Chapter

3 Conduction in Liquid and Gases

Electrical Conduction in Liquid

When electric field is applied through liquid dielectric there is no current initially. As we go on increasing electric field, the impurity, air or liquid molecules get discharged giving small current. When the electric field strength is large enough called breakdown voltage, we get large amount of current suddenly and the liquid acts as conducting medium. This phenomenon is called *Electric breakdown in liquid.*

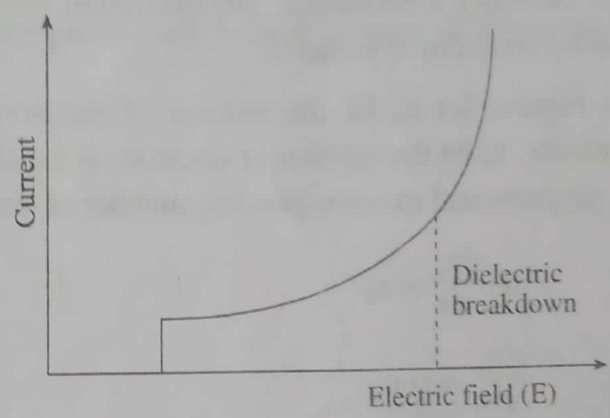

Figure 1: Conduction current versus electric field

The electrical conduction in liquid can be understood in terms of ionic conduction as in electrolysis or electroplating. In electrolysis process we take aqueous media containing the metal to be plated in which two electrodes called cathode and anode are placed when an external potential is applied cations and anions are formed. The positively charged cations move towards cathode and the negatively charged anions move toward anode thus transferring electric current through liquid electrolyte.

The ionic conductivity is given by

$$\sigma = ne\,\mu \qquad \text{...(1)}$$

Where, n = number of ions formed, μ = mobility of ion.

From Einstein's relation, $\frac{D}{\mu} = \frac{KT}{e} \Rightarrow \mu = \frac{eD}{KT}$ ... (2)

The diffusion coefficient varies with temperature as

$$D = D_o\, e^{-\frac{Q}{KT}} \qquad \text{...(3)}$$

Thus equation (1) becomes, $\sigma = ne\frac{e}{KT} D_o\, e^{-Q/KT}$

$$\text{Or, } \sigma = \frac{ne^2 D_o}{KT} e^{-\frac{Q}{KT}}$$

$$= \sigma_o e^{-\frac{Q}{KT}} \text{ where } \sigma_o = \frac{ne^2 D_o}{KT}$$

Taking ln on both side $ln\ \sigma = ln\ \sigma_o + ln\ (e^{-Q/KT})$

$$\text{or } ln\ \sigma = ln\ \sigma_o - \frac{Q}{KT} \quad ...(4)$$

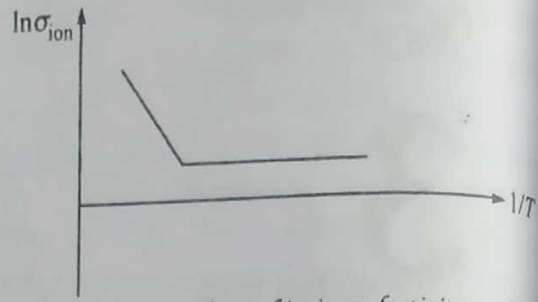

Figure 2: Dependence of ionic conductivity with inverse of temperature.

This relation show that ionic conductivity depends inversely on temperature, as shown in figure below.

Electrical Conduction in Gases

A gas in its normal state is almost a perfect insulator. How ever when a high voltage is applied between two electrodes immersed in gaseous medium, the electric break down occurs and the gas becomes a conductor. The maximum voltage applied at the time of electrical breakdown is called breakdown voltage.

