High Voltage Engineering

Lecture Contents

- Thermal Breakdown in liquids
- Breakdown in solids

Thermal Breakdown in Liquids

- Another mechanism proposed to explain breakdown under pulse conditions is thermal breakdown
- This mechanism is based on the experimental observations of extremely large currents just before breakdown
- This high current pulses are believed to originate from the tips of the microscopic projections on the cathode surface with densities of the order of 1 A/cm^3

- These high density current pulses give rise to localised heating of the oil which may lead to the formation of vapour bubbles
- The vapour bubbles are formed when the energy exceeds 10 W/cm
- When a bubble is formed, breakdown follows, either because of its elongation to a critical size or when it completely bridges the gap between the electrodes

- In either case, it will result in the formation of a spark
- According to this mechanism, the breakdown strength depends on the pressure and the molecular structure of the liquid

Stressed oil Volume theory

- In commercial liquids where minute traces of impurities are present, the breakdown strength is determined by the "largest possible impurity
- On a statistical basis it was proposed that the electrical breakdown strength of the oil is defined by the weakest region in the oil, namely, the region which is stressed to the maximum and by the volume of oil included in that region

- In non-uniform fields, the stressed oil volume is taken as the volume which is contained between the maximum stress (Emax) contour and 0.9 Emax contour
- According to this theory the breakdown strength is inversely proportional to the stressed oil volume.

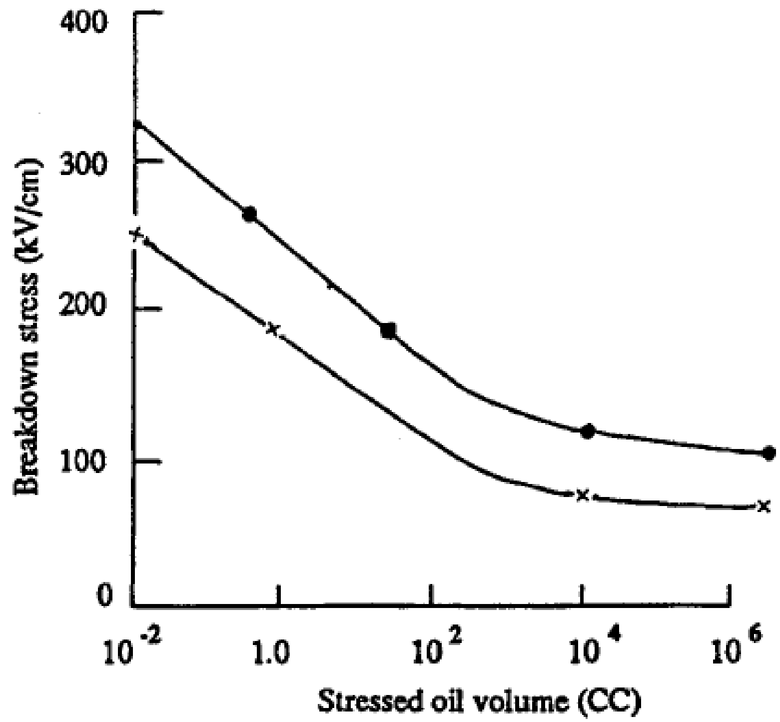


Fig. Power frequency (50 Hz) a.c. breakdown stress as a function of the stressed oil volume

- • With steady voltage rise
- × One minute withstand voltage

Concluding Remarks about breakdown in Liquids

- All the theories discussed above do not consider the dependence of breakdown strength on the gap length
- They all try to account for the maximum obtainable breakdown strength only
- However, the experimental evidence showed that the breakdown strength of a liquid depends on the gap length, given by the following expression,

$$V_b = Ad^n;$$

$$where\, d = gap\, length;$$

$$A = cons\tan t;$$

$$n = cons\tan t\,, less\, than 1$$

- The breakdown voltage also depends on the nature of the voltage, the mode in which the voltage is applied, and the time of application
- The above relationship is of practical importance, and the electrical stress of a given oil used in design is obtained from this
- Worked example is given in next slide;

Example

- In an experiment for determining the breakdown strength of transformer oil, the following observations were made. Determine the power law dependence between the gap spacing and the applied voltage of the oil;

Gap Spacing (mm)	**4**	**6**	**10**	**12**
Voltage at Breakdown (kV)	90	140	210	255

