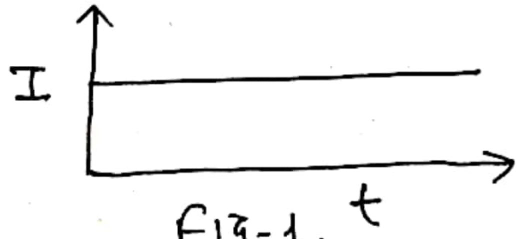


Fig-1.

Alternating current (a.c.)

A current whose magnitude changes in definite time and direction changes periodically is called a.c. e.g. the current produced by a.c. generator or dynamo.

The waveform of a.c. is shown in fig-1.

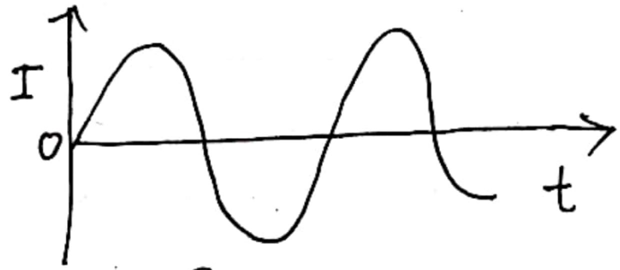


Fig. 1.

Electric current :

The rate of flow of charge per unit time is called electric current. It is denoted by I. If q is the charge flowing in time t, then electric current is given by

$$I = \frac{q}{t}$$

In derivative notation,

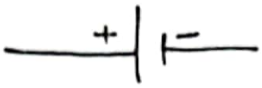
$$I = \frac{dq}{dt}$$

The SI unit of electric current is Ampere (A).

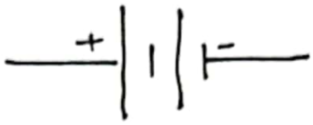
Circuit symbols

1. 

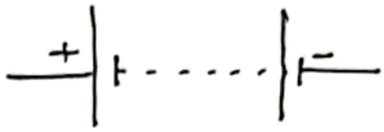
Connecting wire

2. 

Cell



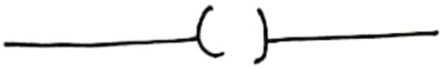
Two cells
or
Battery



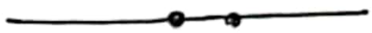
Many cells

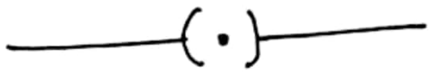
3. 

or



open switch

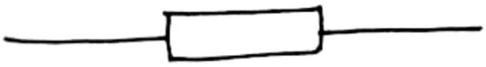




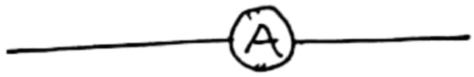
closed switch

4. 

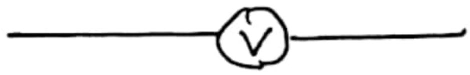
or



Resistor

5. 

Ammeter

6. 

Voltmeter

7. 

Galvanometer

8. 

a.c.

9. 

Rheostat

10. 

Variable resistor.

11. 

or

Bulb

12. 

or

Joined wires

Mechanism of metallic conduction :

As we know the electrons in metal are in random motion in all directions like the molecules of gas confined in a container, so there is no net flow of charge in any direction. If we consider any cross-section of the conductor, the rate at which they pass through it from right to left is same as that from left to right. Therefore, the net flow of charge is zero and hence no current flows in the conductor, as shown in fig-1.

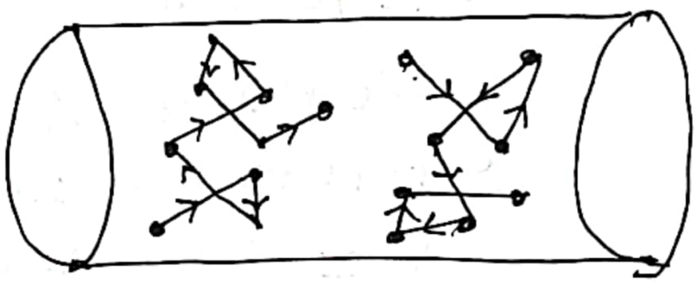


Fig-1.

Average velocity
or
Drift velocity (V_d) :

The average velocity of electrons with which they move in a conductor under the influence of electric field is called drift velocity. It is denoted by V_d.

Expression for drift velocity : (4)

Let us consider a metallic conductor XY of length l, cross-sectional area A and having number of electrons per unit volume n, as shown in fig-1.

When electric field is applied the electrons move with drift velocity V_d from left to right.

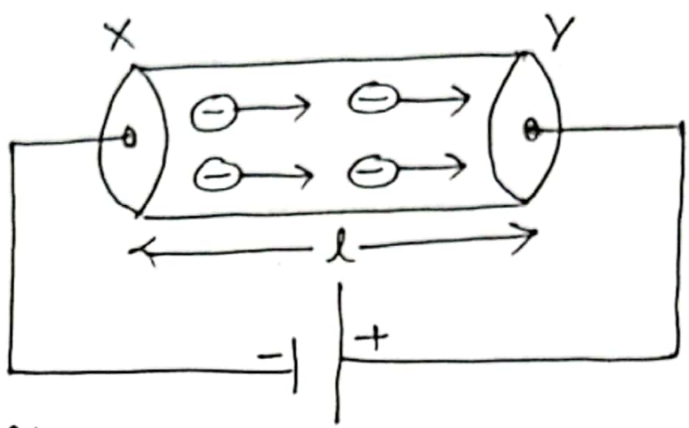


Fig-1.

The volume (V) of conductor is given by

V = Area of cross-section x length

$= A \times l$

∴ total no. of electrons in the conductor is given by

$$N = V \times n = Aln \quad \text{—— (1)}$$

If e be the charge on each electron, then total charge q flowing through the conductor is given by

$$q = Ne = nAle \quad \text{— (2)} \; ; \text{ using eq}^n \text{ (1)}$$

The current I is defined as

$$I = \frac{q}{t} \quad \text{—— (3)}$$

From eqs. (2) & (3), we get

$$I = \frac{nAle}{t} = nAe\left(\frac{l}{t}\right)$$

$$\boxed{I = nAeV_d} \quad \text{—— (4)}$$

From (4),

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

$$\boxed{J = neV_d} \quad \text{—— (5)}$$

where $\frac{l}{t} = V_d$ is the drift velocity of electron.

Eq^n (4) gives the req. relation between current and drift velocity.

Ohm's law! It states that the p.d. across the ends of a conductor is directly proportional to the current flowing through the conductor provided the physical conditions like temperature, dimensions etc are constants.