In Figure, let n_0 be the number of electrons produced by ultraviolet radiation incident on cathode. n_x be the number of electrons at a distance x from cathode. Then concentration gradient is proportional to corresponding number of electrons produced.

$$\text{ie. } \frac{dn_x}{dx} \propto n_x$$

$$\frac{dn_x}{dx} = \alpha\ n_x \quad ...(1)$$

Where α is the average ionizing collision made by electrons per centimeter called Townsend's first ionization coefficient.

$$\frac{dn_x}{n_x} = \alpha dx\text{, integrating,}$$

$$ln\ (n_x) = \alpha x + c$$

$$\text{at } x = 0,\ n_x = n_o$$

$$c = ln\ (n_o)$$

$$ln\ (n_x) = \alpha x + ln\ (n_o) \Rightarrow ln \frac{n_x}{n_o} = \alpha x$$

$$n_x = n_o e^{\alpha x} \quad ...(2)$$

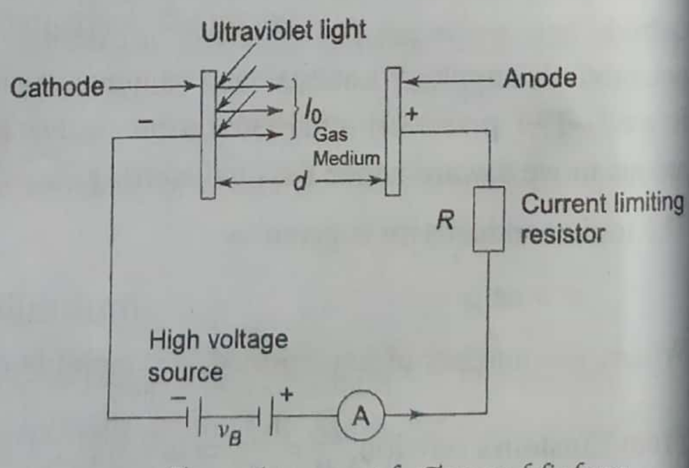

Figure : Arrangement for Townsend discharge

Then the number of electrons reaching the anode (i.e. x = d) will be, $n_d = n_o e^{\alpha d}$ ...(3) and the current produced by those electrons is,

$$I = I_o e^{\alpha d} \quad ...(4)$$

Where I_o is initial current at cathode.

Arc Discharge, Electric Break Down in Gases.

a. **Townsend Discharge Mechanism:**

The excited atom or molecule during discharge of gas may return back to metastable state by emission of photon and this will leads to the emission of electrons due to photo emission. These photons and electrons are responsible for further ionization of gas atom and to carry avalanche of ions. Which results the break down in gases and huge current is produced.

Let n_o be primary electrons, n_o' be the number of secondary electrons produced due to secondary process and n_o'' be the total number of electrons leaving the cathode then.

$$n_o'' = n_o + n_o'$$

The total number of electrons reaching the cathode now becomes

$$n = n_o'' e^{\alpha d} = (n_o + n_o') e^{\alpha d} \qquad ...(1)$$

The secondary electrons produced by secondary process are defined in terms of Townsends secondary ionization coefficient, Γ as

$$n_o' = \Gamma (n - n_o'')$$

$$\text{or, } n_o' = \Gamma (n - n_o - n_o')$$

$$n_o' + \Gamma n_o' = \Gamma (n - n_o)$$

$$n_o' = \frac{\Gamma(n-n_o)}{1+\Gamma} \qquad ...(2)$$

Substituting the value of n_o' from equation (2) in equation (1)

$$n = \left(n_o + \frac{\Gamma(n-n_o)}{1+\Gamma}\right) e^{\alpha d}$$

$$\Rightarrow n = \left(\frac{n_o + n_o\Gamma + n\Gamma - n_o\Gamma}{1+\Gamma}\right) e^{\alpha d}$$

$$n + n\Gamma = n_o e^{\alpha d} + n\Gamma e^{\alpha d}$$

$$n + n\Gamma - n\Gamma e^{\alpha d} = n_o e^{\alpha d}$$

$$n(1 + \Gamma - \Gamma e^{\alpha d}) = n_o e^{\alpha d}$$

$$n = \frac{n_o e^{\alpha d}}{(1 + \Gamma - \Gamma e^{\alpha d})} = \frac{n_o e^{\alpha d}}{(1 - \Gamma e^{\alpha d} + \Gamma)}$$

