BREAKDOWN AND PRE-BREAKDOWN PHENOMENA IN TRANSFORMER OIL
SUBJECTED TO VARIABLE FREQUENCY ELECTRIC FIELDS

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The role of impurity particles on variable frequency pre-breakdown and breakdown behaviour of transformer oil has been investigated. Two types of particles were considered, those which were naturally present in the oil and those which were added, such as conducting copper and non-conducting selenium and silicon particles.

Above a threshold stress and below a critical stress the particles formed bridges at frequencies between 20 Hz and 1000 Hz, when the gap length was below 1.5 mm. The stress required for bridge formation depended on gap and frequency. Bridges sometimes contributed to bubble formation and spurious sparks, which occasionally led to a fully developed breakdown. However, if the stress was increased above the critical value the gap was cleared of particles and breakdown did not occur over a range of stresses higher than that at which spurious sparks have been observed. The breakdown strength as a function of frequency was dependent on the type and size of particles present in the liquid and on the gap setting. It was also found to depend on the gap used for conditioning the samples. Added particles lowered the breakdown strength at all frequencies and for highly purified liquid samples the breakdown strength was found to be less dependent on frequency.

A post-breakdown glow discharge was observed at gaps greater than 200 microns and frequencies higher than 200 Hz.

In the light of the pre-breakdown experimental results a mathematical model for the bridge formation process has been put forward. In this model the relaxation effect of the ion atmosphere of the oscillating particles which are considered as dipoles and Bjerknes' hydrodynamic forces are regarded as mainly responsible for controlling the activity of particles in oil subjected to electric stress.
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1. INTRODUCTION AND SUMMARY

The investigation of the properties of liquid dielectrics dates back to the beginning of this century and since then much work has been done in order to understand the physical processes involved in the electrical conduction and breakdown of insulating liquids when subjected to both direct voltage and alternating voltage at power frequencies. However, relatively little information is available about the pre-breakdown and breakdown behaviour under variable frequency conditions (Skanavi, 1958; Whitehead, 1928). Tests at different frequencies are important in view of the fact that impurity particles, which are invariably present even after finest filtration will oscillate with the applied field at low frequency and behave as stationary particles at higher frequencies because the periodic time is very small compared to the particle transit time. Therefore the breakdown strength may be sensitive to frequency.

A second process which has been subject of much discussion in recent years is the role of space charge on the breakdown of insulating liquids. The change in breakdown strength of a liquid due to the application of an electric stress prior to breakdown, known as the pre-stressing effect, can be marked in the case of impulse measurements but under d.c. conditions pre-stressing occurs automatically and electrode layers would have formed prior to breakdown. Under a.c. conditions, in which the role of anode and cathode are continually reversed, the times associated with the formation of electrode layers may be comparable to the periodic time of the applied stress.

In an effort to understand the time effects associated with particle impurities and layer formation, the breakdown and pre-breakdown behaviour of transformer oil at frequencies between 20 Hz and 1000 Hz has been studied. The maximum test gap considered in this investigation was 200 microns.
A few dc. tests were carried out to compare the oil samples with those of other investigators and good agreement of results was obtained.

A brief review of previous work which has a direct bearing on the present investigation is given in Section 2. Section 3 contains the description of experimental apparatus and includes the methods of preparation of samples and electrodes, the design of test apparatus, the test cell and electronic circuitry, the high voltage equipment and test procedures. The experimental results, which are described in Section 4, are divided into two parts. The first part contains pre-breakdown phenomena including behaviour of particles, bridge formation and surface motion of the liquid at low frequency. The second part contains work concerning the effect of particles on breakdown and post-breakdown glow discharge phenomena.

The results are discussed and analysed in Section 5. An attempt has been made to interpret the bridge formation process mathematically.
In this section the work concerning the effect of impurities and the methods of conditioning of test samples on breakdown strength of transformer oils is reviewed. The influence of gap length, the material, shape and size of electrodes are also considered but the main emphasis, however, is on the effect of the impurities as they have a direct bearing on the present work. The existing published literature on breakdown properties of liquid dielectrics at variable frequencies is also reviewed.

2.1 Test Sample Conditioning

It has been found that the electric strength of an insulating liquid increases or decreases with the first few tens of breakdowns until a steady value is obtained. The number of breakdowns necessary to get reproducible values of dielectric strength depends upon the preparation of electrodes and purification of liquid. The process by which a state of steady electric strength can be obtained is called conditioning. There are two schools of thought about the type of conditioning needed before recording the breakdown strength. Some investigators were content with stress conditioning as opposed to breakdown conditioning favoured by others.