If I be the current flowing through the conductor and V be p.d. across the ends of the conductor, then from Ohm's law, we have

$$V \propto I$$

or, $V = RI$, $\boxed{V = IR}$

where R is a proportionality constant called resistance of the conductor.

Experimental Verification of ohm's law:

The circuit diagram for the verification of ohm's law is shown in fig-1(a).

A battery B', a key K, a rheostat Rh and an ammeter A are connected in series while a voltmeter V is connected in parallel across the resistance R.

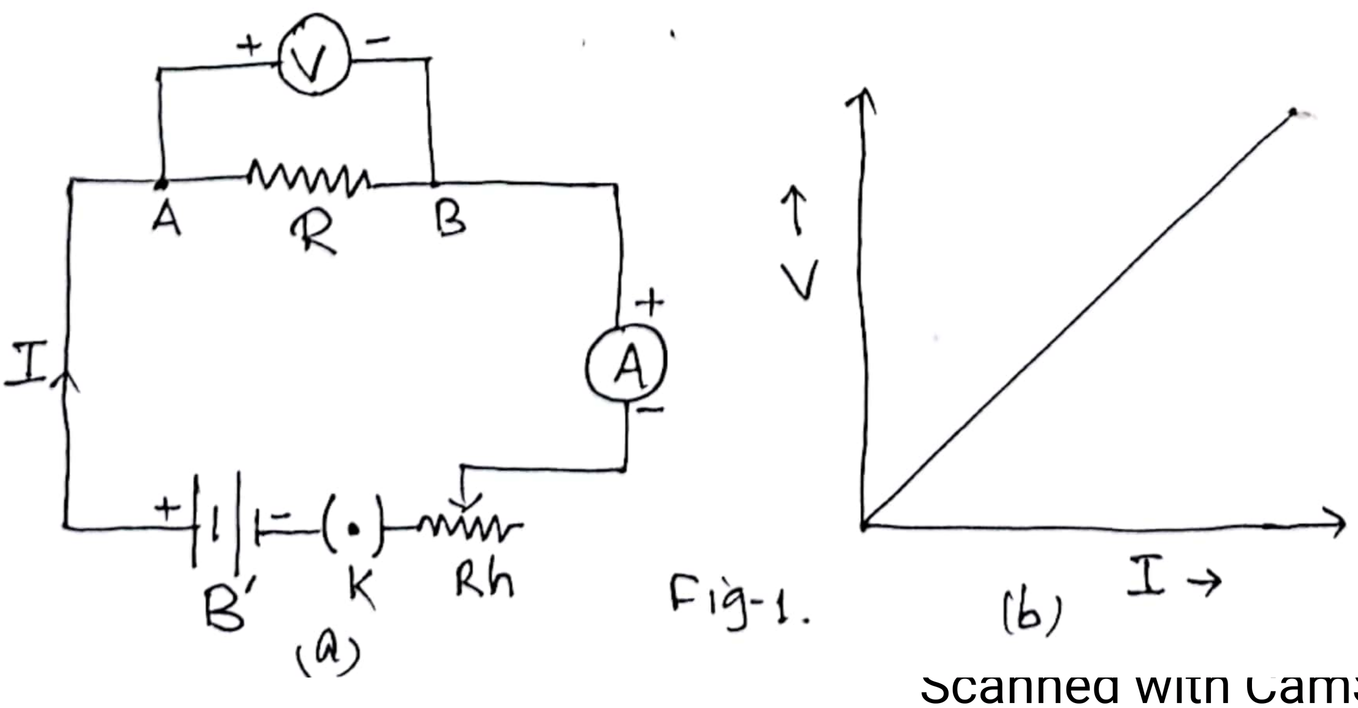


Fig-1.

Firstly, the value of current say I_1 is adjusted in ammeter with the help of rheostat and voltmeter reading is noted. Secondly, the value of current say $I_2, I_3, \ldots$ are gradually adjusted in the ammeter and corresponding voltmeter readings say $V_2, V_3, \ldots$ are noted.

It is found that

$$\frac{V_1}{I_1} = \frac{V_2}{I_2} = \frac{V_3}{I_3} = \text{constant}$$

$$\frac{V}{I} = \text{constant}$$

$$V \propto I$$

Which verifies ohm's law.

If a graph betn. V and I is drawn, it will be a st. line passing through the origin, as shown in fig-1 (b).

Some definitions:

Resistance (R): The property of a conductor that opposes the flow of current in a conductor is called resistance. It is denoted by R. It's SI unit is ohm (Ω).

Conductance (C): The reciprocal of resistance of a conductor is called its conductance. It is denoted by C and given by

$$C = \frac{1}{R}$$

The SI unit of conductance is Ω^{-1} or mho or Siemens.

Resistivity

The resistance R of a conductor is directly proportional to its length (l) and inversely proportional to its cross-sectional area. That is

$$R \propto l \quad \text{—(1)}$$

$$R \propto \frac{1}{A} \quad \text{—(2)}$$

Combining eqs (1) and (2), we get

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

or, $$\boxed{R = \frac{\rho l}{A}} \quad \text{——(3)}$$

where ρ is a proportionality constant called resistivity of material of wire.

When $l = 1\,m$ and $A = 1\,m^2$, then from eq^n. (3), we get

$$\boxed{R = \rho}$$

Hence resistivity of a material is defined as the resistance of a material having unit length and unit cross sectional area.

From eq^n. (3), we get

$$\rho = \frac{RA}{l}$$

The SI unit of ρ is $\frac{\Omega \cdot m^2}{m} = \Omega \cdot m$.

Conductivity (σ): The reciprocal of resistivity of a material is called its conductivity. It is denoted by σ and given by

$$\boxed{\sigma = \frac{1}{\rho}}$$

The SI unit of σ is $(\Omega \cdot m)^{-1}$.

Factors affecting the resistance of a material;

(i) Nature (ii) Length (iii) Cross-sectional area
(iv) Temp.

Temperature coefficient of resistance;

It is defined as the change in resistance per unit resistance at 0°C per unit rise in temp.

If R_θ and R_0 be the resistances of a conductor at θ°C and 0°C respectively, then temp. coefficient of resistance α is given by

$$\alpha = \frac{\text{increase in resistance}}{\text{resistance at 0°C} \times \text{rise in temp.}}$$

$$= \frac{R_\theta - R_0}{R_0 \times (\theta - 0)}$$

After simplifying,

$$R_\theta = R_0 [1 + \alpha\theta]$$

The SI unit of α is $°C^{-1}$ or K^{-1}.

Note: The value of temp. coefficient of resistance is

(a) positive for conductors (because resistance increases with the rise in temp.)

