2

Conduction and Breakdown in Gases

2.1 GASES AS INSULATING MEDIA

The simplest and the most commonly found dielectrics are gases. Most of the electrical apparatus use air as the insulating medium, and in a few cases other gases such as nitrogen (N_2), carbon dioxide (CO_2), freon (CCl_2F_2) and sulphur hexafluoride (SF_6) are also used.

Various phenomena occur in gaseous dielectrics when a voltage is applied. When the applied voltage is low, small currents flow between the electrodes and the insulation retains its electrical properties. On the other hand, if the applied voltages are large, the current flowing through the insulation increases very sharply, and an electrical breakdown occurs. A strongly conducting spark formed during breakdown practically produces a short circuit between the electrodes. The maximum voltage applied to the insulation at the moment of breakdown is called the breakdown voltage. In order to understand the breakdown phenomenon in gases, a study of the electrical properties of gases and the processes by which high currents are produced in gases is essential.

The electrical discharges in gases are of two types, i.e. (*i*) non-sustaining discharges, and (*ii*) self-sustaining types. The breakdown in a gas, called spark breakdown is the transition of a non-sustaining discharge into a self-sustaining discharge. The build-up of high currents in a breakdown is due to the process known as ionization in which electrons and ions are created from neutral atoms or molecules, and their migration to the anode and cathode respectively leads to high currents. At present two types of theories, viz. (*i*) Townsend theory, and (*ii*) Streamer theory are known which explain the mechanism for breakdown under different conditions. The various physical conditions of gases, namely, pressure, temperature, electrode field configuration, nature of electrode surfaces, and the availability of initial conducting particles are known to govern the ionization processes.

2.2 IONIZATION PROCESSES

A gas in its normal state is almost a perfect insulator. However, when a high voltage is applied between the two electrodes immersed in a gaseous medium, the gas becomes a conductor and an electrical breakdown occurs.

The processes that are primarily responsible for the breakdown of a gas are ionization by collision, photo-ionization, and the secondary ionization processes. In insulating gases (also called electron-attaching gases) the process of attachment also plays an important role.

2.2.1 Ionization by Collision

The process of liberating an electron from a gas molecule with the simultaneous production of a positive ion is called ionisation. In the process of ionisation by collision, a free electron collides with a neutral gas molecule and gives rise to a new electron and a positive ion. If we consider a low pressure gas column in which an electric field E is applied across two plane parallel electrodes, as shown in Fig. 2.1 then, any electron starting at the cathode will be accelerated more and more between collisions with other gas molecules during its travel towards the anode. If the energy (ε) gained during this travel between collisions exceeds the ionisation potential, V_i, which is the energy required to dislodge an electron from its atomic shell, then ionisation takes place. This process can be represented as

$$e^- + A \xrightarrow{\varepsilon > V_i} e^- + A^+ + e^- \tag{2.1}$$

Where, A is the atom, A^+ is the positive ion and e^- is the electron.

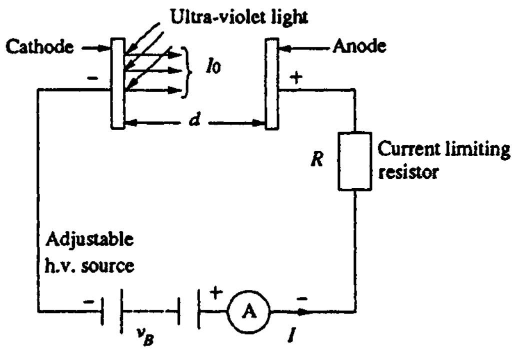

Fig. 2.1 Arrangement for study of a Townsend discharge

A few of the electrons produced at the cathode by some external means, say by ultra-violet light falling on the cathode, ionise neutral gas particles producing positive ions and additional electrons. The additional electrons, then, themselves make 'ionising collisions' and thus the process repeats itself. This represents an increase in the electron current, since the number of electrons reaching the anode per unit time is greater than those liberated at the cathode. In addition, the positive ions also reach the cathode and on bombardment on the cathode give rise to secondary electrons.

2.2.2 Photo-ionization

The phenomena associated with ionisation by radiation, or photo-ionisation, involves the interaction of radiation with matter. Photo-ionisation occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionisation potential.

There are several processes by which radiation can be absorbed by atoms or molecules. They are

(*a*) excitation of the atom to a higher energy state

(*b*) continuous absorption by direct excitation of the atom or dissociation of diatomic molecule or direct ionisation etc.

Just as an excited atom emits radiation when the electron returns to the lower state or to the ground state, the reverse process takes place when an atom absorbs radiation. This reversible process can be expressed as

$$h\nu + A \rightleftharpoons A^{*} \tag{2.2}$$

Ionisation occurs when

$$\lambda \le c \cdot \frac{h.}{V_i} \tag{2.3}$$

where, h is the Planck's constant, c is the velocity of light, λ is the wavelength of the incident radiation and V_i is the ionisation energy of the atom. Substituting for h and c, we get

$$\lambda \le \left(\frac{1.27}{V_i}\right) \times 10^{-6}\text{cm}$$

where V_i is in electron volts (eV). The higher the ionisation energy, the shorter will be the wavelength of the radiation capable of causing ionisation. It was observed experimentally that a radiation having a wavelength of 1250 $A°$ is capable of causing photo-ionisation of almost all gases.

2.2.3 Secondary Ionisation Processes

Secondary ionisation processes by which secondary electrons are produced are the one which sustain a discharge after it is established due to ionisation by collision and photo-ionization.

They are briefly described below.

(a) Electron Emission due to Positive Ion Impact

Positive ions are formed due to ionisation by collision or by photo-ionisation, and being positively charged, they travel towards the cathode.

A positive ion approaching a metallic cathode can cause emission of electrons from the cathode by giving up its kinetic energy on impact. If the total energy of the positive ion, namely, the sum of its kinetic energy and the ionisation energy, is greater than twice the work function of the metal, then one electron will be ejected and a second electron will neutralise the ion. The probability of this process is measured as γ_i which is called the Townsend's secondary ionisation coefficient due to positive ions and is defined as the net yield of electrons per incident positive ion. γ_i increases with ion velocity and depends on the kind of gas and electrode material used.

(b) Electron Emission due to Photons

To cause an electron to escape from a metal, it should be given enough energy to overcome the surface potential barrier. The energy can also be supplied in the form of a photon of ultraviolet light of suitable frequency. Electron emission from a metal surface occurs at the critical condition (see Eq. 2.3)

$$h.\nu \geq \varphi$$

where φ is the work function of the metallic electrode. The frequency (ν) is given by the relationship

$$\nu = \frac{\varphi}{h} \tag{2.4}$$

is known as the threshold frequency. For a clean nickel surface with $\varphi = 4.5$ eV, the threshold frequency will be that corresponding to a wavelength $\lambda = 2755\ \mathring{A}$. If the incident radiation has a greater frequency than the threshold frequency, then the excess energy goes partly as the kinetic energy of the emitted electron and partly to heat the surface of the electrode. Since φ is typically a few electron volts, the threshold frequency lies in the far ultra-violet region of the electromagnetic radiation spectrum.

(c) Electron Emission due to Metastable and Neutral Atoms

A metastable atom or molecule is an excited particle whose lifetime is very large (10^{-3}s) compared to the lifetime of an ordinary particle (10^{-8}s). Electrons can be ejected from the metal surface by the impact of excited (metastable) atoms, provided that their total energy is sufficient to overcome the work function. This process is most easily observed with metastable atoms, because the lifetime of other excited states is too short for them to reach the cathode and cause electron emission, unless they originate very near to the cathode surface. Therefore, the yields can also be large nearly 100%, for the interactions of excited *He* atom with a clean surface of molybdenum, nickel or magnesium. Neutral atoms in the ground state also give rise to secondary electron emission if their kinetic energy is high ($\approx$ 1000 eV). At low energies the yield is considerably less.

2.2.4 Electron Attachment Process

The types of collisions in which electrons may become attached to atoms or molecules to form negative ions are called attachment collisions. Electron attachment process depends on the energy of the electron and the nature of the gas and is a very important process from the engineering point of view. All electrically insulating gases, such as O_2, CO_2, Cl_2, F_2, C_2F_6, C_3F_8, C_4F_{10}, CCl_2F_2, and SF_6 exhibit this property. An electron attachment process can be represented as:

$$\text{Atom} + e^{-} + k \longrightarrow \text{negative atomic ion} + (E_a + K) \tag{2.5}$$

The energy liberated as a result of this process is the kinetic energy K plus the electron affinity E_a. In the attaching or insulating gases, the atoms or molecules have vacancies in their outermost shells and, therefore, have an affinity for electrons. The attachment process plays a very important role in the removal of free electrons from an ionised gas when arc interruption occurs in gas-insulated switchgear. The effect of attachment on breakdown in gases is discussed in sec. 2.7 of this chapter.

2.3 TOWNSEND'S CURRENT GROWTH EQUATION

Referring to Fig. 2.1 let us assume that n_0 electrons are emitted from the cathode. When one electron collides with a neutral particle, a positive ion and an electron are formed. This is called an ionizing collision. Let α be the average number of ionizing collisions made by an electron per centimetre travel in the direction of the field (α depends on gas pressure p and E/p, and is called the Townsend's first ionization coefficient). At any distance x from the cathode, let the number of electrons be n_x. When these n_x electrons travel a further distance of dx they give rise to ($\alpha n_x dx$) electrons.

At
$$x = 0, n_x = n_0 \tag{2.6}$$

Also,
$$\frac{dn_x}{dx} = \alpha n_x; \text{ or } n_x = n_0 \exp(\alpha x) \tag{2.7}$$

Then, the number of electrons reaching the anode ($x = d$) will be

$$n_d = n_0 \exp(\alpha d) \tag{2.8}$$

The number of new electrons created, on the average, by each electron is

$$\exp(\alpha d) - 1 = \frac{nd - n_0}{n_0} \tag{2.9}$$

Therefore, the average current in the gap, which is equal to the number of electrons travelling per second will be

$$I = I_0 \exp(\alpha d) \tag{2.10}$$

where I_0 is the initial current at the cathode.

2.4 CURRENT GROWTH IN THE PRESENCE OF SECONDARY PROCESSES

The single avalanche process described in the previous section becomes complete when the initial set of electrons reaches the anode. However, since the amplification of electrons [exp(αd)] is occurring in the field, the probability of additional new electrons being liberated in the gap by other mechanisms increases, and these new electrons create further avalanches. The other mechanisms are

(*i*) The positive ions liberated may have sufficient energy to cause liberation of electrons from the cathode when they impinge on it.