$$n = \frac{n_o e^{\alpha d}}{1 - \Gamma(e^{\alpha d} - 1)} \qquad ...(3)$$

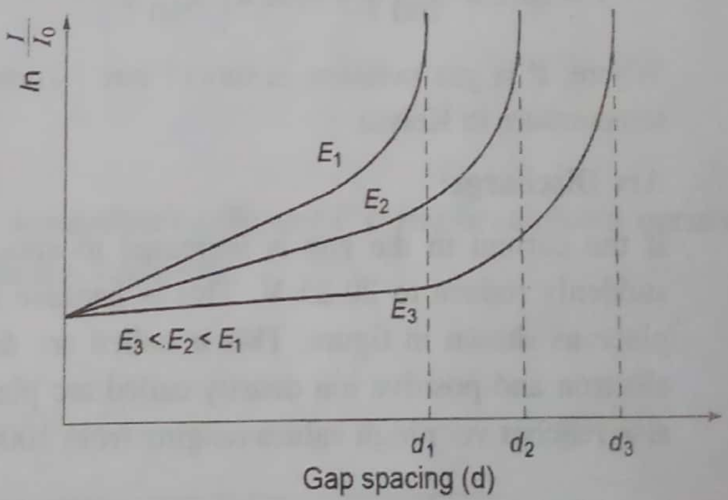

Figure 1: Growth of current in Townsend discharge

Therefore the current produced due to this number of electrons reaching at anode is:

$$I = \frac{I_o e^{\alpha d}}{1 - \Gamma(e^{\alpha d} - 1)} \qquad ...(4)$$

b. Streamer Theory of Electric Break Down: (and Arc Discharge)

According to this theory a single electron starting at the cathode by ionization builds up an avalanche of charges. The electrons in this avalanche being very light in comparison with the positive ions move very fast across the gap. So, by time electrons reach the anode, positive ions are at their initial position forming a positive space charge layer at anode. This positive charge layers makes strong electric field between the gaps.

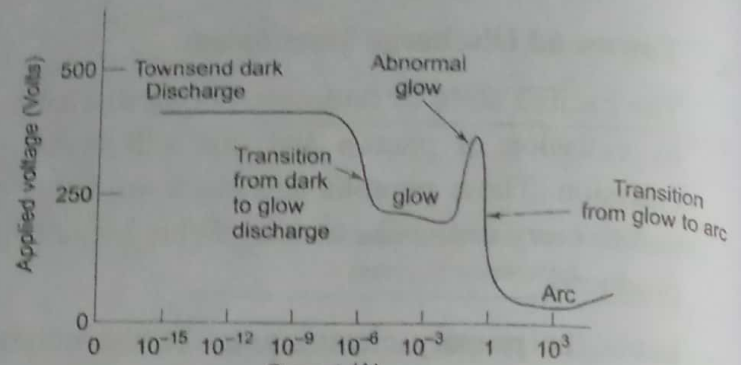

Figure 2 : I-V characteristics in Discharg Phenomena

Although this charge layer occurs initially at anode, due the very high speed of process, it will extend up to the cathode. This process creates a luminous track from anode to cathode, called streamer. As soon as streamer approaches the cathode, a stream of electrons rushes from the cathode to neutralize the positive charges in the streamer. This results in spark break down.

Experimentally, the break down potential of air is found as

$$V = 24.2 \times \frac{293\text{ pd}}{760\text{ T}} + 6.08 \times \left[\frac{293\text{ pd}}{760\text{ T}}\right]^{1/2}$$

Where, P is gas pressure in torr (1 torr - 1mm of mercury) d is distance in cm and T is temperature in Kelvin.

Arc Discharge:

If the current in the gap is increased to about 1A or more, the voltage across the gap suddenly reduce to 20-25 V. This is because a very luminous and noisy discharge takes place as shown in figure. This is called arc discharge. The discharge contains very high electron and positive ion density called arc plasma. During arc discharge, the temperature also reaches very high values ranging from 1000°C to several thousand degrees Celsius.