(b) negative for semiconductors like Si, Ge (because resistance decreases with rise in temp.)

(c) zero for superconductors

Some alloys like Nichrome, Magnin, Constantan etc are negligibly affected by temp. Due to these reasons, such materials are used for making standard resistors.

Prove: $J = \sigma E$

Proof: The relation betn. R, l and A is given by

$$R = \frac{\rho l}{A} \quad \text{---(1)}$$

Where ρ is the resistivity of material of conductor.

Accn. to ohm's law,

$$V = IR$$

$$\text{or, } R = \frac{V}{I} \quad \text{---(2)}$$

From eqn. (1) and (2), we get

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

$$\text{or, } \frac{V}{l} = \rho \times \frac{I}{A}$$

$$\text{or, } E = \rho \times J \quad \text{---(3)}$$

Where $\frac{V}{l} = E$ is electric field intensity

and $\frac{I}{A} = J$ is called current density.

From eqn (3), we get

$$J = \frac{E}{\rho} = \frac{1}{\rho} \times E$$

$$\text{or, } \boxed{J = \sigma E} \quad \text{---(4)}$$

Where $\frac{1}{\rho} = \sigma$ is called conductivity of material. Eqn. (4) gives the relation betn current density (J), electric field intensity (E) and conductivity (σ).

Differences betn ohmic and non-ohmic conductors:

Ohmic conductor	Non-ohmic conductor
1. The conductor which strictly follows the ohm's law is called ohmic conductor.	1) The conductor which doesn't follow the ohm's law is called non-ohmic conductor.
2. For examples, metals like Cu, Fe, Ag, Al, etc.	2) For example, semiconductor diode, triode valve, electrolyte etc.
3. The graph betn V and I is linear for ohmic conductor.	3) The graph betn V and I is non-linear for non-ohmic conductor

Differences betn resistance and resistivity

Resistance	Resistivity
1) It is the property of a conductor that opposes the flow of charge through it.	1) It is defined as the resistance of a conductor having unit length and unit cross-sectional area.
2. It depends upon the dimensions of the conductor	2. It depends upon the nature of material of conductor
3. The SI unit of resistance is ohm (Ω).	The SI unit of resistivity is $\Omega \cdot m$.

Factors affecting the resistivity of material:

(i) It depends upon nature of the material.
(ii) It depends on temperature $[\rho = \rho_0(1+\alpha\theta)]$
(iii) It is independent of shape and size of the conductor.

Combination of resistors:

(1) **Resistance in Series:** Resistances are said to be in series if they are connected end to end consecutively.

Consider three resistors having resistances

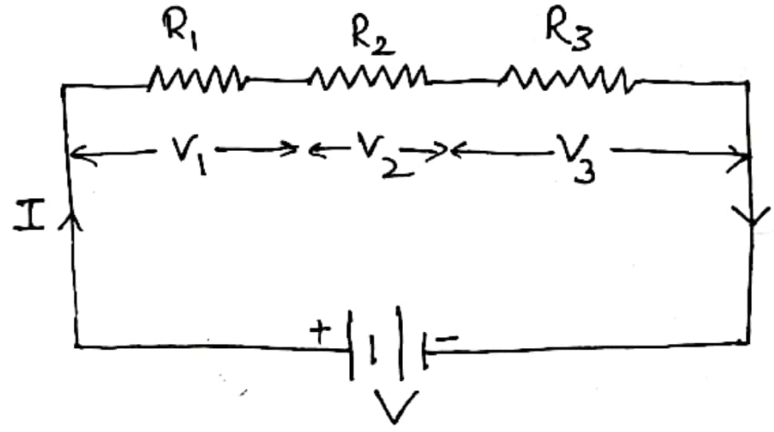


Fig-1.

R_1, R_2 and R_3 are connected in series with a d.c. source of V volt, as shown in fig-1. If V_1, V_2 and V_3 be the p.d. across R_1, R_2 and R_3 respectively, then we have,

$$V = V_1 + V_2 + V_3 \quad \text{——(1)}$$

If I be the current flowing through each resistor then from ohm's law

$$V_1 = IR_1, \quad V_2 = IR_2 \text{ and } V_3 = IR_3$$

putting the value of V_1, V_2 and V_3 in eqn. (1), we get

$$V = IR_1 + IR_2 + IR_3$$

$$\text{or, } V = I(R_1 + R_2 + R_3) \quad \text{——(2)}$$

If R_s be the effective resistance of this combination then

$$V = IR_s \quad \text{——(3)}$$

From eqs. (2) and (3), we get

$$IR_s = I(R_1 + R_2 + R_3)$$

$$\therefore \boxed{R_s = R_1 + R_2 + R_3} \quad \text{——(4)}$$

Hence, in series combination the equivalent resistance is equal to the sum of the resistances of individual resistor.

If there are n no. of resistors having resistances $R_1, R_2, R_3, \ldots, R_n$, are connected in series, then equivalent resistance is given by

$$R_s = R_1 + R_2 + R_3 + \cdots + R_n$$

(2) Resistors in parallel: Resistances are said to be in parallel, if one end of all the resistors are connected to one common point and others ends are connected to other common point.

Consider three resistors having resistances R_1, R_2 and R_3 are connected in parallal with a d.c. source of V volt, as shown in fig-1.

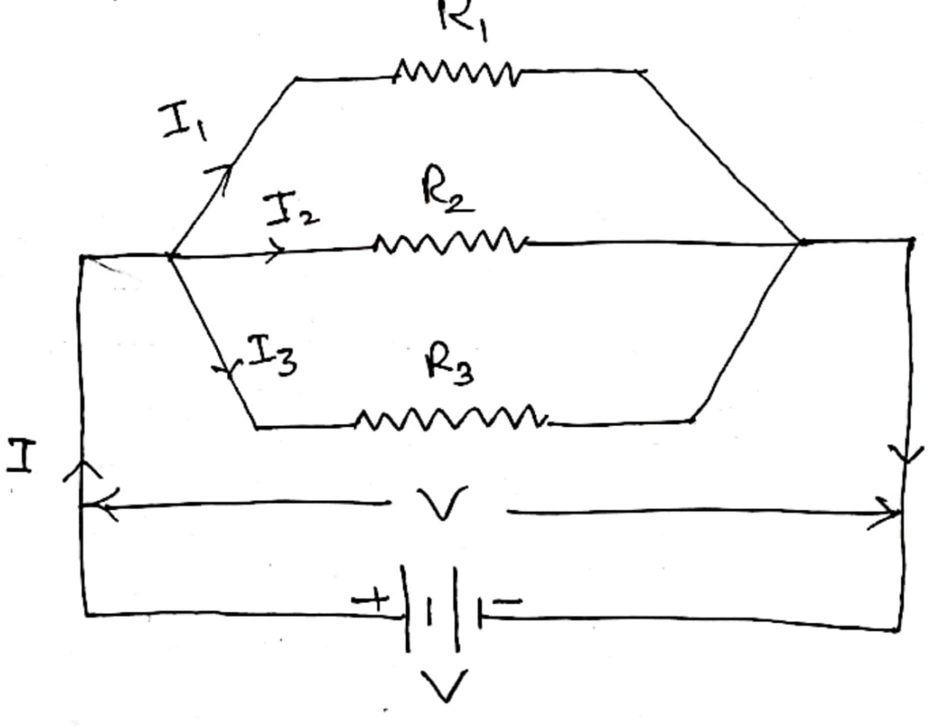


Fig-1.