(*ii*) The excited atoms or molecules in avalanches may emit photons, and this will lead to the emission of electrons due to photo-emission.

(*iii*) The metastable particles may diffuse back causing electron emission.

The electrons produced by these processes are called secondary electrons. The secondary ionization coefficient γ is defined in the same way as α, as the net number of secondary electrons produced per incident positive ion, photon, excited particle, or metastable particle, and the total value of γ is the sum of the individual coefficients due to the three different processes, i.e., $\gamma = \gamma_1 + \gamma_2 + \gamma_3$. γ is called the Townsend's secondary ionization coefficient and is a function of the gas pressure p and E/p.

Following Townsend's procedure for current growth, let us assume

n_0' = number of secondary electrons produced due to secondary (γ) processes.

Let n_0'' = total number of electrons leaving the cathode.

Then
$$n_0'' = n_0 + n_0 \tag{2.11}$$

The total number of electrons n reaching the anode becomes,

$$n = n_0'' \exp(\alpha d) = (n_0 + n_0') \exp(\alpha d);$$

and
$$n_0' = \gamma\,[n - (n_0 + n_0')]$$

Eliminating n_0',
$$n = \frac{n_0 \exp(\alpha d)}{1 - \gamma\,[\exp(\alpha d) - 1]}$$

or
$$I = \frac{I_0 \exp(\alpha d)}{1 - \gamma\,[\exp(\alpha d) - 1]} \tag{2.12}$$

2.5 TOWNSEND'S CRITERION FOR BREAKDOWN

Equation (2.12) gives the total average current in a gap before the occurrence of breakdown. As the distance between the electrodes d is increased, the denominator of the equation tends to zero, and at some critical distance $d = d_s$.

$$1 - \gamma\,[\exp(\alpha d) - 1] = 0 \tag{2.13}$$

For values of $d < d_s$, I is approximately equal to I_0, and if the external source for the supply of I_0 is removed, I becomes zero. If $d = d_s$, $I \to \infty$ and the current will be limited only by the resistance of the power supply and the external circuit. This condition is called Townsend's breakdown criterion and can be written as

$$\gamma\,[\exp(\alpha d) - 1] = 1$$

Normally, $\exp(\alpha\, d)$ is very large, and hence the above equation reduces to

$$\gamma \exp(\alpha d) = 1 \tag{2.14}$$

For a given gap spacing and at a give pressure the value of the voltage V which gives the values of α and γ satisfying the breakdown criterion is called the spark breakdown voltage V_s and the corresponding distance d_s is called the sparking distance.

The Townsend mechanism explains the phenomena of breakdown only at low pressures, corresponding to $p \times d$ (gas pressure $\times$ gap distance) values of 1000 torr-cm and below.

2.6 EXPERIMENTAL DETERMINATION OF COEFFICIENTS α AND γ

The experimental arrangement is shown in Fig. 2.2. The electrode system consists of two uniform field electrodes. The high voltage electrode is connected to a variable high voltage d.c. source (of 2 to 10 kV rating). The low voltage electrode consists of a central electrode and a guard electrode. The central electrode is connected to the ground through the high resistance of an electrometer amplifier having an input resistance of 10^9 to 10^{13} ohms. The guard electrode is directly earthed. The electrometer amplifier measures currents in the range 10^{-14} to 10^{-8} A.

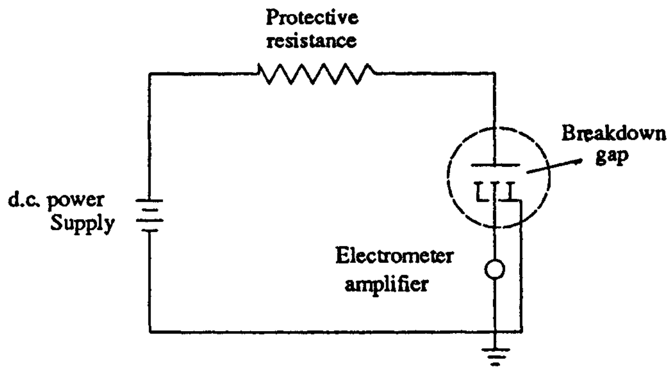

Fig. 2.2 Experimental arrangement to measure ionization coefficients α and η

The electrode system is placed in an ionization chamber which is either a metal chamber made of chromium plated mild steel or stainless steel, or a glass chamber. The electrodes are usually made of brass or stainless steel. The chamber is evacuated to a very high vacuum of the order of 10^{-4} to 10^{-6} torr. Then it is filled with the desired gas and flushed several times till all the residual gases and air are removed. The pressure inside the chamber is adjusted to a few torr depending on the gap separation and left for about half an hour for the gas to fill the chamber uniformly.

The cathode is irradiated using an ultra-violet (U.V.) lamp kept outside the chamber. The U.V. radiation produces the initiatory electrons (n_0) by photo-electric emission.

When the d.c. voltage is applied and when the voltage is low, the current pulses start appearing due to electrons and positive ions as shown in Figs. 2.3a and 2.3b. These records are obtained when the current is measured using a cathode ray oscillograph.

When the applied voltage is increased, the pulses disappear and an average d.c. current is obtained as shown in Fig. 2.4. In the initial portion (T_0), the current increases slowly but unsteadily with the voltage applied. In the regions T_1 and T_2, the current increases steadily due to the Townsend mechanism. Beyond T_2 the current rises very sharply, and a spark occurs.

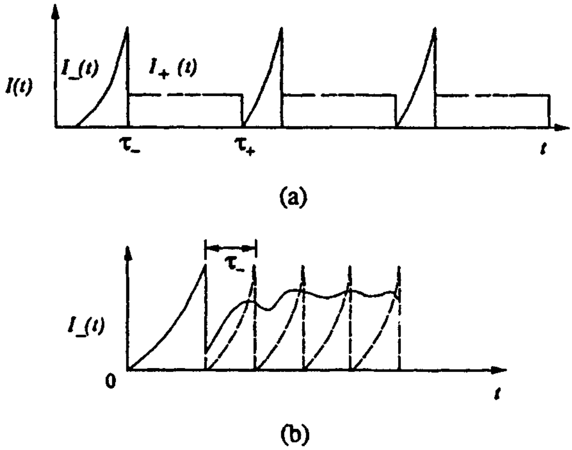

Fig. 2.3 Current as a function of time

(a) When secondary electrons are produced at the cathode by positive ions.

(b) When secondary electrons are produced by photons at the cathode.

--- ideal, —— actual.

$I(t)$ is the total current and I_- and I_+ are electron ion currents. τ_- and τ_+ are the electron and ion transit times.

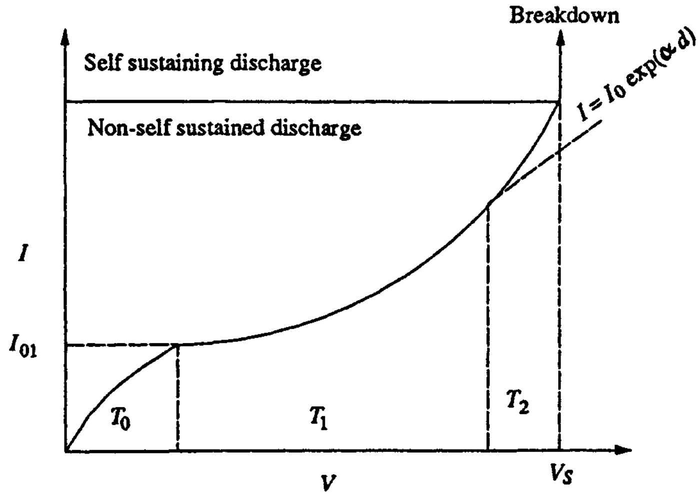

Fig. 2.4 Typical current growth curve in a townsend discharge

For determining the α and γ coefficients, the voltage-current characteristics for different gap settings are obtained. From these results, a log I/I_0 versus gap distance plot is obtained under constant field (E) conditions as shown in Fig. 2.5. The slope of the initial portion of the curves gives the value of α. Knowing α, γ can be found from Eq. (2.12) using points on the upcurving portion of the graphs. The experiment can be repeated for different pressures.

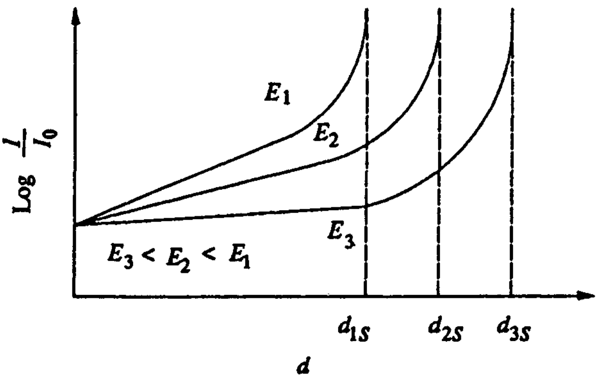

Fig. 2.5 Townsend type log (I/I_0) vs. d plot

It can be easily seen that α/p and γ are functions of E/p. The spark-over voltage for any gap length d_s is $V_s = Ed_s$ where d_s is the critical gap length for that field strength as obtained from the graph. It may be noted that if I_0, the initial current, is more, the average anode current I will also be more, and the relation log I/I_0 versus remains the same. Typical values of α and γ are shown in Figs. 2.6 and 2.7.

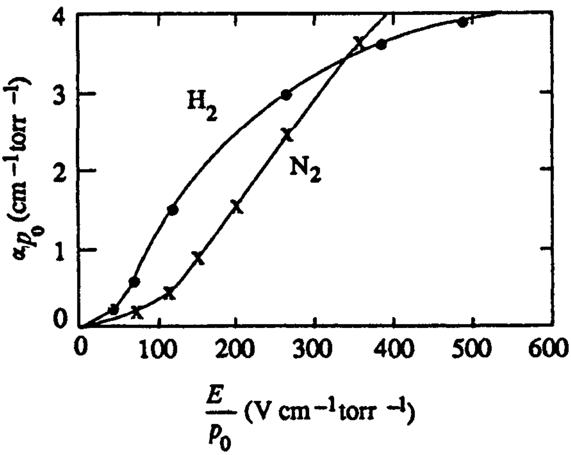

Fig. 2.6 The variation of α/p with E/p in hydrogen and nitrogen, p_0 in both x and y axes refers to values of pressure reduced to 0°C

2.7 BREAKDOWN IN ELECTRONEGATIVE GASES

It has been recognised that one process that gives high breakdown strength to a gas is the electron attachment in which free electrons get attached to neutral atoms or molecules to form negative ions. Since negative ions like positive ions are too massive to produce ionization due to collisions, attachment represents an effective way of removing electrons which otherwise would have led to current growth and breakdown at low voltages. The gases in which attachment plays an active role are called electronegative gases.