2.1.1 Stress Conditioning

Gosling (1960) found that stress conditioning for d.c. fields depended upon the material of the electrode. Using nickel and iron electrodes the test samples were usually conditioned in 1½ to 2 hours, with aluminium electrodes it took about 5 to 6 hours and with zinc electrodes the test samples were not conditioned even after 8 hours stressing. Using direct voltage he found that as a result of stress
conditioning small particles usually settled down on either one or both electrode surfaces but larger particles oscillated assuming trajectories along the lines of the field forces. The distance of these trajectories from the common axis of the spherical electrodes increased with increasing voltage and eventually the particles moved out of the influence of the applied field into the bulk of the liquid.

Megahed (1965) confirmed Gosling's observations about stress conditioning. He further observed that the removal of particles from the gap due to stress conditioning was found to be speeded up by increasing the temperature.

Nossier et al. (1965) reported that stress conditioning of an oil sample containing sulphur hexafluoride considerably reduced its breakdown strength. This may be due to a reduction in the concentration of sulphur hexafluoride in the high stress region when the sample is stress conditioned.

An interesting result was obtained by Ward (1961) in his tests with impulse voltages. He found that impulse breakdown voltage could be increased by prestressing the gap with direct voltage prior to impulse testing. The increase was largest when the direct voltage used for prestressing was opposite in polarity to the impulse voltage and strength as large as 2.5 MV/cm was measured.

Stress conditioning has also been adopted in conduction current measurements and for example House (1955) was able to obtain reproducible conduction current values in n-hexane after prolonged stressing. Later House (1957) by using a special conditioning technique was able to measure conduction currents in hexane up to 1.5 MV/cm. He observed that with small over-stresses, the current pulses gradually died away thus allowing the stress to be raised again. These measurements were
carried when a high speed diverter unit was used in parallel with the test cell to prevent damage to the electrometer by large pulses. Thus it was possible to make the system free from spurious pulses up to the breakdown stress and no further conditioning was necessary even when the applied voltage was of different polarity. He suggested that the conditioning was due to removal of minute bubbles from the high stress region of the liquid and from the central portion of the spherical electrode surface or due to stripping of lightly absorbed layers from the electrode surface.

2.1.2 Breakdown conditioning

Kok (1961) concluded that if a large series resistance is used to limit the current then no appreciable amount of carbonization or acid formation will occur as a result of breakdown discharge or spurious discharges. These discharges will result in the disintegration of particles. Although the number of particles per unit volume of the insulating liquid will be higher after disintegration the breakdown strength of the liquid will be higher because small particles are less effective in reducing the breakdown strength than the larger ones. Watson and Higham (1953) also suggested that the particles play an important part in conditioning the liquid. They carried out tests with alternating and impulse voltages and found that fibres are destroyed during the conditioning process. As much as 100% increase of breakdown strength during the first 50-100 breakdowns were recorded by them (see Fig 2.1). Lewis (1953) employing an efficient diverter unit to limit the energy of the spark discharge and using smooth electrodes found that the conditioning process was reduced to 5 breakdowns or less in n-hexane in direct voltage tests. He attributed this to the much reduced damage of both electrodes and liquid. Saxe and Lewis (1955) suggested that during the conditioning
process each spark tended to remove an active site from the surface of the electrodes and thus conditioning will be area dependent.

Conditioning was considered also by Ferrant (1934) as an electrode process, the electrode surface irregularities being changed and hence a conditioning effect. In a resume of the research work carried out under his supervision Tropper (1961) reported that the conditioning in finely filtered oil is an electrode effect. This is due to the fact that once the electrodes were conditioned in a particular oil sample, they remained conditioned and same breakdown values were obtained when the electrodes were retained and the sample was replaced by another one of the same kind. Fresh conditioning was, however, found to be necessary when a new pair of electrodes was used.