Let I be the current supplied by battery and I_1, I_2 and I_3 be the currents flowing through resistances R_1, R_2 and R_3 respectively. Then, we have

$$I = I_1 + I_2 + I_3 \qquad \text{—(1)}$$

If V be p.d. across the combination, then from Ohm's law

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

putting the value of I_1, I_2 and I_3 in eqn. (1), we get

$$I = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

$$I = V\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right] \quad \text{—— (2)}$$

If R_p be the equivalent resistance in this combination, then

$$V = I R_p$$

$$\text{or, } I = \frac{V}{R_p} \quad \text{—— (3)}$$

From eqn. (2) and (3), we get

$$\frac{V}{R_p} = V\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right]$$

$$\therefore \boxed{\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \quad \text{—— (3)}$$

Hence, in parallel combination, the reciprocal of equivalent resistance is equal to the sum of reciprocals of resistances of individual resistors.

If there are n resistors having resistances $R_1, R_2, \ldots, R_n$ are connected in parallel, then equivalent resistance R_p is given by

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n}$$

Shunt :

A very low resistance, connected in parallel with galvanometer in order to convert it into an ammeter, is called shunt. It is denoted by R_s or S.

Galvanometer:

A sensitive device that is used to detect very small current flowing in an electric circuit is called galvanometer. It is denoted by G and symbolises as —(G)—.

Ammeter:

A device that is used to measure the current flowing in the circuit is called an ammeter. It is symbolises as —(A)—.

Voltmeter: A device which is used to measure potential difference (p.d.) betn two points in a circuit is called voltmeter. It is denoted by

—(V)—.

Imp.
Conversion of galvanometer into an ammeter

Let a galvanometer having coil resistance G is converted into an ammeter of range $(0-I)$ ampere. For this a small

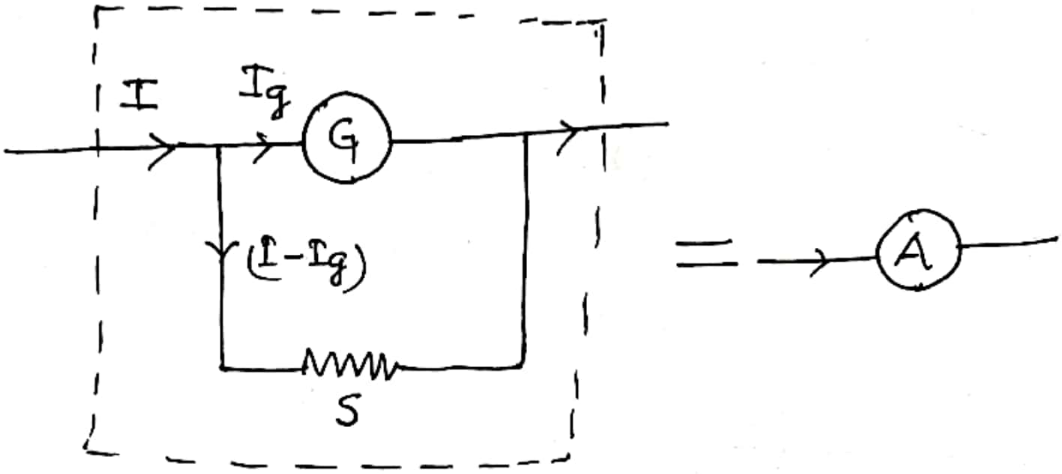


Fig-1.

resistance S called shunt is connected in parallel with a galvanometer, as shown in fig-1. Let I_g be the maximum current allowed through galvanometer for its full deflection. Then, the current flowing through shunt is $(I-I_g)$.

Since the galvanometer (G) and shunt (S) are connected in parallel, so

p.d. across G = p.d. across S

$$I_g \cdot G = (I-I_g) \cdot S$$

or, $$\boxed{S = \frac{I_g \cdot G}{I-I_g}} \quad \text{---(1)}$$

which is required value of shunt that when connected in parallel with a galvanometer, it is converted into an ammeter of given range 0 to IA.

The equivalent resistance (R) of circuit is given by

$$\frac{1}{R} = \frac{1}{G} + \frac{1}{S} = \frac{S+G}{GS}$$

$$\therefore \boxed{R = \frac{G.S}{S+G}} \quad \text{--- (2)}$$

Uses of shunt (Significance).

(i) It is used to convert galvanometer into an ammeter.

(ii) It reduces the total resistance of ammeter.

(iii) It protects galvanometer from damaging.

Conversion of galvanometer into a voltmeter:

Let a galvanometer having coil resistance G is converted into a voltmeter of range (0-V).

For this a very high resistance R, called multiplier is connected in series with a galvanometer (G), as shown in fig-1.

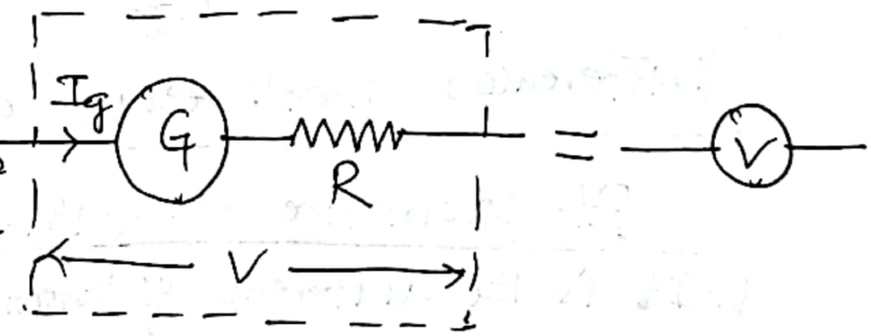


Fig-1.