The most common attachment processes encountered in gases are (*a*) the direct attachment in which an electron directly attaches to form a negative ion, and (*b*) the dissociative attachment in which the gas molecules split into their constituent atoms and the electronegative atom forms a negative ion. These processes may be symbolically represented as:

(*a*) Direct attachment

$$AB + e \longrightarrow AB^- . \tag{2.15}$$

(*b*) Dissociative attachment

$$AB + e \longrightarrow A + B^- \tag{2.16}$$

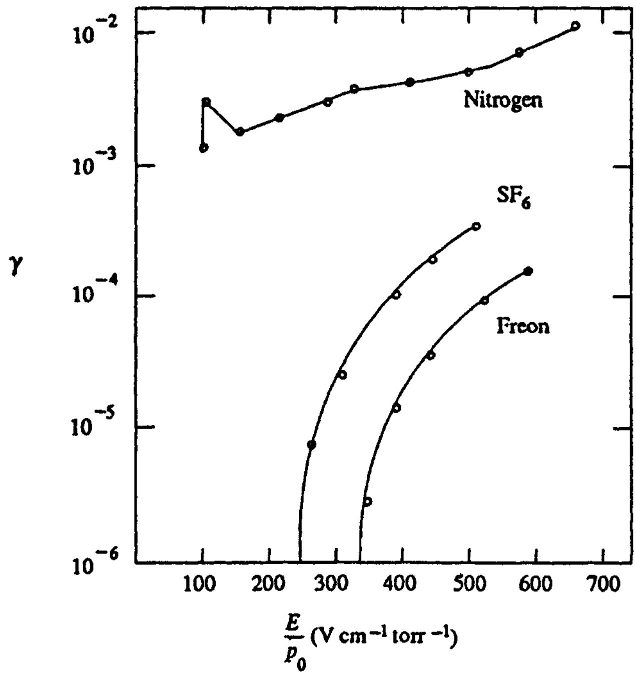

Fig. 2.7 Secondary ionization coefficient (γ) as a function of E/p in nitrogen, freon and SF_6 gases

A simple gas of this type is oxygen. Other gases are sulphur hexafluoride, freon, carbon dioxide, and fluorocarbons. In these gases, 'A' is usually sulphur or carbon atom, and 'B' is oxygen atom or one of the halogen atoms or molecules.

With such gases, the Townsend current growth equation is modified to include ionization and attachment. An attachment coefficient (η) is defined, similar to α, as the number of attaching collisions made by one electron drifting one centimetre in the direction of the field. Under these conditions the current reaching the anode, can be written as

$$I = I_0 \frac{[\{\alpha/(\alpha-\eta)\}\exp(\alpha-\eta)d] - [\eta/(\alpha-\eta)]}{1-\left\{\gamma\frac{\alpha}{(\alpha-\eta)}[\{\exp(\alpha-\eta)d\}-1]\right\}} \tag{2.17}$$

The Townsend breakdown criterion for attaching gases can also be deduced by equating the denominator in Eq. (2.17) to zero, i.e.

$$\gamma\frac{\alpha}{(\alpha-\eta)}[\exp(\alpha-\eta)d-1] = 1 \tag{2.18}$$

This shows that for $\alpha > \eta$, breakdown is always possible irrespective of the values of α, η, and γ. If on the other hand, $\eta > \alpha$ Eq. (2.18) approaches an asymptotic form with increasing value of d, and

$$\gamma\frac{\alpha}{(\alpha-\eta)} = 1\text{ ; or } \alpha = \frac{\eta}{(1-\gamma)} \tag{2.19}$$

Normally, γ is very small ($\leq 10^{-4}$) and the above equation can be written as $\alpha = \eta$. This condition puts a limit for *E/p* below which no breakdown is possible irrespective of the value of *d*, and the limit value is called the critical *E/p*. Critical *E/p* for SF_6 is 117 V cm^{-1} $torr^{-1}$, and for CCl_2F_2 it is 121 V cm^{-1} $torr^{-1}$ (both at 20°C). η values are also experimentally determined as described in Sec. 2.6. Typical values of η in a few gases are shown in Fig. 2.8.

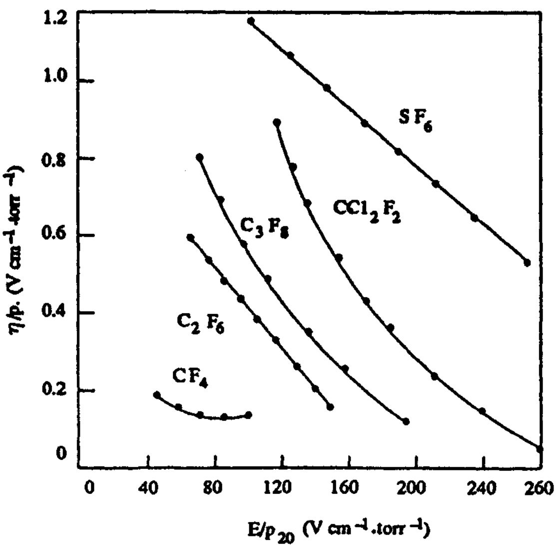

Fig. 2.8 The variation of η/p with *E/p* in some insulating gases. p_{20} refers to values of pressure reduced to 20°C

2.8 TIME LAGS FOR BREAKDOWN

In the previous section, the mechanism of spark breakdown is considered as a function of ionization processes under uniform field conditions. But in practical engineering designs, the breakdown due to rapidly changing voltages or impulse voltages is of great importance. Actually, there is a time difference between the application of a voltage sufficient to cause breakdown and the occurrence of breakdown itself. This time difference is called the time lag.

The Townsend criterion for breakdown is satisfied, only if at least one electron is present in the gap between the electrodes. In the case of applied d.c. or slowly varying (50 Hz a.c) voltages, there is no difficulty in satisfying this condition. However, with rapidly varying voltages of short duration ($\approx 10^{-6}$ s), the initiatory electron may not be present in the gap, and in the absence of such an electron breakdown cannot occur. The time t which lapses between the application of the voltage sufficient to cause breakdown and the appearance of the initiating electron is called a statistical time lag (t_s) of the gap. The appearance of electrons is usually statistically distributed. After the appearance of the electron, a time t_f is required for the ionization processes to develop fully to cause the breakdown of the gap, and this time is called the formative time lag (t_f). The total time $t_s + t_f = t$ is called the total time lag.

Time lags are of considerable practical importance. For breakdown to occur the applied voltage V should be greater than the static breakdown voltage V_s as shown in Fig. 2.9. The difference in voltage $\Delta V = V - V_s$ is called the overvoltage, and the ratio V/V_s is called the impulse ratio. The variation of t_f with overvoltage (ΔV) is shown in Fig. 2.10. The volt-time characteristics of different electrical apparatus, which are very important in insulation co-ordination, are shown in Fig. 2.11. It can be seen from the Fig. 2.11 that a rod gap will protect a bushing, whereas a sphere gap is required for the complete protection of a transformer against high voltage surges (see also Chapter 8).

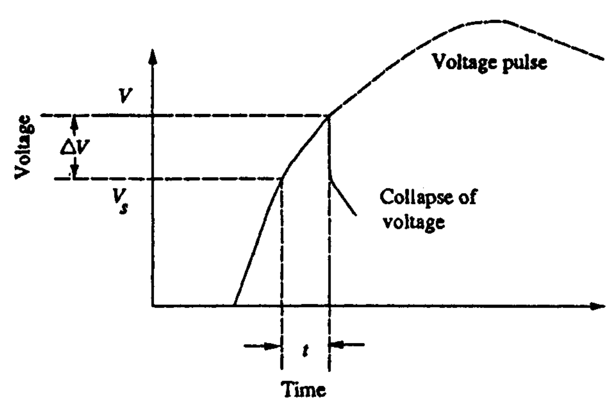

Fig. 2.9 Breakdown on the front of the applied impulse voltage wave

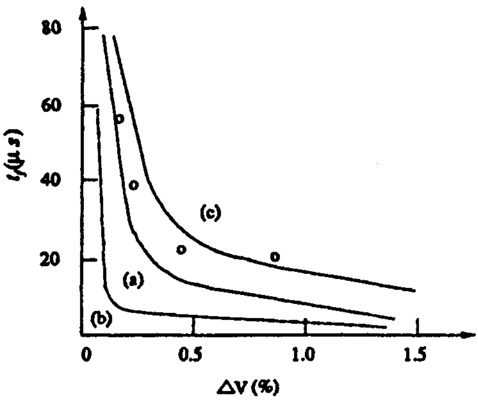

Fig. 2.10 Formative time lag (t_f) as a function of ΔV. *a, b, c* are for different gap spacings
0 experimental point, — calculated
ref: F. Llewellyn Jones, ionization and breakdown in gases, Methuen, London (1957)

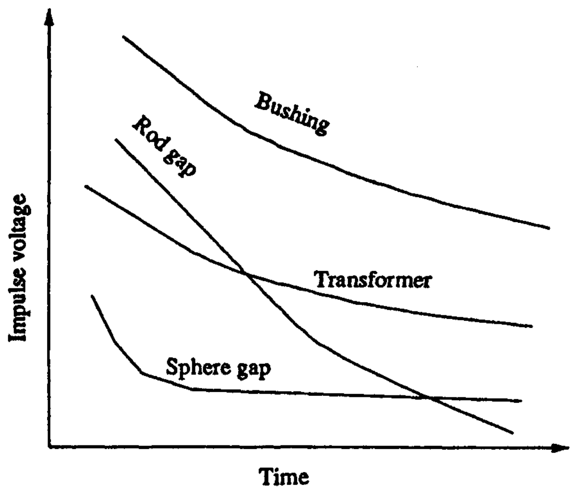

Fig. 2.11 Impulse voltage-time to flashover characteristics

2.9 STREAMER THEORY OF BREAKDOWN IN GASES

Townsend mechanism when applied to breakdown at atmospheric pressure was found to have certain drawbacks. Firstly, according to the Townsend theory, current growth occurs as a result of ionization processes only. But in practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap. Secondly, the mechanism predicts time lags of the order of 10^{-5}s, while in actual practice breakdown was observed to occur at very short times of the order of 10^{-8}s. Also, while the Townsend mechanism predicts a very diffused form of discharge, in actual practice, discharges were found to be filamentary and irregular. The Townsend mechanism failed to explain all these observed phenomena and as a result, around 1940, Raether and, Meek and Loeb independently proposed the Streamer theory.