The relationship between the breakdown voltage and gap is normally given as

$$V = Kd^n$$

or, $$\log V = \log K + n \log d$$

i.e., $$\log V - \log K = n \log d$$

or, $$n = \frac{\log V - \log K}{\log d}$$

$$= \text{slope of the straight line}$$

$$= 0.947$$

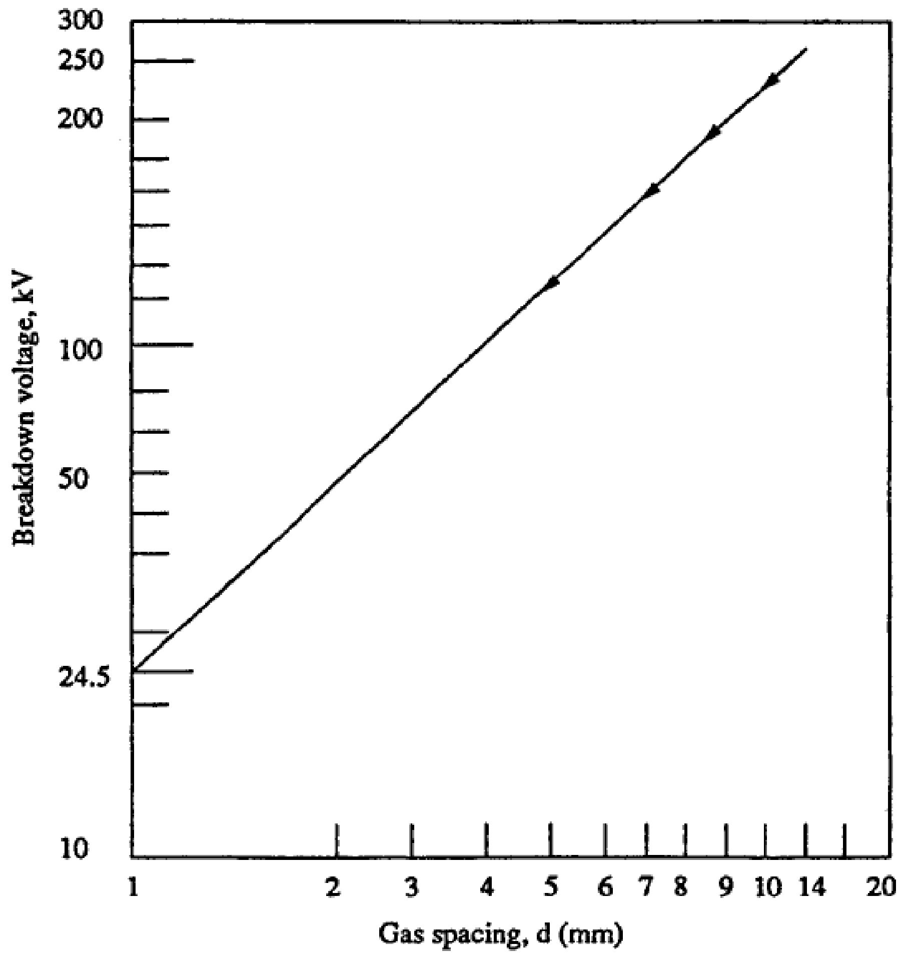
$$K = 24.5$$

$\therefore$ Relationship between the breakdown voltage and the gap spacing for the transformer oil studied is

$$V = 24.5\, d^{0.947}$$

where V is in kV and d is in mm.

Breakdown Vs Gap Spacing



Breakdown in solids

- Solid dielectric materials are used in all kinds of electrical circuits and devices to insulate one current carrying part from another when they operate at different voltages
- A good dielectric should have low dielectric loss, high mechanical strength, should be free from gaseous inclusions, and moisture, and be resistant to thermal and chemical deterioration. Solid dielectrics have higher breakdown strength compared to liquids and gases

- The mechanism of breakdown is a complex phenomena in the case of solids, and varies depending on the time of application of voltage as shown in Fig
- The various breakdown mechanisms can be classified as follows:
  - *(a) intrinsic or ionic breakdown,*
  - *(b) electromechanical breakdown,*
  - (c) failure due to treeing and tracking,
  - *(d) thermal breakdown,*
  - *(e) electrochemical breakdown, and*
  - *(J) breakdown due to internal discharges.*