Let I_g be the current through galvanometer for its full deflection. If V be the p.d. across G and R, then we have

$$V = I_g(G+R)$$

or, $$\frac{V}{I_g} = G+R$$

or, $$\boxed{R = \frac{V}{I_g} - G} \quad \text{--- (1)}$$

which is the req. value of high resistance that to be chosen to convert galvanometer into a voltmeter of range 0 to V.

Define Electromotive force (emf), terminal p.d. and internal resistance of a cell. Establish a relation between them.

Electromotive force (E): It is defined as the difference in potentials between two electrodes of a cell in an open circuit. It is denoted by E.

Terminal p.d. It is defined as the difference of potentials between any two points in a closed circuit. It is denoted by V.

Internal resistance of a cell: The resistance offered by electrolyte and electrodes of a cell is called internal resistance of a cell. It is denoted by r.

Differences betn. emf and p.d.

Electromotive force (Emf)	Potential difference (p.d.)
1. It is the difference of potentials between two terminal of a cell in an open circuit.	1. It is the difference betn. two points in a closed ckt.
2. It does not depend upon external resistance	2. It depends upon external resistance.
3. It is greater than p.d. during discharging	3. It is greater than emf during charging.
4. It is a cause.	4. It is an effect

Relation between E, V and r: Let us consider a cell of emf E and internal resistance r is connected in series with an external resistance R provided with a Key K, as shown in fig-1. Let I be the current flowing through the circuit, then from Ohm's law, we have

$$\text{Current} = \frac{\text{Emf}}{\text{total resistance}}$$

The total resistance of circuit is $(R+r)$.

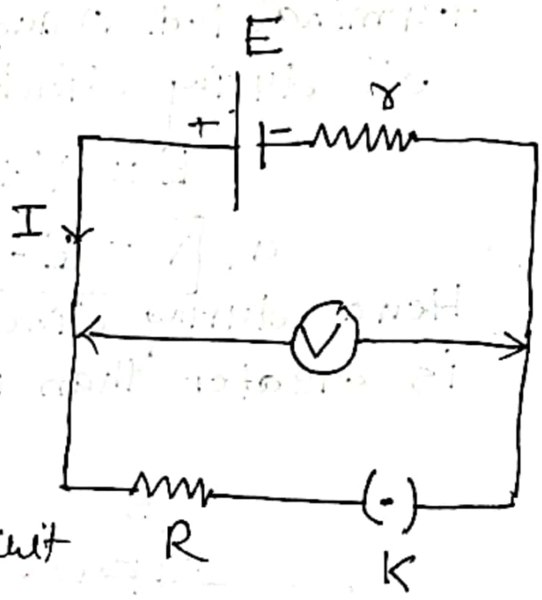


Fig-1.

$$\therefore I = \frac{E}{R+r}$$

or, $E = I(R+r)$

or, $E = IR + Ir$ —— (1)

If V be the p.d. across R, then we have

$$V = IR \quad \text{—— (2)}$$

From eqs. (1) and (2), we get

$$E = V + Ir$$

or, $E - V = Ir$

or, $r = \frac{E-V}{I}$ —— (3)

From eq. (2) & (3), we get

$$r = \frac{E-V}{V/R}$$

$$\boxed{r = \left(\frac{E-V}{V}\right)R} \quad \text{—— (4)}$$

which is the req. expression for internal resistance of a cell and eq^n (4) is called circuit formula.

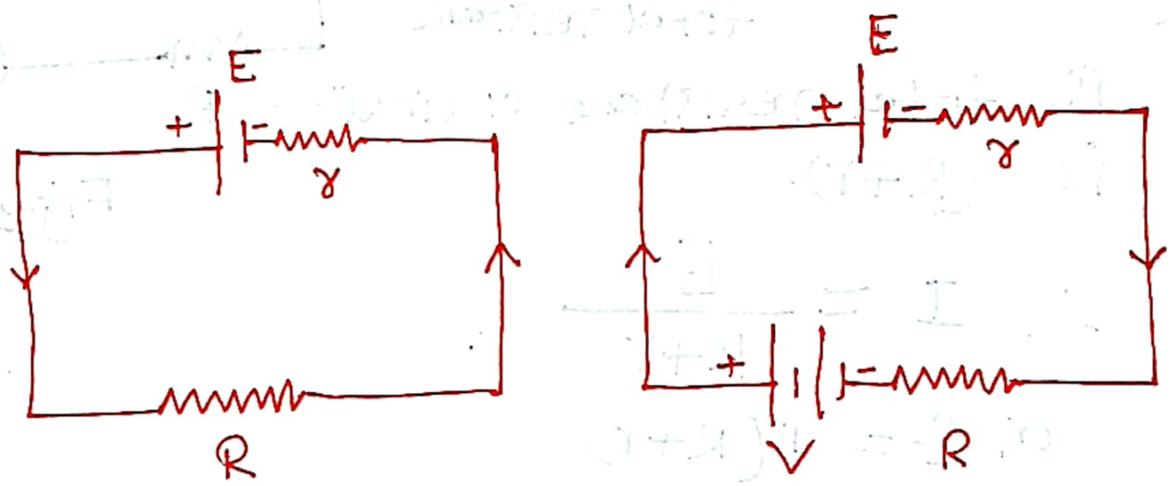
Emf and terminal p.d. of a cell during charging and discharging:

The relation between emf (E), terminal p.d. (V) and internal resistance (r) of a cell during discharging is given by

$$E = V + Ir$$

or, $$\boxed{V = E - Ir} \quad \text{——(1)}$$

Hence, during discharging the cell, the emf of cell is greater than its terminal p.d., as shown in fig-1(a)



(a) Discharging (b) Charging

Fig-1.

However, during charging the cell, a current I is passed through the cell by an external source V, as shown in fig-1(b). In such condition the current flows through the circuit against the emf of cell and thus replacing I by −I in eqn.(1), we get

$$V = E - (-I)r$$

$$\boxed{V = E + Ir} \quad \text{——(2)}$$

Hence, the terminal p.d. of the cell is greater than its emf during charging of cell.