The theories predict the development of a spark discharge directly from a single avalanche in which the space charge developed by the avalanche itself is said to transform the avalanche into a plasma streamer. Consider Fig. 2.12. A single electron starting at the cathode by ionization builds up an avalanche that crosses the gap. The electrons in the avalanche move very fast compared with the positive ions. By the time the electrons reach the anode the positive ions are virtually in their original positions and form a positive space charge at the anode. This enhances the field, and the secondary avalanches are formed from the few electrons produced due to photo-ionization in the space charge region. This occurs first near the anode where the space charge is maximum. This results in a further increase in the space charge. This process is very fast and the positive space charge extends to the cathode very rapidly resulting in the formation of a streamer. Comparatively narrow lumimous tracks occurring at breakdown at high pressures are called streamers. As soon as the streamer tip approaches the cathode, a cathode spot is formed and a stream of electrons rush from the cathode to neutralize the positive space charge in the streamer; the result is a spark, and the spark breakdown has occurred. The three successive stages in the development of the streamer are shown diagrammatically in Fig. 2.13 in which (*a*) shows the stage when avalanche has crossed the gap, (*b*) shows that the streamer has crossed half the gap length, and (*c*) shows that the gap has been bridged by a conducting channel.

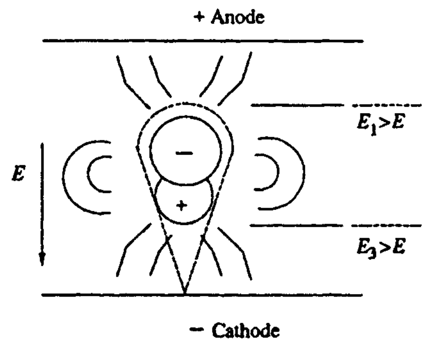

Fig. 2.12 Effect of space charge produced by an avalanche on the applied electric field

Meek proposed a simple quantitative criterion to estimate the electric field that transforms an avalanche into a streamer. The field E_r produced by the space charge, at the radius r, is given by

$$E_r = 5.27 \times 10^{-7} \frac{\alpha \exp(\alpha x)}{(x/p)^{1/2}} \text{ V/cm} \tag{2.20}$$

where α is Townsend's first ionization coefficient, p is the gas pressure in torr, and x is the distance to which the streamer has extended in the gap. According to Meek, the minimum breakdown voltage is obtained when $E_r = E$ and $x = d$ in the above equation.

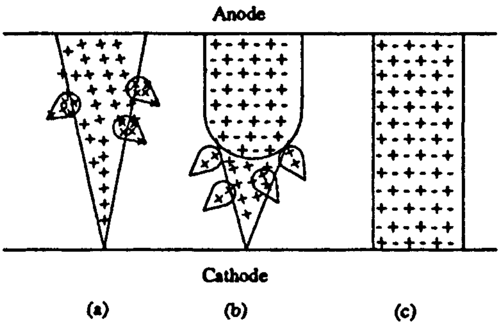

Fig. 2.13 Cathode directed streamer

The equation simplifies into,

$$\alpha d + \ln\left(\frac{\alpha}{p}\right) = 14.5 + \ln\left(\frac{E}{p}\right) + \frac{1}{2}\ln\left(\frac{d}{p}\right) \tag{2.21}$$

This equation is solved between α/p and E/p at which a given p and d satisfy the equation. The breakdown voltage is given by the corresponding product of E and d.

The above simple criterion enabled an agreement between the calculated and the measured breakdown voltages. This theory also neatly fits in with the observed filamentary, crooked channels and the branching of the spark channels, and cleared up many ambiguities of the Townsend mechanism when applied to breakdown in a high pressure gas across a long gap.

It is still controversial as to which mechanism operates in uniform field conditions over a given range of pd values. It is generally assumed that for pd values below 1000 torr-cm and gas pressures varying from 0.01 to 300 torr, the Townsend mechanism operates, while at higher pressures and pd values the Streamer mechanism plays the dominant role in explaining the breakdown phenomena. However, controversies still exist on these statements.

2.10 PASCHEN'S LAW

It has been shown earlier (refer Sec. 2.5) that the breakdown criterion in gases is given as

$$\gamma\,[\exp(\alpha d) - 1] = 1 \tag{2.22}$$

where the coefficients α and γ are functions of E/p, i.e

$$\frac{\alpha}{p} = f_1\left(\frac{E}{p}\right)$$

and

$$\gamma = f_2\left(\frac{E}{p}\right)$$

Also

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

Substituting for E in the expressions for α and γ and rewriting Eq. (2.18) we have

$$f_2\left(\frac{V}{pd}\right)[\exp\left\{pdf_1\left(\frac{V}{pd}\right)\right\} - 1] = 1 \tag{2.23}$$

This equation shows a relationship between V and pd, and implies that the breakdown voltage varies as the product pd varies. Knowing the nature of functions f_1 and f_2 we can rewrite Eq. (2.22) as,

$$V = f(pd) \tag{2.24}$$

This equation is known as Paschen's law and has been experimentally established for many gases, and it is a very important law in high voltage engineering.

The Paschen's curve, the relationship between V and pd is shown in Fig. 2.14 for three gases CO_2, air and H_2. It is seen that the relationship between V and pd is not linear and has a minimum value for any gas. The minimum breakdown voltages for various gases are given in Table 2.1

Table 2.1 Minimum Sparking Potential For Various Gases

Gas	V_s min (V)	pd at V_s min (torr-cm)
Air	327	0.567
Argon	137	0.9
H_2	273	1.15
Helium	156	4.0
CO_2	420	0.51
N_2	251	0.67
N_2O	418	0.5
O_2	450	0.7
SO_2	457	0.33
H_2S	414	0.6

The existence of a minimum sparking potential in Paschen's curve may be explained as follows:

For values of $pd > (pd)_{min}$, electrons crossing the gap make more frequent collisions with gas molecules than at $(pd)_{min}$, but the energy gained between collisions is lower. Hence, to maintain the desired ionization more voltage has to be applied. For $pd < (pd)_{min}$, electron may cross the gap without even making a collision or making only less number of collisions. Hence, more voltage has to be applied for breakdown to occur.

However, in some gases Paschen's law is not strictly obeyed, and sparking potentials at larger spacings for a given value of pd are higher than at lower spacings for the same pd value. This is attributed to the loss of electrons from the gap due to diffusion.

The sparking potentials for uniform field gaps in air, CO_2 and H_2 at 20°C are shown in Fig. 2.14. It has been observed that the cathode materials also affect the breakdown values. This is shown in Fig. 2.15 for cathodes made of barium, magnesium and aluminium.

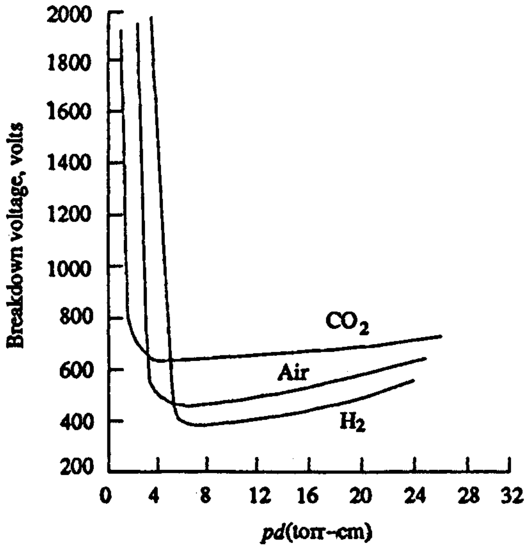

Fig. 2.14 Breakdown voltage-*pd* characteristics for air, CO_2 and hydrogen

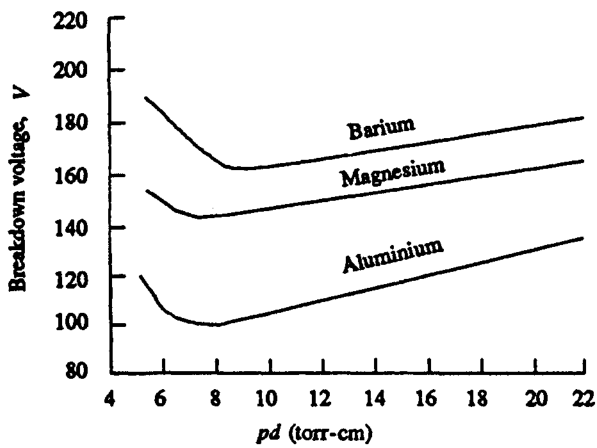

Fig. 2.15 Dependence of breakdown voltage on the cathode materials

In order to account for the effect of temperature, the Paschen's law is generally stated as $V = f(Nd)$ where N is the density of the gas molecules. This is necessary, because the pressure of the gas changes with temperature according to the gas law pv = NRT, where v is the volume of the gas, T is the temperature, and R is a constant.

Based on the experimental results, the breakdown potential of air is expressed as a power function in pd as

$$V = 24.22\left[\frac{293\,pd}{760T}\right] + 6.08\left[\frac{293\,pd}{760T}\right]^{1/2} \tag{2.25}$$

It may be noted from the above formula that the breakdown voltage at constant pressure and temperature is not constant.

At 760 torr and 293°K.

$$E = V/d = 24.22 + \left[\frac{6.08}{\sqrt{d}}\right] \text{kV/cm} \tag{2.26}$$

This equation yields a limiting value for E of 24 kV/cm for long gaps and a value of 30 kV/cm for $\left(\frac{293pd}{760T}\right) = 1$, which means a pressure of 760 torr at 20°C with 1 cm gap. This is the usually quoted breakdown strength of air at room temperature and at atmospheric pressure.

2.11 BREAKDOWN IN NON-UNIFORM FIELDS AND CORONA DISCHARGES

2.11.1 Corona Discharges

If the electric field is uniform, a gradual increase in voltage across a gap produces a breakdown of the gap in the form of a spark without any preliminary discharges. On the other hand, if the field is non-uniform, an increase in voltage will first cause a discharge in the gas to appear at points with highest electric field intensity, namely at sharp points or where the electrodes are curved or on transmission lines. This form of discharge is called a corona discharge and can be observed as a bluish luminiscence. This phenomenon is always accompanied by a hissing noise, and the air surrounding the corona region becomes converted into ozone. Corona is responsible for considerable loss of power from high voltage transmission lines, and it leads to the deterioration of insulation due to the combined action of the bombardment of ions and of the chemical compounds formed during discharges. Corona also gives rise to radio interference.