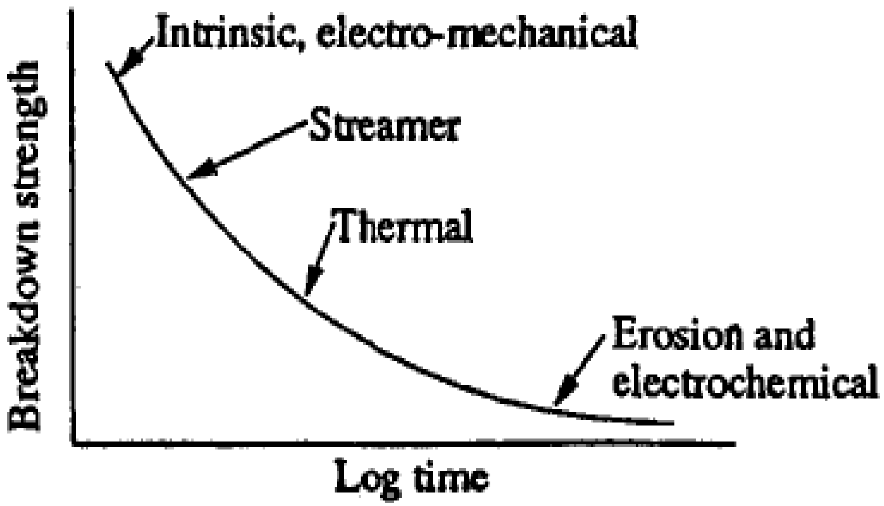


Fig. Variation of breakdown strength with time after application of voltage

Intrinsic Breakdown

- When voltages are applied only for short durations of the order of 10^{-8}S the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength
- The maximum electrical strength recorded is 15 MV*/cm for poly vinyl-alcohol* at - 196^0C. The maximum strength usually obtainable ranges from 5 MV/cm to 10 MV/cm

- Intrinsic breakdown depends upon the presence of free electrons which are capable of migration through the lattice of the dielectric
- Usually, a small number of conduction elections are present in solid dielectrics, along with some structural imperfections and small amounts of impurities

- Intrinsic breakdown is divided into;
  - Electronic Breakdown
  - Avalanche or streamer breakdown

Electronic Breakdown

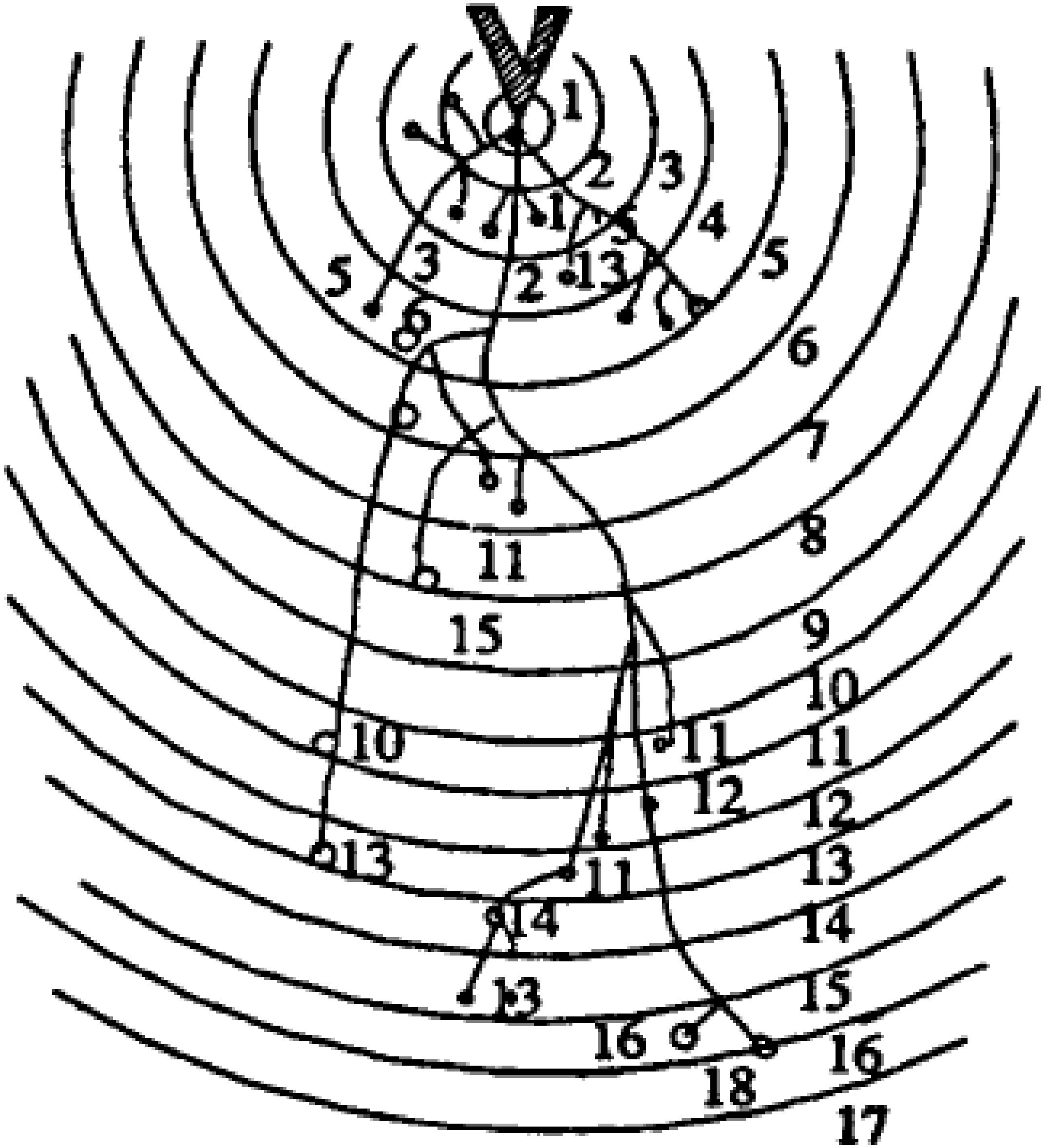
- Intrinsic breakdown occurs in time of the order of 10^{-8}s and therefore is assumed to be electronic in nature
- The initial density of conduction (free) electrons is also assumed to be large, and electron-electron collisions occur
- When an electric field is applied, electrons gain energy from the electric field and cross the forbidden energy gap from the valency to the conduction band
- When this process is repeated, more and more electrons become available in the conduction band, eventually leading to breakdown