Combination Of Cells

(1) Series Combination of Cells:

Let us consider n cells each of emf E and internal resistance r are connected in series with an external resistance R, as shown in fig-1. Then

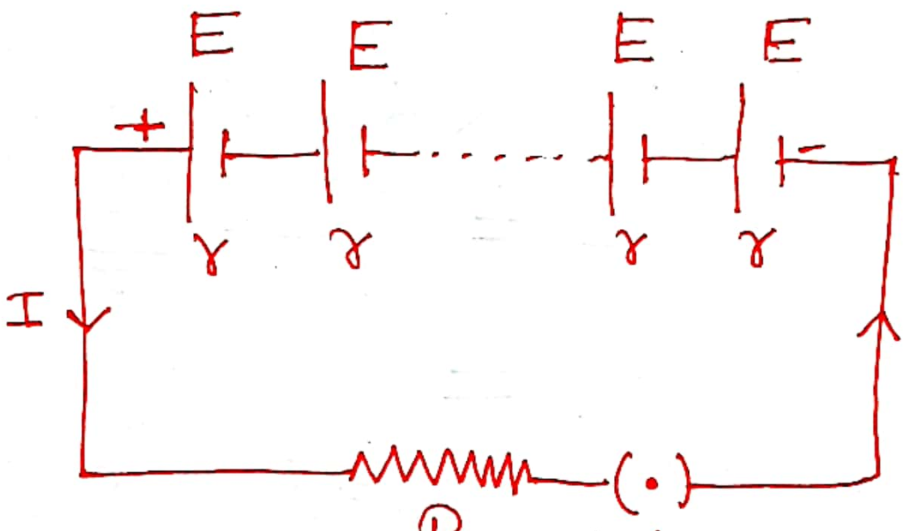


fig-1.

Total emf of n cells $= nE$

Total internal resistance $= r + r + \cdots + r$

$= nr$

Total circuit resistance $= R + nr$

If I be the current flowing through the ckt, then from ohm's law

$$\text{Current } (I) = \frac{\text{Total emf}}{\text{Total resistance}}$$

$$\boxed{I = \frac{nE}{R+nr}} \quad \text{——} (1)$$

Case-I If $R >> nr$, then from eqⁿ. (1), we have

$$I = \frac{nE}{R} = n \times \frac{E}{r}$$

= n times the current drawn from a single cell.

Case-II If $R << nr$, then from eqⁿ. (1)

$$I = \frac{n.E}{nr} = \frac{E}{r}$$

= same as the current given by one cell.

Hence, to obtain maximum current, the cells should be joined in series such that external resistance should be very large as compared to total internal resistance.

(2) Parallel combination of cells:

Let us consider n-cells each of emf E and internal resistance r are connected in parallel with an external

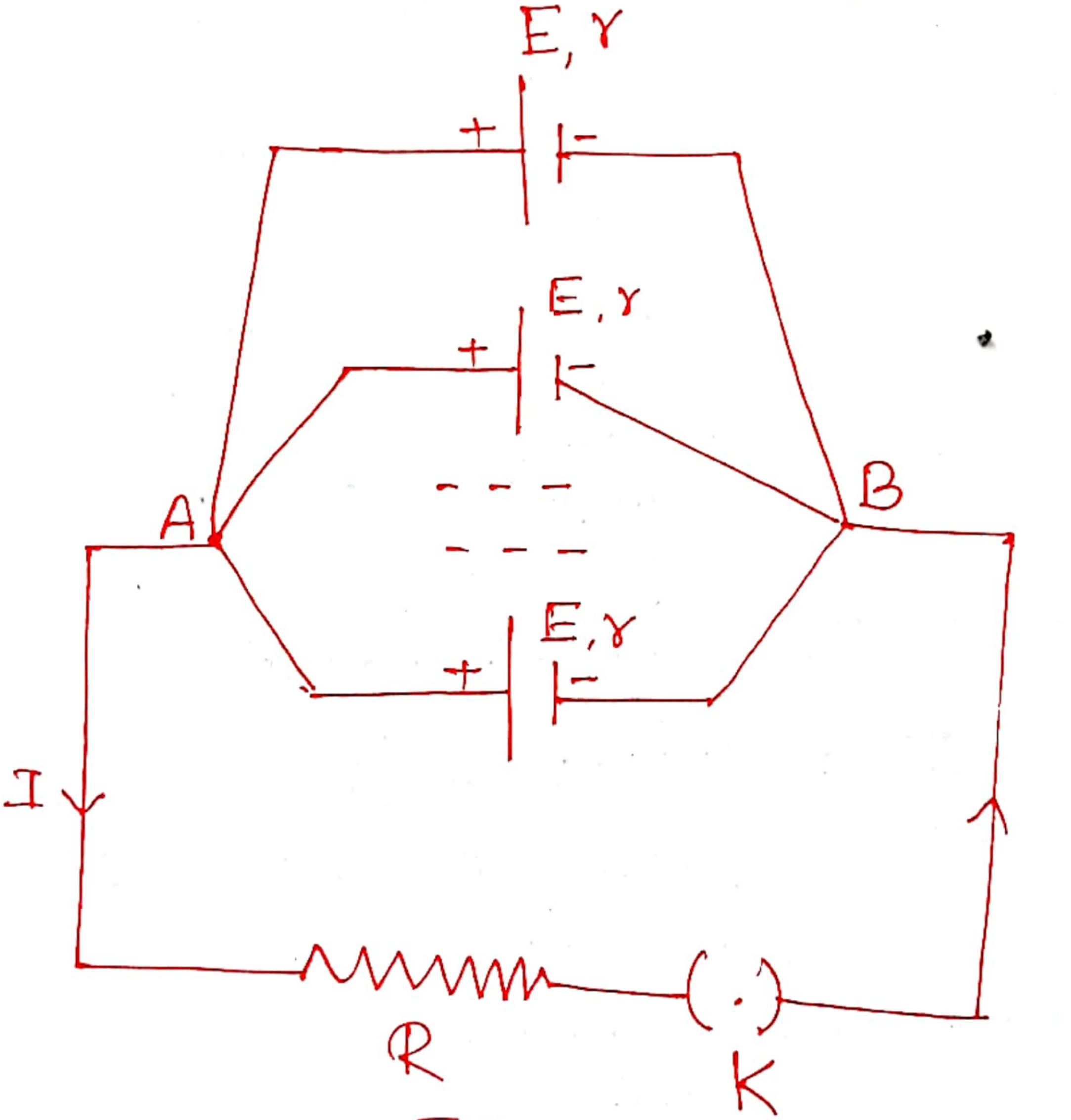


Fig-1.

resistance R and key K, as shown in fig-1. Then, we have

Total emf of n cells = E

Total internal resistance r' is given by

$$\frac{1}{r'} = \frac{1}{r} + \frac{1}{r} + \dots + \frac{1}{r}$$

$$\frac{1}{r'} = \frac{n}{r}$$

or, $r' = \frac{r}{n}$

$\therefore$ Total ckt resistance $= R + \frac{r}{n}$

If I be the current flowing in the ckt, then from ohm's law, we have

$$\text{current} = \frac{\text{Total emf}}{\text{Total resistance}}$$

$$I = \frac{E}{R + \frac{r}{n}} = \frac{E}{\frac{nR+r}{n}}$$

or, $$\boxed{I = \frac{nE}{nR+r}} \quad \text{—— (1)}$$

<u>case-I</u> If $r >> nR$, then from eq^n (1)

$$I = \frac{nE}{r} = n \times \frac{E}{r}$$

= n times the current given by one cell.