The voltage gradient required to produce visual a.c. corona in air at a conductor surface, called the corona inception field, can be approximately given for the case of parallel wires of radius r as

$$E_v = 30md\left[1 + \frac{0.301}{\sqrt{dr}}\right] \tag{2.27}$$

For the case of coaxial cylinders, whose inner cylinder has a radius r the equation becomes

$$E_c = 31md\left[1 + \frac{0.308}{\sqrt{dr}}\right] \tag{2.28}$$

where m is the surface irregularity factor which becomes equal to unity for highly polished smooth wires; d is the relative air density correction factor given by,

$$d = \frac{0.392b}{(273+t)} \tag{2.29}$$

where b is the atmospheric pressure in torr, and t is the temperature in °C, $d = 1$ at 760 torr and 25°C. The expressions were found to hold good from atmospheric pressure down to a pressure of several torr.

On the high voltage conductors at high pressures there is a distinct difference in the visual appearance of the corona under positive and negative polarities of the applied voltage. When the voltage is positive, corona appears as a uniform bluish white sheath over the entire surface of the conductor. On the other hand, when the voltage is negative, the corona will appear like reddish glowing spots distributed along the length of the wire. Investigations with point-plane gaps in air showed that when point is negative, corona appears as current pulses called Trichel pulses, and the repetition frequency of these pulses increases as the applied voltage is increased and decreases with decrease in pressure. On the other hand, observations when the point is positive in air showed that the corona current increases steadily with voltage. At sufficiently high voltage, current amplification increases rapidly with voltage, up to a current of about 10^{-7}A, after which the current becomes pulsed with repetition frequency of about 1 kHz composed of small bursts. This form of corona is called burst corona. The average current then increases steadily with applied voltage leading to breakdown.

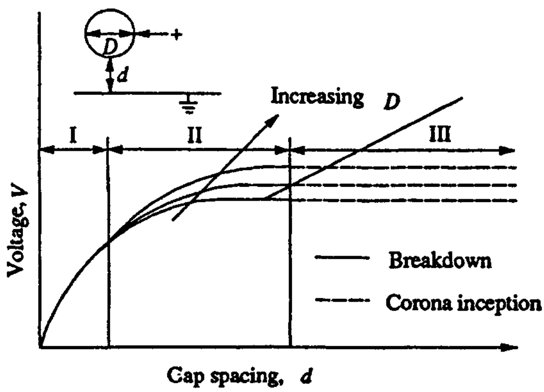

Fig. 2.16 Breakdown and corona inception characteristics for spheres of different diameters in sphere-plane gap geometry

The corona inception and breakdown voltages of the sphere-plane arrangement are shown in Fig. 2.16. From this figure it can be seen that

(*a*) at small spacings (region I), the field is uniform, and the breakdown voltage mainly depends on the spacing;

(*b*) at fairly large spacings (region II), the field is non-uniform, and the breakdown voltage depends both on the sphere diameter and the spacing; and

(*c*) at large spacings (region III), the field is non-uniform, and the breakdown is preceded by corona and is controlled only by the spacing. The corona inception voltage mainly depends on the sphere diameter.

The actual breakdown characteristics of the sphere-plane gap in air is shown in Fig. 2.17. It may be summarized that the study of corona and non-uniform field breakdown is very complicated and investigations are still under progress.

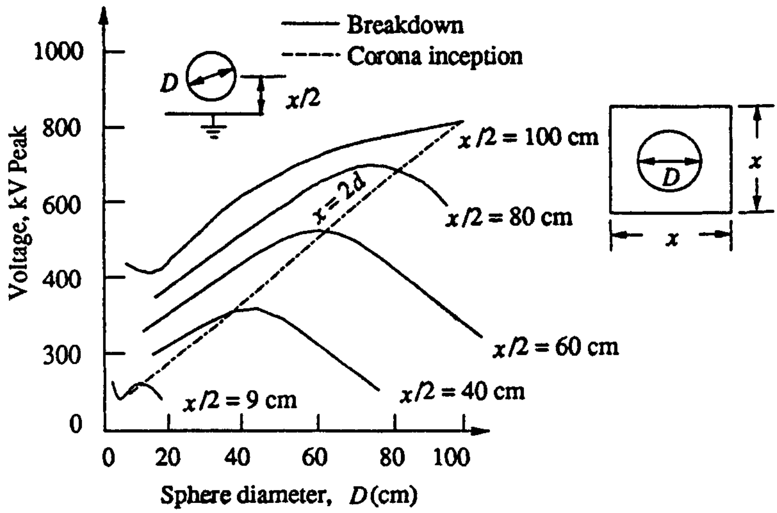

Fig. 2.17 Breakdown and corona inception characteristics of sphere-plane geometry in air, x is the fixed overall dimension of a system as shown

ref: B.L. Goodlet, F.S. Edwards and F.R. Perry, Journal of the Institution of Electrical Engineers; vol. 69, 695 (1931)

2.11.2 Breakdown in Non-uniform Fields

In non-uniform fields, such as coaxial cylinders, point-plane and sphere-plane gaps, the applied field varies across the gap. Similarly, Townsend's first ionization coefficient (α) also varies with the gap. Hence αd in Townsend's criterion [refer to Eq. (2.14)] is rewritten by replacing αd by $\int_0^d \alpha\, dx$. Townsend's criterion for breakdown now becomes

$$\gamma\left\{\exp\left[\int_0^d \alpha dx\right] - 1\right\} = 1 \qquad (2.30)$$

Meek and Raether also discussed the non-uniform field breakdown process as applied to their Streamer theory, and the Meek's equation [Eq. (2.19)] for the radial field at the head of an avalanche when it has crossed a distance x is modified as

$$E_r = \frac{5.27 \times 10^{-7} \alpha_x \exp\left(\int_0^x \alpha dx\right)}{(x/p)^{1/2}} \text{ V/cm} \tag{2.31}$$

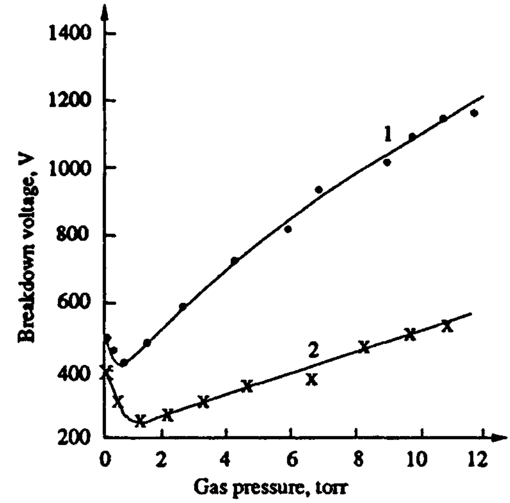

Fig. 2.18 Breakdown characteristics for nitrogen between a wire and a coaxial cylinder of radii 0.083 and 2.3 cm. 1-wire positive, 2-wire negative

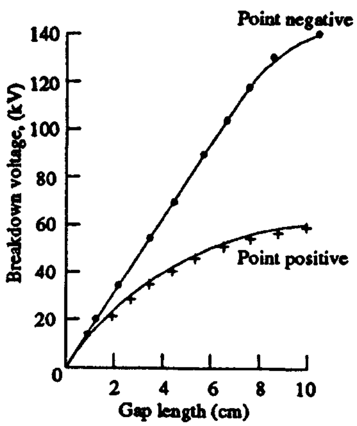

Fig. 2.19 d.c. breakdown characteristics for air between 30° conical point and a plane

where α_x is the value of α at the head of the avalanche, and p is the gas pressure. The criterion for the formation of the streamer is reached when the space charge field E_r approaches a value equal to the applied field at the head of the avalanche.

This equation has been successfully used for determining the corona onset voltages of many non-uniform geometries. However, the condition for the advancement of streamers has not been arrived at so far. Figures 2.18 and 2.19 show the d.c. breakdown characteristics for a wire-coaxial cylinder geometry in nitrogen and for a point-plane geometry in air, respectively.

From the practical engineering point of view, rod-rod gap and sphere-sphere gap are of great importance, as they are used for the measurement of high voltages and for the protection of electrical apparatus such as transformers. The breakdown characteristics of rod-rod gaps are shown n Fig. 2.20. From this figure it can be seen that the breakdown voltages are higher for negative polarity. The breakdown voltages were also observed to depend on humidity in air. In the case of rod gaps the field is non-uniform, while in the case of sphere gaps field is uniform, if the gap is small compared with the diameter. In the case of sphere gaps, the breakdown voltages do not depend on humidity and are also independent of the voltage waveform. The formative time lag is quite small (~ 0.5 μ s) even with 5% over voltage. Hence sphere gaps are used for breakdown voltage (peak value) measurements. These are further discussed in Chapter 7 (Sec. 7.2.6).

2.12 POST-BREAKDOWN PHENOMENA AND APPLICATIONS

This is the phenomenon which occurs after the actual breakdown has taken place and is of technical importance. Glow and arc discharges are the post-breakdown phenomena, and there are many devices that operate over these regions. In a Townsend discharge (see Fig. 2.21) the current increases gradually as a function of the applied voltage. Further to this point (B) only the current increases, and the discharge changes from the Townsend type to Glow type (BC). Further increase in current results in a very small reduction in voltage across the gap (CD) corresponding to the normal glow region. The gap voltage again increases (DE), when the current is increased more, but eventually leads to a considerable drop in the applied voltage. This is the region of the arc discharge (EG). The phenomena that occur in the region CG are the post-breakdown phenomena consisting of glow discharge (CE) and the arc discharge (EG):

Glow Discharge

A glow discharge is characterized by a diffused luminous glow. The colour of the glow discharge depends on the cathode material and the gas used. The glow discharge covers the cathode partly and the space between the cathode, and the anode will have intermediate dark and bright regions. This is called normal glow. If the current in the normal glow is increased such that the discharge covers the entire cathode surface, then it becomes abnormal glow. In a glow discharge, the voltage drop between the electrodes is substantially constant, ranging from 75 to 300 V over a current range of 1 mA to 100 mA depending on the type of the gas. The properties of the glow discharge are used in many practical applications, such as cold cathode gaseous voltage stabilized tubes (voltage regulation tubes or VR tubes), for rectification, as a relaxation oscillator, and as an amplifier.