One of the possible reasons of increasing breakdown strength during the conditioning with alternating voltage could be the removal of moisture during the first few breakdowns. This was suggested by Race (1940) who measured the dielectric strength of insulating liquids in a continuously circulating system. Salvage (1951) showed that fewer breakdowns were needed for conditioning of the liquid when the filtering was improved. The scatter of the values for the breakdown strength was also found to be less with low porosity filters than with coarse filters. It was reported by Zein Eldine and Tropper (1956) that the conditioning depends on the number of degassing cycles for a transformer oil filtered through a number 4 sintered glass filter. With the increased number of degassing cycles less breakdowns were found to be necessary for conditioning. The conditioning, in their opinion, is an equilibrium between the gas evolution and absorption after which the breakdown strength of the liquid remains steady. For insulating liquids with high gas content the breakdown strength decreases with the first few breakdowns and then remains steady.
For non-dried and non-filtered oil the increase of breakdown strength was suggested by Clark (1962) to be due to removal of moisture and particles from the test gap by the discharges. Maksiejewski and Tropper (1954) also discussed the conditioning as an electrode effect and not that of the liquid. This, they considered, is because the breakdown strength of organic dielectric liquid (n-hexane) with unconditioned electrode was found to be pressure dependent. They suggested that the gas absorbed in the microcavities on the electrode surface was gradually released with the successive breakdowns and as a result the breakdown strength increased.

Because no conditioning effect was found with degassed oil as against conditioning with non-degassed oil while testing transformer oil under impulse voltages Hancox and Tropper (1957) suggested that the conditioning is associated with a gas layer on the electrodes and steady breakdown values are obtained when a dynamic equilibrium between gas absorption and evolution by both the electrodes and the liquid is reached. It was also observed by them that if the test cell was not completely filled, thus allowing the oil to absorb gas, conditioning did not occur.

It was found by Kao (1965), using d.c. voltage, that the electric strength of transformer oil and pure liquids increased during the first few tens of breakdowns with electrodes not carefully prepared; but when the electrodes were carefully polished and cleaned the electric strength decreased with the first few breakdowns. This effect was attributed to the oxide layer formation on the metallic electrode surfaces and subsequent polymerization due to breakdowns. These layers act as barriers to positive ions and thereby control electron emission from the cathode and breakdown process. Therefore, Kao suggested that the cathode rather than the anode is responsible for the conditioning process. However, Zaky et. al. (1965) observed that the conditioning of mineral oil is not only an electrode effect but it is also a combined effect of
both electrode surface and bulk liquid conditions. Their results are shown in Fig 2.2. They found that with bare preconditioned electrodes the conditioning reappeared after a prolonged period of waiting or by sudden large reduction of the gap. This effect was observed both with copper and stainless steel electrodes.

2.2 Effect of Impurities

It is generally agreed that the breakdown strength of an insulating liquid is the measure of its purity. Of all impurities viz. gaseous, liquid and solid, solid insoluble impurities are invariably present even with the finest filtration and degassing of the liquid. Some are also produced as a result of breakdowns. The main emphasis of this work is on the effects of insoluble particle impurities but the effects of other types of impurities are briefly mentioned.

2.2.1 Gaseous Impurities

Usually in commercial applications insulating liquids are degassed. Preliminary work in this investigation showed instability in breakdown behaviour of non-degassed transformer oil and therefore further investigation was concentrated on gas free insulating liquids.

Gas may be present in insulating liquids both in dissolved and free forms. On application of an electric field the dissolved gases are released and bubbles form. The other contributing factors toward bubble formation are high local conduction due to particle bridge, change of temperature, change of pressure and mechanical agitation. According to Spath (1923) fibre bridges when loaded with gases are a very important cause of breakdown.

Clark (1933) was perhaps the first to carry out systematic investigation into the effects of gases and hydrostatic pressure on the
Fig. 2.1 VARIATION IN BREAKDOWN STRENGTH WITH NUMBER OF BREAKDOWNS (after Watson and Higham)

(a) untreated oil     (b) fibre-free oil

Fig. 2.2 EFFECT OF PROLONGED WAITING PERIOD AND OF GAP REDUCTION ON THE CONDITION IN MINERAL OIL

(after Zaky et al.)
breakdown strength of insulating oils using 60 Hz alternating voltage. He suggested that insulating liquids should be classified as pure, including those liquids free from dissolved gases as primary impurities and impure, including those liquids which contain dissolved gases. The dielectric strength of a degassed oil when exposed to atmosphere first falls to a minimum and then as the air saturation increases the strength rises to a maximum. Further saturation results in a slow decrease in strength (see Fig 2.3). Khamanonda (1958) and Darveniza (1959) confirmed his results under direct voltage conditions. Sletten (1960) studied the effects of oxygen, hydrogen, nitrogen and carbon dioxide when dissolved in hexane. He found that oxygen, if present in small amounts, was responsible for increasing the breakdown strength of the liquid. Brignell and House (1965) supported Sletten's observations that the presence of oxygen increases the breakdown strength. Apart from oxygen, Gosling (1960) found nitrogen, while in solution, to increase the breakdown strength of transformer oil. In liquid argon Swan (1959) has also found a beneficial effect of oxygen. While confirming Swan's results Gallagher (1964) observed that unless present in large quantities oxygen has no effect under impulse voltage conditions.