<u>case-II</u> If $r << nR$, then from (1)

$$I = \frac{nE}{nR} = \frac{E}{R}$$

= Same as the current drawn from one cell.

Hence, to obtain maximum current, the cells should be joined in parallel such that external resistance is much small in comparison to internal resistance.

(3) Mixed combination of cells: Let us consider n cells each of emf E and internal resistance r are connected in series and m such rows are connected in parallel with an external resistance R provided with a Key K, as shown in fig-1. Then, we have

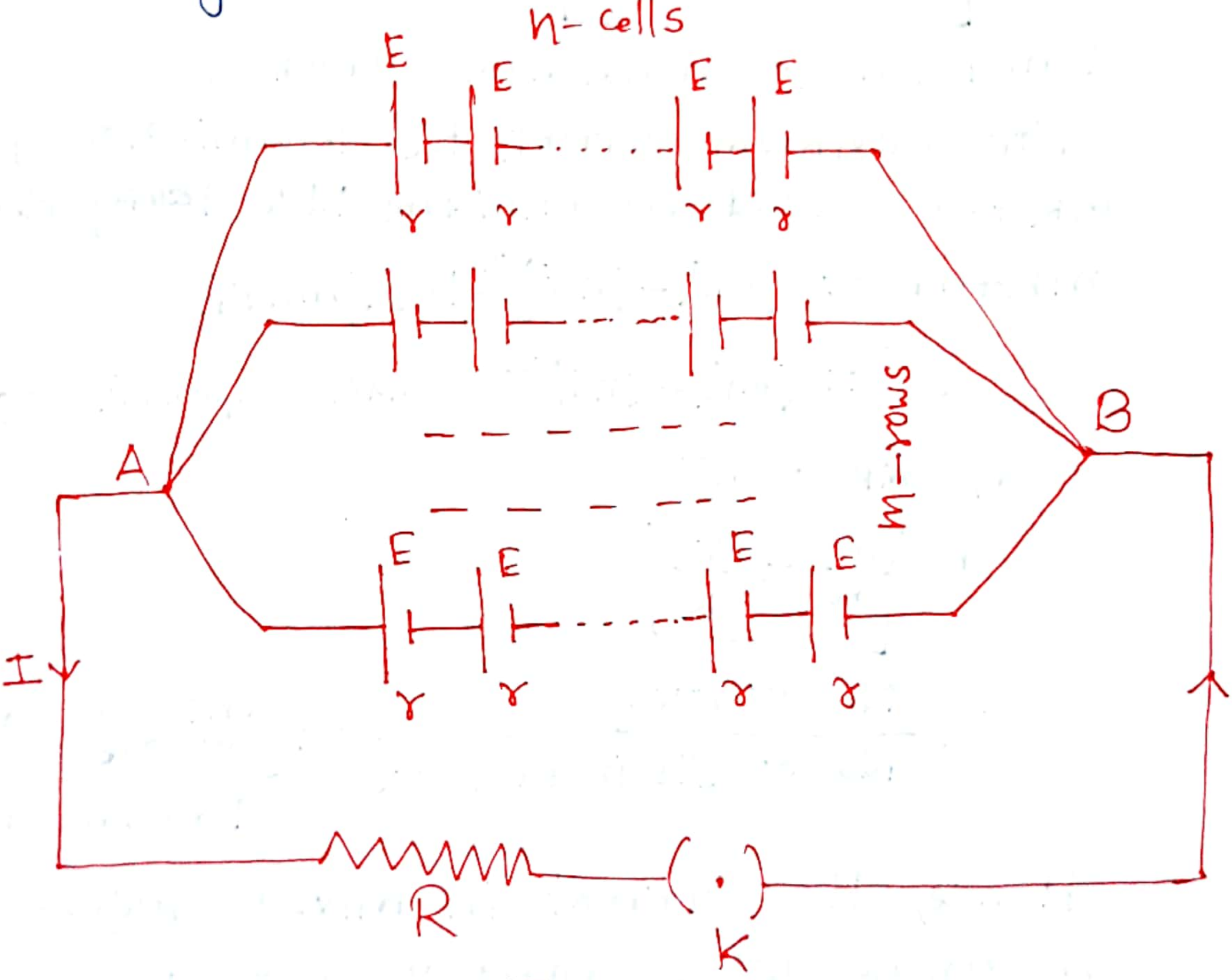


Fig-1.

Total no. of cells $= m \times n = mn$

Emf of each row $= nE$

Total emf $= nE$

Internal resistance in each row $= nr$

$\therefore$ Total internal resistance $\left(\frac{1}{r'}\right) = \frac{1}{nr} + \frac{1}{nr} + \dots$ to m term

$$\frac{1}{r'} = \frac{m}{nr}$$

or, $r' = \frac{nr}{m}$ (26)

$\therefore$ Total ckt resistance $= R + \frac{nr}{m}$

If I be the current flowing in the circuit, then from ohm's law,

$$I = \frac{\text{Total emf}}{\text{Total resistance}} = \frac{nE}{R+\frac{nr}{m}} = \frac{nE}{\frac{mR+nr}{m}}$$

$$\therefore \boxed{I = \frac{mnE}{mR+nr}} \quad \text{—— (1)}$$

Condition for maximum current:

For maximum current, the denominator of eq^n.(1) $mR+nr$ should be minimum. Now, taking denomi.

$$mR+nr = (\sqrt{mR}-\sqrt{nr})^2 + 2\sqrt{mnrR}$$

$$0 = (\sqrt{mR}-\sqrt{nr})^2 \quad \text{Since } 2\sqrt{mnrR} \neq 0$$

or, $mR = nr$

or, $\boxed{\frac{m}{n} = \frac{r}{R}}$

$$\therefore \frac{\text{No. of rows}}{\text{No. of cells in each row}} = \frac{\text{Internal resistence of one cell}}{\text{External resistence}}$$

Hence, the current in mixed grouping is maximum when ratio of no. of rows to no. of cells in each row should be equal to ratio of internal resistance of one cell to the external resistance.

Joule's law of heating: According to Joule the amount of heat (H) produced in a conductor due to flow of current is

(i) directly proportional to the square of current

i.e. $H \propto I^2$ (at R and t constant)

(ii) directly proportional to the resistance R of a conductor

i.e. $H \propto R$ (at I and t constant)

(iii) directly proportional to the time t for which current flows.

i.e. $H \propto t$ (at I and R constant)

Combining all above, we get

$$H \propto I^2 R t \quad \text{—(1)}$$

$$H = I^2 R t \quad \text{(in SI)} \quad \text{—(2)}$$

$$H = \frac{I^2 R t}{J} \quad \text{(in C.G.S.)} \quad \text{—(3)}$$

Where $1J = 4.18$ J/Cal is a conversion factor.