Arc Discharge

If the current in the gap is increased to about 1 A or more, the voltage across the gap suddenly reduces to a few volts (20-50 V). The discharge becomes very luminous and noisy (region EG in Fig. 2.21). This phase is called the arc discharge and the current

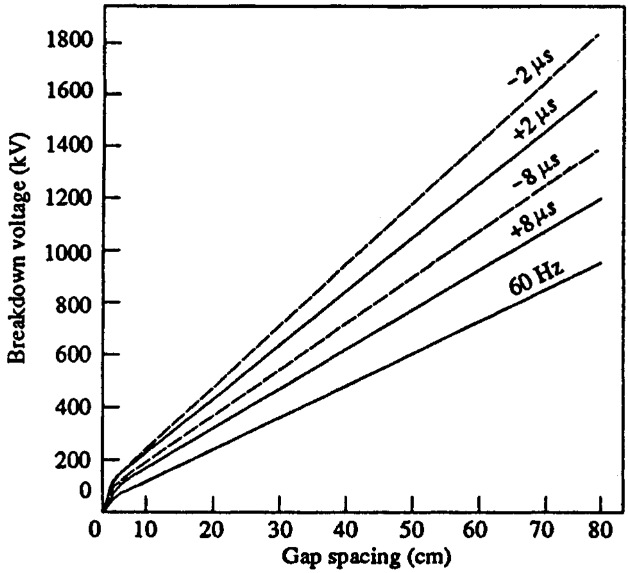

Fig. 2.20 Power frequency (60 Hz) and impulse breakdown voltage curves for a rod-rod gap in air at n.t.p. One rod is earthed. Absolute humidity is 6.5 gms/ft^2. impulse breakdown curves are for various times of breakdown on the wave tail
ref.: B.S.S. 171: 1959, power transformers

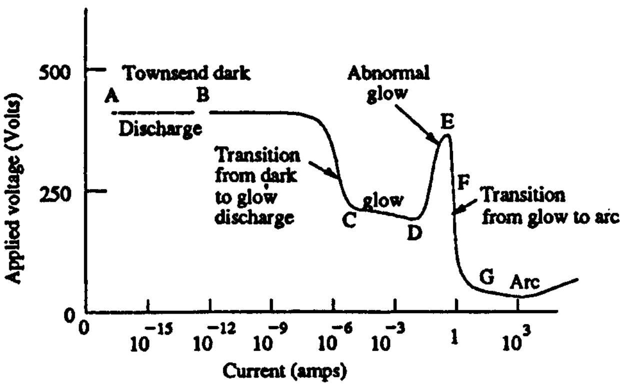

Fig. 2.21 d.c. voltage-current characteristic of an electrical discharge with electrodes having no sharp points or edges

density over the cathode region increases to very high values of 10^3 to 10^7 A/cm^2. Arcing is associated with high temperatures, ranging from 1000°C to several thousand degrees celsius. The discharge will contain a very high density of electrons and positive ions, called the arc plasma. The study of arcs is important in circuit breakers and other switch contacts. It is a convenient high temperature high intensity light source. It is used for welding and cutting of metals. It is the light source in lamps such as carbon arc lamp. High temperature plasmas are used for generation of electricity through magneto-hydro dynamic (MHD) or nuclear fusion processes.

2.13 PRACTICAL CONSIDERATIONS IN USING GASES FOR INSULATION PURPOSES

In recent years, considerable amount of work has been done to adopt a specific gas for practical use. Before adopting a particular gas for a practical purpose, it is useful to gain a knowledge of what the gas does, what its composition is, and what the factors that influence its performance are. The greater the versatility of the operating performance demanded from an insulating gas, the more rigorous would be the requirements which the gas should meet. These requirements needed by a good dielectric gas do not exist in a majority of the gases. Generally, the preferred properties of a gaseous dielectric for high voltage applications are:

(*a*) high dielectric strength,
(*b*) thermal stability and chemical inactivity towards materials of construction,
(*c*) non-flammability and physiological intertness,
(*d*) low temperature of condensation,

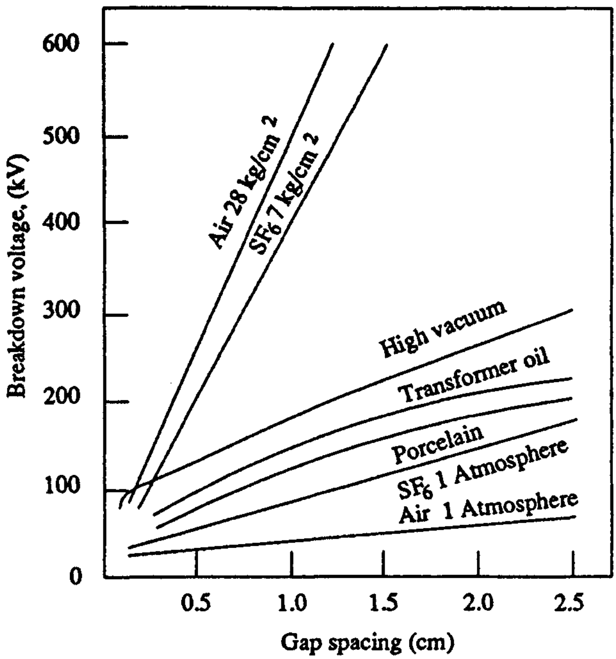

Fig. 2.22 d.c. breakdown strength of typical solid, liquid, gas and vacuum insulations in uniform fields

Table 2.2 Properties of Insulating Gases

Name of the gas	Formula	Molecular weight	Melting point at 760 torr °C	Boiling point at 760 torr °C	Relative dielectric strength ($N_2 = 1$)	Dielectric constant	Specific gravity (Air = 1)	Flammability	Toxicity
Air	—	29	—	−194	1	1.00059	1.00000	No	Physio-inert
Nitrogen	N_2	28	−210	−196	1	1.00058	0.96724	No	-do-
Hydrogen	H_3	2	−259	−253	—	1.00026	0.06952	Yes	-do-
Carbon tetrafluoride	CF_4	88	−183	−128	1.01	1.00050	—	No	-do-
Hexafluoro-ethane	C_2F_6	138	−101	−78	2.02	1.00200	—	No	-do-
Perfluoro-propane	C_3F_8	188	−160	−37	2.2	—	—	No	-do-
Perfluoro-butane	C_4F_{10}	238	−80	−2	2.6	—	—	No	-do-
Perfluoro-n-butane	C_4F_8	200		+2	3.6	1.00340	7.3323	No	-do-
Sulphur hexafluoride	SF_6	146		−63	2.5	1.00191	5.1900	No	-do-
30% SF_6 + 70% Air (Vol.) (Vol.)					2.0			No	-do-
Freon-12	CCl_2F_2	121	−158	−30	2.46	1.00160	—	No	P*

*P: Physio-inert for durations of 2 hr or less with 20% concentration.

Table 2.3

Set 1:									
Gap distance (mm)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
Applied voltage V (volts)	1000	2000	3000	4000	5000	6000	7000	8000	10000
Observed current I (A)	10^{-13}	3×10^{-13}	6×10^{-13}	10^{-12}	4×10^{-12}	10^{-11}	10^{-10}	10^{-9}	5×10^{-7}
Set 2:									
V (volts)	500	.1000	1500	2000	2500	3000	3500	4000	4500
I (A)	5×10^{-14}	1.5×10^{-13}	3×10^{-13}	6×10^{-13}	10^{-12}	5×10^{-12}	5×10^{-11}	3×10^{-10}	10^{-8}

The minimum current observed when 150 V was applied was 5×10^{-14} A.

Table 2.4

Gap (mm)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
I/I_0 for $E_1 = 20$ k V/cm	2	6	12	20	80	200	2×10^3	2×10^4	5×10^7
$\log I/I_0$	0.3010	0.7181	1.0792	1.3010	1.9031	2.3010	3.3010	4.3010	7.6990
I/I_0 for $E_2 = 10$ k V/cm	1	3	6	12	20	100	1000	6000	2×10^5
$\log I/I_0$	0	0.4771	0.7781	1.0792	1.3010	2.0	3.0	3.7781	5.3010

(*e*) good heat transfer, and

(*f*) ready availability at moderate cost.

Sulphur hexafluoride (SF_6) which has received much study in recent years has been found to possess most of the above requirements.

Of the above properties, dielectric strength is the most important property of a gaseous dielectric for practical use. The dielectric strength of gases is comparable with those of solid and liquid dielectrics (see Fig. 2.22). In recent years, the dielectric properties of many complex chlorinated and flourinated molecular compounds have also been studied. These are shown in Fig. 2.23. This feature of high dielectric strength of gases is attributed to the molecular complexity and the high rates of electron attachment (see Sec. 2.7). The relative dielectric strengths and the chemical and physical properties of some of the commercially important gases are shown in Table 2.2.

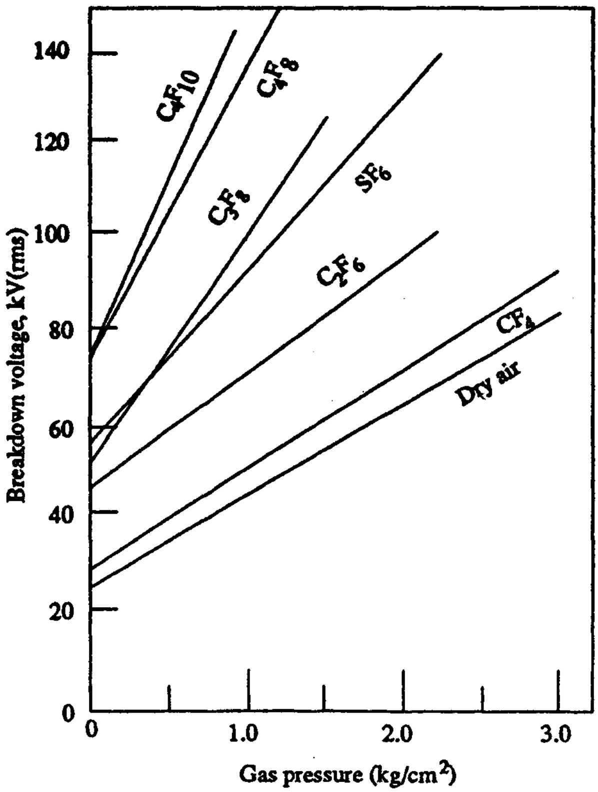

Fig. 2.23 Breakdown strength of insulating gases for 75 cm diameter uniform field electrodes having 12 mm gap

From the figures and the table, it can be seen that SF_6 has high dielectric strength and low liquification temperature, and it can be used over a wide range of operating conditions. SF_6 was also found to have excellent arc-quenching properties. Therefore, it is widely used as an insulating as well as arc-quenching medium in high voltage apparatus such as high voltage cables, current and voltage transformers, circuit-breakers and metal enclosed substations. It can also be seen from the table that addition of 30% SF_6 to air (by volume) increases the dielectric strength of air by 100%. One of the qualitative effects of mixing SF_6 to air is to reduce the overall cost of the gas, and at the same time attaining relatively high dielectric strength or simply preventing the onset of corona at desired operating voltages. In addition to the use of SF_6 gas in recent times, everyone knows of the essential quality of air as an insulating medium for overhead power transmission lines and in air blast circuit-breakers.