Avalanche or Streamer breakdown

- This is similar to breakdown in gases due to cumulative ionization
- Conduction electrons gain sufficient energy above a certain critical electric field and cause liberation of electrons from the lattice atoms by collisions
- Under uniform field conditions, if the electrodes are embedded in the specimen, breakdown will occur when an electron avalanche bridges the electrode gap

- An electron within the dielectric, starting from the cathode will drift towards the anode and during this motion gains energy from the field and loses it during collisions
- When the energy gained by an electron exceeds the lattice ionization potential, an additional electron will be liberated due to collision of the first electron. This process repeats itself resulting in the formation of an electron avalanche
- Breakdown will occur, when the avalanche exceeds a certain critical size

- In practice, breakdown does not occur by the formation of a single avalanche itself, but occurs as a result of many avalanches formed within the dielectric and extending step by step through the entire thickness of the material as shown in Fig as in next slide



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Electromechanical Breakdown

- When solid dielectrics are subjected to high electric fields, failure occurs due to electrostatic compressive forces which can exceed the mechanical compressive strength
- If the thickness of the specimen is *4$ and is compressed to* a thickness *d under an applied voltage V, then the electrically developed compressive stress is in equilibrium if;*

$$\varepsilon_0 \, \varepsilon_r \frac{V^2}{2d^2} = Y \ln\left[\frac{d_0}{d}\right] \qquad (4.1)$$

where Y is the Young's modulus.

From Eq. (4.1)

$$V^2 = d^2 \left[\frac{2Y}{\varepsilon_0 \, \varepsilon_r}\right] \ln\left[\frac{d_0}{d}\right] \qquad (4.2)$$

Usually, mechanical instability occurs when

$$d/d_0 = 0.6 \text{ or } d_0/d = 1.67$$

Substituting this in Eq. 4.2, the highest apparent electric stress before breakdown,

$$E_{max} = \frac{V}{d_0} = 0.6\left[\frac{Y}{\varepsilon_0 \varepsilon_r}\right]^{\frac{1}{2}} \tag{4.3}$$

The above equation is only approximate as Y depends on the mechanical stress.

Thermal Breakdown

- In general, the breakdown voltage of a solid dielectric should increase with its thickness
- But this is true only up to a certain thickness above which the heat generated in the dielectric due to the flow of current determines the conduction
- When an electric field is applied to a dielectric, conduction current, however small it may be, flows through the material
- The current heats up the specimen and the temperature rises

- The heat generated is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces
- Equilibrium is reached when the heat used to raise the temperature of the dielectric, plus the heat radiated out, equals the heat generated

Heat Generated under D.C and A.C fields

$$W_{d.c.} = E^2\sigma \qquad \text{W/cm}^3$$

where, σ is the d.c. conductivity of the specimen.
Under a.c. fields, the heat generated

$$W_{a.c.} = \frac{E^2 f \varepsilon_r \tan\delta}{1.8 \times 10^{12}} \qquad \text{W/cm}^3$$

where, f = frequency in Hz,

δ = loss angle of the dielectric material, and

E = rms value.