Heating effect of current

Joule's law of heating: (Theoretical proof)

Let us consider a conducting wire of resistance R is connected to a cell of emf E, as shown in fig-1. If q be the charge flowing

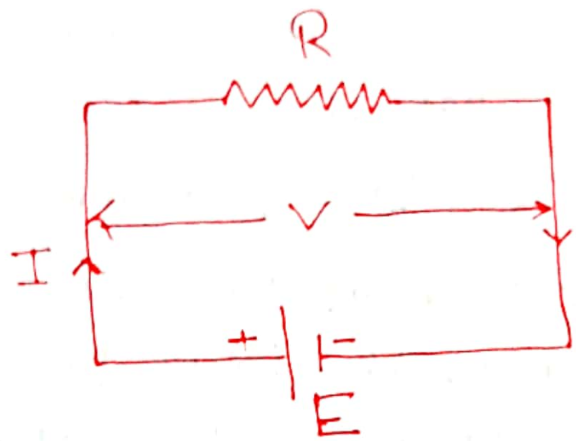


Fig-1.

through the resistance R in time t, then from defn. of current, we have

$$I = \frac{q}{t}$$

or, $q = It$ —(1)

According to ohm's law,

$$V = IR \quad \text{—(2)}$$

The amount of work done in moving the charge q through p.d. V is given by

$$W = q \times V \quad \text{—(3)}$$

From eqs. (1), (2) and (3), we get

$$W = It \times IR = I^2Rt \quad \text{—(4)}$$

This amount of work done is converted into heat energy H.

$\therefore$ $\boxed{H = I^2Rt}$ (Joule's law of heating)

which is the required expression for heat developed in a conductor due to passage of current called Joule's law of heating.

Experimental Verification of Joule's law:-

The experimental arrangement for the verification of Joule's law of heating is shown in fig-1. In figure a calorimeter

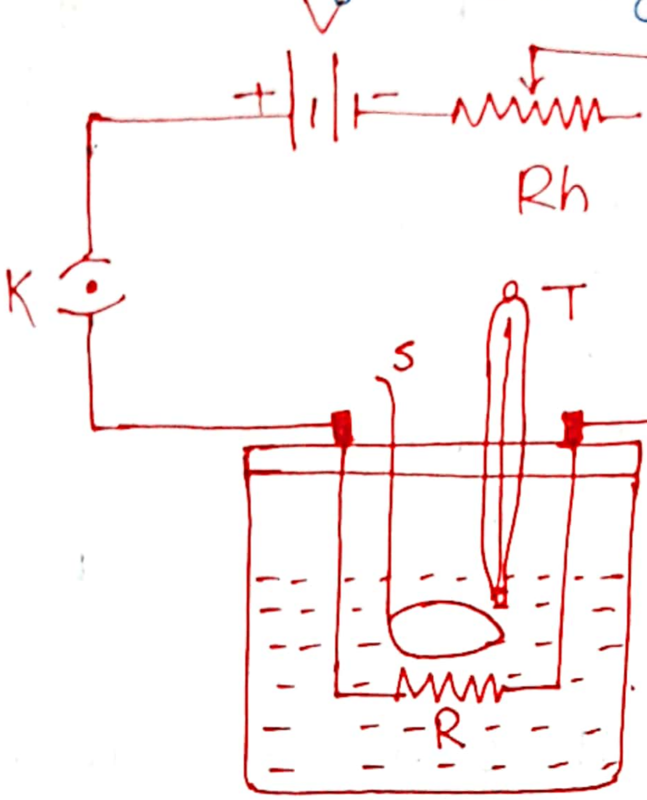


Fig-1.

of water equivalent W is partially filled with water. A heating coil of resistance R is immersed inside the water and ckt is completed as in figure. A stirrer s is taken. and initial temp. θ_1 is noted by thermometer T.

(i) To verify $H \propto I^2$, a known current I_1 is passed for a given time and final temp. θ_2 of the mixture is noted. The amount of heat developed is calculated by $H_1 = W(\theta_2 - \theta_1)$. The same procedure is repeated with different values of current and corresponding quantities of heat produced can be calculated.

It is found that

$$H \propto I^2. \quad -(1)$$

A graph betn. H and I^2 is shown in fig-1(a).

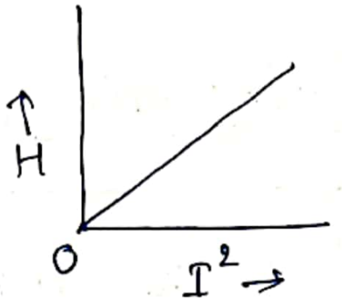
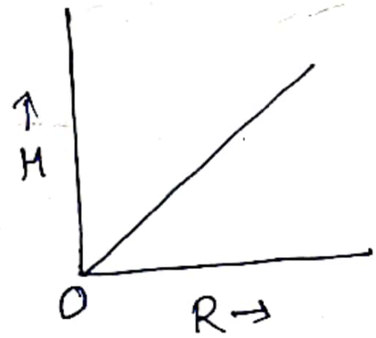


fig.2(a)

(ii) To verify $H \propto R$, the same amount of current is passed for same time through different coils of different resistances and corresponding amount of heat produced can be calculated. Then, it is found that

$$H \propto R \quad -(2)$$

A graph betn. H and R is shown in fig-2(b)

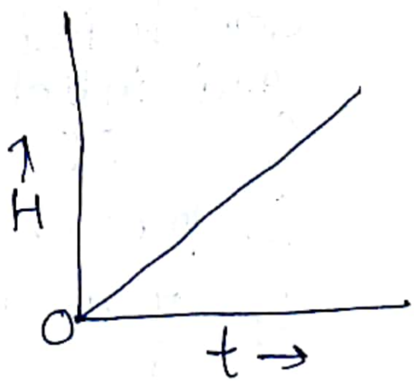


(b)

(iii) To verify $H \propto t$, the same current I is passed through the same resistance R but for different interval of time and corresponding amount of heat produced can be determined. Then, it is found that

$$H \propto t \quad -(3)$$

A graph betn. H and t is shown in fig-2(c)



(C)

Combining eqs.(1), (2) and (3), we get

$$H \propto I^2Rt$$

In SI unit,

$$H = I^2Rt$$

Which verifies Joule's Law of heating