2.14 VACUUM INSULATION

2.14.1 Introduction

The idea of using vacuum for insulation purposes is very old. According to the Townsend theory, the growth of current in a gap depends on the drift of the charged particles. In the absence of any such particles, as in the case of perfect vacuum, there should be no conduction and the vacuum should be a perfect insulating medium. However, in practice, the presence of metallic electrodes and insulating surfaces within the vacuum complicate the issue and, therefore, even in vacuum, a sufficiently high voltage will cause a breakdown.

In recent years a considerable amount of work has been done to determine the electrical properties of high vacuum. This is mainly aimed at adopting such a medium for a wide range of applications in devices such as vacuum contractors and interrupters, high frequency capacitors and relays, electrostatic generators, microwave tubes, etc. The contractors and circuit breakers using vacuum as insulation are finding increasing applications in power systems.

2.14.2 What Is Vacuum?

A vacuum system which is used to create vacuum is a system in which the pressure is maintained at a value much below the atmospheric pressure. In vacuum systems the pressure is always measured in terms of millimetres of mercury, where one standard atmosphere is equal to 760 millimetres of mercury at a temperature of 0°C. The term "millimetres of mercury" has been standardised as "Torr" by the International Vacuum Society, where one millimetre of mercury is taken as equal to one Torr. Vacuum may be classified as

High vacuum : 1×10^{-3} to 1×10^{-6} Torr

Very high vacuum : 1×10^{-6} to 1×10^{-8} Torr

Ultra high vacuum : 1×10^{-9} torr and below.

For electrical insulation purposes, the range of vacuum generally used is the "high vacuum", in the pressure range of 10^{-3} Torr to 10^{-6} Torr.

2.14.3 Vacuum Breakdown

In the Townsend type of discharge in a gas described earlier, electrons get multiplied due to various ionisation processes and an electron avalanche is formed. In a high vacuum, even if the electrodes are separated by, say, a few centimetres, an electron crosses the gap without encountering any collisions. Therefore, the current growth prior to breakdown cannot be due to the formation of electron avalanches. However, if a gas is liberated in the vacuum gap, then, breakdown can occur in the manner described by the Townsend process. Thus, the various breakdown mechanisms in high vacuum aim at establishing the way in which the liberation of gas can be brought about in a vacuum gap.

During the last 70 years or so, many different mechanisms for breakdown in vacuum have been proposed. These can be broadly divided into three categories

(*a*) Particle exchange mechanism
(*b*) Field emission mechanism
(*c*) Clump theory

(a) Particle Exchange Mechanism

In this mechanism it is assumed that a charged particle would be emitted from one electrode under the action of the high electric field, and when it impinges on the other electrode, it liberates oppositely charged particles. These particles are accelerated by the applied voltage back to the first electrode where they release more of the original type of particles. When this process becomes cumulative, a chain reaction occurs which leads to the breakdown of the gap.

The particle-exchange mechanism involves electrons, positive ions, photons and the absorbed gases at the electrode surfaces. Qualitatively, an electron present in the vacuum gap is accelerated towards the anode, and on impact releases A positive ions

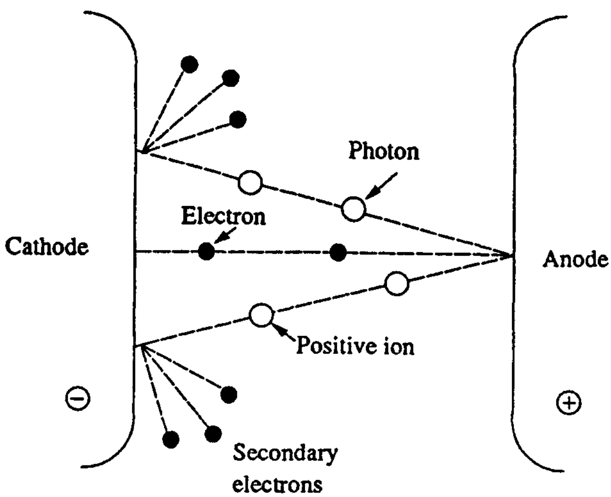

Fig. 2.24 Particle exchange mechanism of vacuum breakdown

and C photons. These positive ions are accelerated towards the cathode, and on impact each positive ion liberates B electrons and each photon liberates D electrons. This is shown schematically in Fig. 2.24. The breakdown will occur if the coefficients of production of secondary electrons exceeds unity. Mathematically, the condition for breakdown can be written as

$$(AB + CD) > 1 \tag{2.32}$$

Later, Trump and Van de Graaff measured these coefficients and showed that they were too small for this process to take place. Accordingly, this theory was modified to allow for the presence of negative ions and the criterion for breakdown then becomes

$$(AB + EF) > 1 \tag{2.33}$$

Where A and B are the same as before and E and F represent the coefficients for negative and positive ion liberation by positive and negative ions. It was experimentally found that the values of the product EF were close enough to unity for copper, aluminium and stainless steel electrodes to make this mechanism applicable at voltages above 250 kV.

(b) Field Emission Theory

(i) Anode Heating Mechanism

This theory postulates that electrons produced at small micro-projections on the cathode due to field emission bombard the anode causing a local rise in temperature and release gases and vapours into the vacuum gap. These electrons ionise the atoms of the gas and produce positive ions. These positive ions arrive at the cathode, increase the primary electron emission due to space charge formation and produce secondary electrons by bombarding the surface. The process continues until a sufficient number of electrons are produced to give rise to breakdown, as in the case of a low pressure Townsend type gas discharge. This is shown schematically in Fig. 2.25.

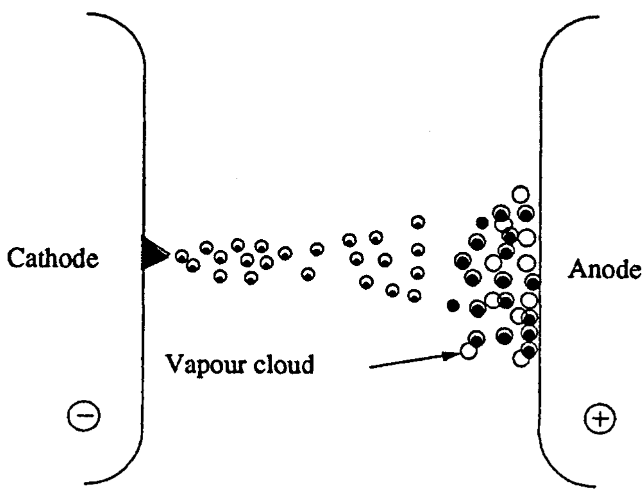

Fig. 2.25 Electron beam anode heating mechanism of vacuum breakdown

(ii) Cathode Heating Mechanism

This mechanism postulates that near the breakdown voltages of the gap, sharp points on the cathode surface are responsible for the existence of the pre-breakdown current, which is generated according to the field emission process described below.

This current causes resistive heating at the tip of a point and when a critical current density is reached, the tip melts and explodes, thus initiating vacuum discharge. This mechanism is called field emission as shown schematically in Fig. 2.26. Thus, the initiation of breakdown depends on the conditions and the properties of the cathode surface. Experimental evidence shows that breakdown takes place by this process when the effective cathode electric field is of the order of 10^6 to 10^7 V/cm.

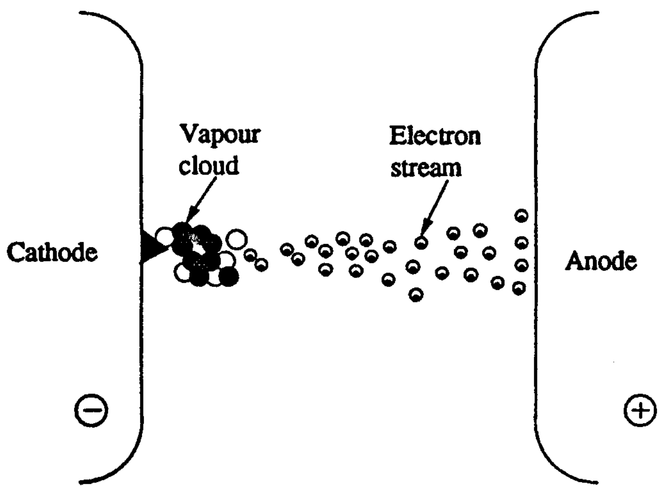

Fig. 2.26 Breakdown in vacuum caused by the heating of a microprojection on the cathode

(c) Clump Mechanism

Basically this theory has been developed on the following assumptions (Fig. 2.27):

(*i*) A loosely bound particle (clump) exists on one of the electrode surfaces.

(*ii*) On the application of a high voltage, this particle gets charged, subsequently gets detached from the mother electrode, and is accelerated across the gap.

(*iii*) The breakdown occurs due to a discharge in the vapour or gas released by the impact of the particle at the target electrode.