The heat dissipated (W_T) is given by

$$W_T = C_V \frac{dT}{dt} + \text{div}\,(K\ \text{grad}\ T)$$

where, C_V = specific heat of the specimen,

T = temperature of the specimen,

K = thermal conductivity of the specimen, and

t = time over which the heat is dissipated.

- Equilibrium is reached when the heat generated ($W_{d.c}$ or $W_{a.c}$.) becomes equal to the heat dissipated *(W_T). In actual practice there is always some heat that is radiated* out
- Breakdown occurs when $W_{d.c}$ or $W_{a.c}$ *exceeds* W_T

- This is of great importance to practising engineers, as most of the insulation failures in high voltage power apparatus occur due to thermal breakdown
- Thermal breakdown sets up an upper limit for increasing the breakdown voltage when the thickness of the insulation is increased
- For a given loss angle and applied stress, the heat generated is proportional to the frequency and hence thermal breakdown is more serious at high frequencies

Breakdown due to treeing and Tracking

- When a solid dielectric subjected to electrical stresses for a long time fails, normally two kinds of visible markings are observed on the dielectric materials
- They are:
- *(a) the presence of a conducting path across the surface of the insulation;*
- *(b) a mechanism whereby leakage current passes through the conducting path* finally leading to the formation of a spark
- Insulation deterioration occurs as a result of these sparks

- The spreading of spark channels during *tracking, in the form of the branches of a* tree is called *treeing*
- Consider a system of a solid dielectric having a conducting film and two electrodes on its surface
- In practice, the conducting film varies often is formed due to moisture
- On application of voltage, the film starts conducting, resulting in generation of heat, and the surface starts becoming dry
- The conducting film becomes separate due to drying, and so sparks are drawn damaging the dielectric surface

- With organic insulating materials such as paper and bakelite, the dielectric carbonizes at the region of sparking, and the carbonized regions act as permanent conducting channels resulting in increased stress over the rest of the region
- This is a cumulative process, and insulation failure occurs when carbonized tracks bridge the distance between the electrodes

- This phenomena, called tracking is common between layers of Bakelite, paper and similar dielectrics built of laminates
- On the other hand treeing occurs due to the erosion of material at the tips of the spark
- Erosion results in the roughening of the surfaces, and hence becomes a source of dirt and contamination

- This causes increased conductivity resulting either in the formation of a conducting path bridging the electrodes or in a mechanical failure of the dielectric

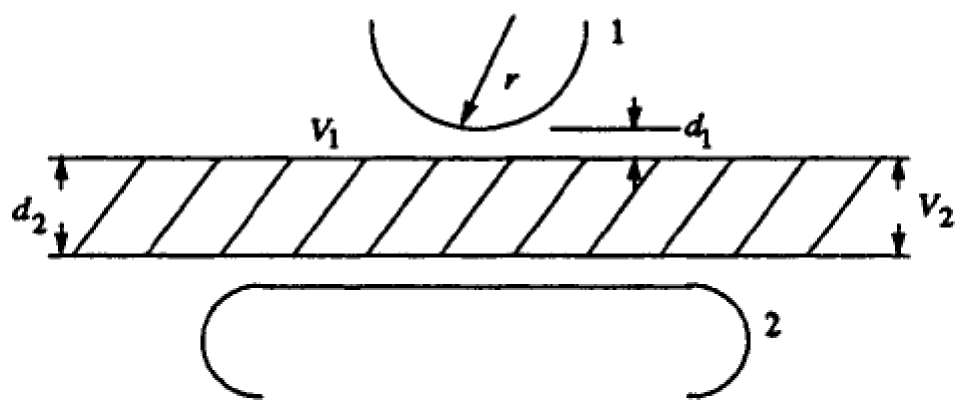

Fig. Arrangement for study of treeing phenomena. 1 and 2 are electrodes

- When a dielectric material lies between two electrodes as shown in Fig, there is a possibility for two different dielectric media, the air and the dielectric, to come in series
- The voltages across the two media are as shown *(V1 across the air gap, and V2* across the dielectric)

Voltage across air gap (v1) where V is applied voltage

$$V_1 = \frac{V d_1}{d_1 + \left(\frac{\varepsilon_1}{\varepsilon_2}\right) d_2}$$