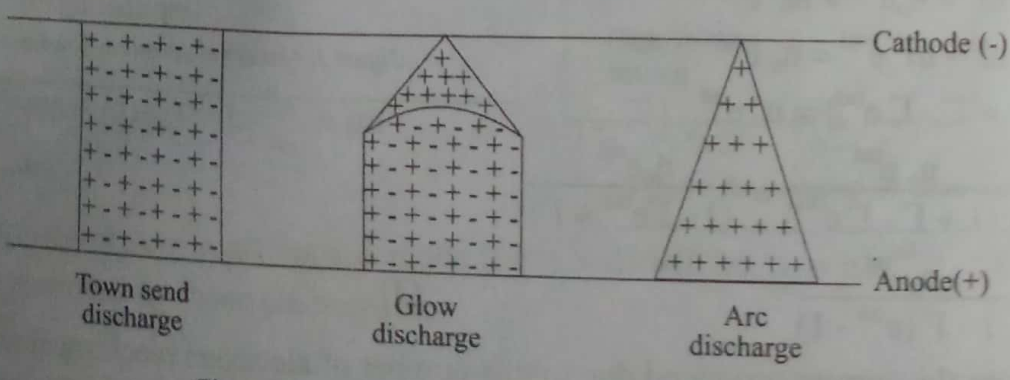

Figure 3 : Streamer directed from anode to cathode

Solved Examples

1. **In an experiment in a certain gas it was found that the steady state current is 5.5×10^{-8} A at 8kV at a distance of 0.4 cm between the plane electrodes keeping the field constant and reducing the distance to 0.1 cm results in a current of 5.5×10^{-9}A. Calculate Townsend's primary ionization coefficient α.**

Solution:

Here, $I_1 = 5.5 \times 10^{-8}$ A, $V = 8$ KV $= 8 \times 10^3$V, $d_1 = 0.4$ cm

$d_2 = 0.1$ cm

$I_2 = 5.5 \times 10^{-9}$ A

We have, $I_1 = I_o e^{\alpha d_1}$, $I_2 = I_o e^{\alpha d_2}$

$$\frac{I_1}{I_2} = e^{\alpha(d_1 - d_2)}$$

$$\alpha (d_1 - d_2) = ln\left(\frac{I_1}{I_2}\right)$$

$$\alpha = \frac{1}{(d_1 - d_2)} ln\left(\frac{I_1}{I_2}\right) = \frac{1}{(0.4\text{-}0.1)} \cdot ln\left(\frac{5 \times 10^{-8}}{5 \times 10^{-9}}\right)$$

$$= \frac{ln\,(10)}{0.3}$$

$$= 7.676 \text{ / cm}$$

2. **Calculate the Townsend's secondary ionization coefficient Γ if the breakdown occurs when the gap distance is 0.9 cm. Given $\alpha = 7.676$/cm.**

Solution:

We have, $I = \dfrac{I_o e^{\alpha d}}{1 - \Gamma (e^{\alpha d} - 1)}$

For break down the current 'I' should be maximum for this, $1 - \Gamma (e^{\alpha d} - 1) = 0$

$$\Rightarrow \Gamma = \frac{1}{e^{\alpha d} - 1}$$

$$= \frac{1}{e^{7.676 \times 0.9} - 1}$$

$$= 1 \times 10^{-3}$$

Exercise

1. Describe ionic conduction in electrolyte and show that ionic conduction in electrolyte depends on temperature.
2. Show that ionic conduction in liquid decreases with increase in temperature and increases with increases in electric field.
3. What is ionic conduction? Derive the relation for ionic conductivity as $\sigma_{ionic} = \sigma_o \exp\left[-\frac{Q}{KT}\right]$
4. Explain, how electrical conduction takes places in liquid.
5. What are the principle conduction mechanisms in liquids? Explain.
6. Explain the principle conduction mechanism in liquids? Derive also the expression for conductivity.
7. The ionic conductivity of liquid is given by $\sigma_{ion} = e\, N_{ion}\, \mu_{ion}$. Where N_{ion} is ionic concentration and μ_{ion} is ionic drift mobility. Illustrate the temperature dependency of ionic conductivity in liquid with necessary expressions and graphs.
8. Define the electrical conduction in gases. Describe the Townsend's secondary ionization and hence derive the current growth equation.
9. Explain electrical conduction in gases with necessary diagram.
10. Explain, how electrical conduction takes place in gases.
11. What do you mean by electrical breakdown in gaseous medium? Explain with Townsend mechanism.
12. How conduction takes place in gases? Explain briefly on the basis of Townsend's break down mechanism.
13. Define Townsend's first and second ionization coefficients. How is the condition for breakdown obtained in a Townsend discharge?
14. Explain the streamer theory of break down in air at atmospheric pressure.
15. Discuss in brief the arc discharge phenomenon is gases.
16. For a certain gap with uniform field electrodes, α was 7.5/cm with a gap distance of 6mm before breakdown. What will be the secondary ionization coefficient Γ?

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