Cranberg was the first to propose this theory. He initially assumed that breakdown will occur when the energy per unit area, W, delivered to the target electrode by a clump exceeds a value C, a constant, characteristic of a given pair of electrodes. The quantity W is the product of gap voltage (V) and the charge density on the clump. The latter is proportional to the electric field E at the electrode of origin. The criterion for breakdown, therefore, is

$$VE = C' \qquad (2.34)$$

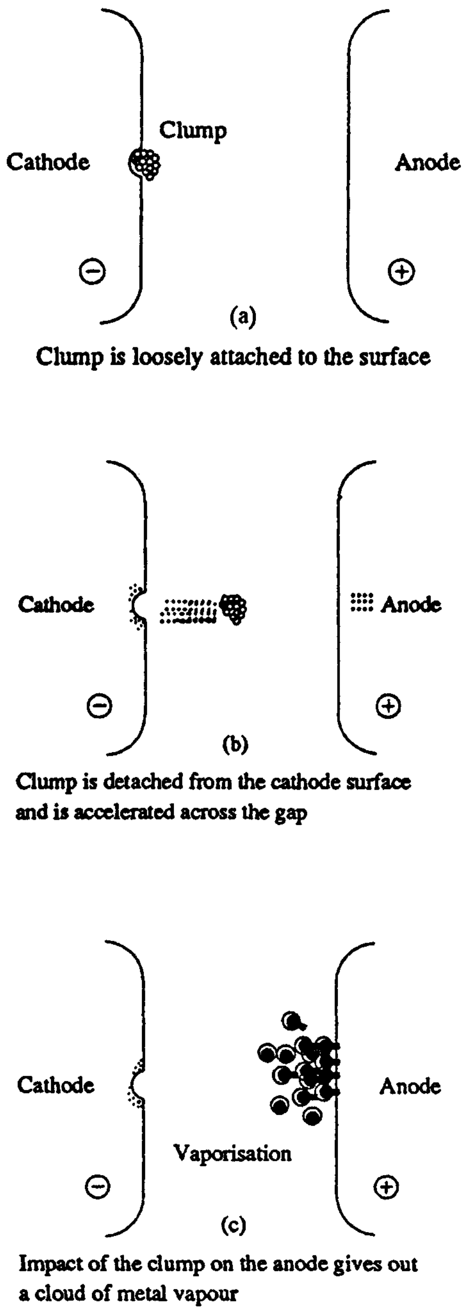

Fig. 2.27 (*a, b, c*) Clump mechanism of vacuum breakdown

In case of parallel plane electrodes the field $E = V/d$, where d is the distance between the electrodes. So the generalised criterion for breakdown becomes

$$V = (C\, d)^{1/2} \tag{2.35}$$

where C is another constant involving C and the electrode surface conditions.

Cranberg presented a summary of the experimental results which satisfied this breakdown criterion with reasonable accuracy. He stated that the origin of the clump was the cathode and obtained a value for the constant C as $60 \times 10^{10}\ V^2/\text{cm}$ (for iron particles). However the equation was later modified as $V = C\, d^{\alpha}$, where α varies between 0.2 and 1.2 depending on the gap length and the electrode material, with a maximum at 0.6. The dependence of V on the electrode material, comes from the observations of markings on the electrode surfaces. Craters were observed on the anode and melted regions on the cathode or vice-versa after a single breakdown.

(d) Summary

Although there has been a large amount of work done on vacuum breakdown phenomena, so far, no single theory has been able to explain all the available experimental measurements and observations. Since experimental evidence exists for all the postulated mechanisms, it appears that each mechanism would depend, to a great extent, on the conditions under which the experiments were performed. The most significant experimental factors which influence the breakdown mechanism are: gap length, geometry and material of the electrodes, surface uniformity and treatment of the surface, presence of extraneous particles and residual gas pressure in the vacuum gap. It was observed that the correct choice of electrode material, and the use of thin insulating coatings in long gaps can increase the breakdown voltage of a vacuum gap. On the other hand, an increase of electrode area or the presence of particles in the vacuum gap will reduce the breakdown voltage.

QUESTIONS

Q.2.1 Explain the difference between photo-ionisation and photo-electric emission.

Q.2.2 Explain the term "electron attachment". Why are electron attaching gases useful for practical use as insultants when compared to non-attaching gases.

Q.2.3 Describe the current growth phenomenon in a gas subjected to uniform electric fields.

Q.2.4 Explain the experimental set-up for the measurement of pre-breakdown currents in a gas.

Q.2.5 Define Townsend's first and second ionization coefficients. How is the condition for breakdown obtained in a Townsend discharge?

Q.2.6 What are electronegative gases? Why is the breakdown strength higher in these gases compared to that in other gases?

Q.2.7 Derive the criterion for breakdown in electronegative gases.

Q.2.8 Explain the Streamer theory of breakdown in air at atmospheric pressure.

Q.2.9 What are the anode and the cathode streamers? Explain the mechanism of their formation and development leading to breakdown.

Q.2.10 What is Paschen's law? How do you account for the minimum voltage for breakdown under a given '$p \times d$' condition?

Q.2.11 Describe the various factors that influence breakdown in a gas.

Q.2.12 What is vacuum? How is it categorised? What is the usual range of vacuum used in high voltage apparatus?

Q.2.13 Describe how vacuum breakdown is different from normal breakdown of a gas.

Q.2.14 Discuss the various mechanisms of vacuum breakdown.

WORKED EXAMPLES

Example 2.1: Table 2.3 gives the sets of observations obtained while studying the Townsend phenomenon in a gas. Compute the values of the Townsend's primary and secondary ionization coefficients from the data given.

Solution: The current at minimum applied voltage, I_0, is taken as 5×10^{-14} A, and the graph of d versus $\log I/I_0$ is plotted as shown in Fig. E.2.1. The values of $\log I/I_0$ versus d for two values of electric field, $E_1 = 20$ kV/cm and $E_2 = 10$ kV/cm are given in Table 2.4.

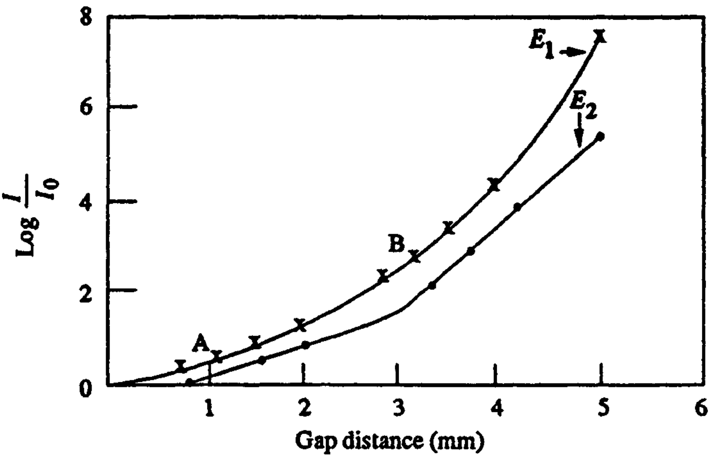

Fig. E.2.1 Log I/I_0 as a function of gap distance

Value of α at E_1(= 20 kV/cm) i.e. α_2 = slope of curve E_1

$$= \frac{2.9}{2.5 \times 10^{-1}}$$

$$= 11.6 \text{ cm}^{-1} \text{torr}^{-1}$$

Value of α at E_2 (= 10 kV/cm) i.e. α_1 = slope of curve E_2

$$= \frac{13}{2 \times 10^{-1}}$$

$$= 6.5 \text{ cm}^{-1} \text{torr}^{-1}$$

As the sparking potential and the critical gap distance are not known, the last observations will be made use in determining the values of γ.

For a gap distance of 5 mm, at $E_1 = 20$ kV/cm,

$$I = \frac{I_0 \exp(\alpha d)}{1 - \gamma[\exp(\alpha d) - 1]}$$

$$\frac{I}{I_0} = \frac{\exp(\alpha d)}{1 - \gamma[\exp(\alpha d) - 1]}$$

Substituting $\alpha_1 = 11.6$, $d = 0.5$ cm, and $I/I_0 = 5 \times 10^7$

$$5 \times 10^7 = \frac{\exp(5.8)}{1 - \gamma[\exp(5.8) - 1]}$$

$$= \frac{330.3}{1 - \gamma(330.3 - 1)}$$

or $\qquad \gamma = 3.0367 \quad 10^{-3}/\text{cm . torr, at } E_1 = 20 \text{ kV/cm}$

(Check this value with other observations also.)

For $\qquad E_2 = 10$ kV/cm

$\alpha_2 = 6.5$/cm . torr

$d = 0.5$ cm

and $\qquad I/I_0 = 2 \times 10^5$

Substituting these values in the same equation,

$$2 \times 10^5 = \frac{\exp(3.25}{1\gamma[\exp(3.25) - 1]}$$

$$= \frac{25.79}{1 - \gamma(25.79 - 1)}$$

or, $\qquad \gamma = 4.03 \times 10^{-2}/\text{cm . torr, at } E_2 = 10 \text{ kV/cm}$

Example 2.2 : A glow discharge tube is to be designed such that the breakdown occurs at the Paschen minimum voltage. Making use of Fig. 2.14 suggest the suitable gap distance and pressure in glow discharge tube when the gas in it is *(a)* hydrogen, *(b)* air.

Solution : In the case of hydrogen, the Paschen minimum voltage occurs at a *pd* (product of pressure and gap spacing) of 7.5 torr-cm, and in the case of air the corresponding value of *pd* is 4.5 torr-cm (see Fig. 2.14).

Since the usual gap distance used for glow discharge tubes of smaller sizes is about 3 mm, the gas pressure used in case of hydrogen will be

$$\frac{7.5}{0.3} = 25 \text{ torr}$$

and in the case of air it will be $\dfrac{4.5}{0.3} = 15$ torr.

Example 2.3 : What will the breakdown strength of air be for small gaps (1 mm) and large gaps (20 cm) under uniform field conditions and standard atmospheric conditions?

Solution : The breakdown strength of air under uniform field conditions and standard atmospheric conditions is approximately given by

$$E = \frac{V}{d} = \left(24.22 + \frac{6.08}{d^{1/2}}\right) \text{kV/cm}$$

Substituting for 1 mm gap,

$$E = 24.22 + \frac{6.08}{(0.1)^{1/2}} = 43.45 \text{ kV/cm}$$

for 20 cm gap,

$$E = 24.22 + \frac{6.08}{(20.1)^{1/2}} = 25.58 \text{ kV/cm}$$

Example 2.4 : In an experiment in a certain gas it was found that the steady state current is 5.5×10^{-8} A at 8 kV 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: The current at the anode I is given by

$$I = I_0 \exp(\alpha d)$$

where I_0 is the initial current and d is the gap distance.
Given,

$$d_1 = 0.4 \text{ cm} \qquad d_2 = 0.1 \text{ cm}$$

$$I_1 = 5.5 \times 10^{-8} A \qquad I_2 = 5.5 \times 10^{-9} A$$

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

i.e., $$10 = \exp(\alpha \times 0.3)$$

i.e., $$0.3\alpha = \ln(10)$$

$\therefore$ $$\alpha = 7.676/\text{cm . torr}$$

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