- Since $\varepsilon_2 > \varepsilon_1$, most of the voltage appears across *d, the air gap*
- *Sparking will* occur in the air gap and, charge accumulation takes place on the surface of the insulation
- Sometimes the spark erodes the surface of the insulation
- As time passes, breakdown channels spread through the insulation in an irregular "tree" like fashion leading to the formation of conducting channels
- This kind of channeling is called treeing

- Under a.c. voltage conditions treeing can occur in a few minutes or several hours
- Hence, care must be taken to see that no series air gaps or other weaker insulation gaps are formed
- Usually, tracking occurs even at very low voltages of the order of about 100 V, whereas treeing requires high voltage
- For testing of tracking, low and medium voltage tracking tests are specified

- These tests are done at low voltages but for times of about 100 hr or more
- The insulation should not fail. Sometimes the tests are done using 5 to 10 kV with shorter durations of 4 to 6 hr
- The numerical value of voltage that initiates or causes the formation of a track is called the "tracking index" and this is used to qualify the surface properties of dielectric materials

- Treeing can be prevented by having clean, dry, and undamaged surfaces and a clean environment
- The materials chosen should be resistant to tracking
- Sometimes moisture repellant greases are used. But this needs frequent cleaning and regreasing
- Increasing creepage distances should prevent tracking, but in practice the presence of moisture films defeat the purpose
- Usually, treeing phenomena is observed in capacitors and cables, and extensive work is being done to investigate the real nature and causes of this phenomenon

Breakdown due to internal discharges

- Solid insulating materials, and to a lesser extent liquid dielectrics contain voids or cavities within the medium or at the boundaries between the dielectric and the electrodes
- These voids are generally filled with a medium of lower dielectric strength, and the dielectric constant of the medium in the voids is lower than that of the insulation

- Hence, the electric field strength in the voids is higher than that across the dielectric
- Therefore, even under normal working voltages the field in the voids may exceed their breakdown value, and breakdown may occur
- Let us consider a dielectric between two conductors as shown in Fig. a
- If we divide the insulation into three parts, an electrical network of C1, *C2 and C3 can be* formed as shown in Fig. b

- In this C1 represents the capacitance of the void or cavity, *C2 is the capacitance of the dielectric which is in series with the void, and C3* is the capacitance of the rest of the dielectric
- When the applied voltage is *V, the* voltage across the void, V1 is given by the same equation as;

$$V_1 = \frac{V d_1}{d_1 + \left(\frac{\varepsilon_0}{\varepsilon_1}\right) d_2}$$

where d_1 and d_2 are the thickness of the void and the dielectric, respectively, having permittivities ε_0 and ε_1. Usually $d_1 \ll d_2$, and if we assume that the cavity is filled with a gas, then

$$V_1 = V \varepsilon_r \left(\frac{d_1}{d_2}\right) \tag{4.8}$$

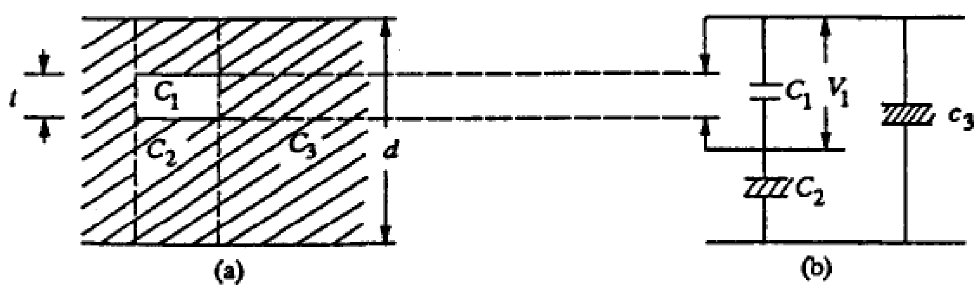

Fig. Electrical discharge in a cavity and its equivalent circuit

- When a voltage *V is applied, V1 reaches the breakdown strength of the medium in* the cavity (Vi) and breakdown occurs. *Vi is called the' 'discharge inception voltage''.*
- When the applied voltage is a.c., breakdown occurs on both the half cycles and the number of discharges will depend on the applied voltage

- When the first breakdown across the cavity occurs the breakdown voltage across it becomes zero
- When once the voltage *V1 becomes zero, the spark gets extinguished and again the voltage rises till* breakdown occurs again
- This process repeats again and again, and current pulses, will be obtained both in the positive and negative half cycles

Next Lecture

- Composite dielectrics