Tropper (1961) suggested that when small amounts of dissolved air are present in transformer oil, the initial rise in breakdown strength was due to electron trapping by \( O_2 \) molecules in air. The subsequent decrease when more air was added was explained by the greater ease of micro-bubble formation with the suspended particles serving as nucleation sites. The final rise of strength was attributed to field distortion caused by the space charge of positive ions in the vicinity of the cathode. (See Fig 2.4) Nosseir et al. (1965) reported that dissolved sulphur hexaflouride in transformer oil at an equilibrium pressure of
Fig. 2.3 Dielectric strength of transformer oil as a function of its dissolved air content

(AFTER CLARK)

Fig. 2.4 Electric strength vs. partial pressure of dissolved air

curve 1 - electrodes conditioned in degassed oil before test, curve 2 - fresh electrodes for each point (after Tropper)
1 torr. considerably reduced the breakdown strength of the oil. The only exception was the findings of Priaroggia and Palandri (1960), who found that the dielectric strength of insulating oil is absolutely independent of the gas pressure provided a perfect equilibrium is reached between the dissolved gas and the free gas on top of the oil surface.

**Effect of hydrostatic pressure.** This investigation is important to get an indication whether the breakdown mechanism of insulating liquid involves a vapour or a gaseous phase. Clark (1933) studying the effects of applied hydrostatic pressure on degassed transformer oil observed that the breakdown strength increases with the increase of pressure. Hoover and Hixson (1949) found that the 60 Hz dielectric strength of insulating oil initially increases with increased hydrostatic pressure and then remains steady. For negative pressures the breakdown value decreases. Watson and Higham (1953) using alternating voltage and Zein Eldine and Tropper (1956) with impulse voltages confirmed the observations of Hoover and Hixson for positive pressures. Kao (1965) also found an increase in electric strength over the pressure range from 5 mm mercury to 350 lbs/in² gauge pressure regardless of the geometry of electrodes used for liquids ranging from transformer oil to pure hydrocarbons with and without gas dissolved, and for voltages ranging from direct and alternating to pulses of 1 microsecond duration (see fig 2.5).

### 2.2.2 Effect of liquid impurities

Moisture is one of the impurities which has been extensively studied by previous workers. It has been found that the presence of moisture in solution does not necessarily reduce the breakdown strength of dielectric liquids. According to Clark (1942) it reduces the breakdown strength only when it separates from the oil solution, but if the moisture is present in dissolved form it has little effect on the breakdown strength.
When moisture separates from the oil it either sticks to the impurity particles or on the surface of the electrodes. Since liquid dielectrics of commercial purity invariably contain impurity particles, the presence of moisture usually reduces the breakdown strength. Fig 2.6 shows a typical relation of moisture content and breakdown strength of transformer oil.

Koppleman (1931) reported that emulsified water was apparently found to be much more effective in reducing breakdown strength than is dissolved water. The same conclusion was drawn by Lazereu (1934) who investigated the hydroscopicity in liquid dielectrics. Fallow and Thibault (1963) concluded that a water content of 30 ppm in fresh oil greatly reduces the electric strength whereas in oxidised oil even greater quantities of water have no effect.

Although insulating oils of varying compositions react differently with moisture Armstrong (1913), Flight (1921), Friese (1922), Schroter (1923), Spath (1923), Peck (1929), Zein Eldine and Tropper (1955) and France (1963) all agree that moisture content in oil greatly reduces its breakdown strength. Whitehead (1928) summarised the effects of moisture in lowering the breakdown strength of an insulating oil in the following ways:-

(a) By the intrinsic effect of solution,
(b) By the intrinsic effect of emulsion,
(c) By the formation of strings, bridges, etc. in an emulsion,
(d) By absorption in fibres or condensation round nuclei,
(e) By dissolving other impurities, particularly electrolytes.

It was observed by Krasucki (1962) that if an insulating oil contains a globule of water gas formation and discharges can result from elongation and instability of the impurity in the field. When subjected to an electric field, the globule will elongate in the direction of the
Fig. 2.5 ELECTRIC STRENGTH AS A FUNCTION OF PRESSURE FOR DEGASSED LIQUIDS (after Kao)

Fig. 2.6 BREAKDOWN VOLTAGE OF TRANSFORMER OIL AS AFFECTED BY ITS DISSOLVED MOISTURE CONTENT (after Clark)
field as its permittivity is different from that of the medium. If the ratio of permittivity of the globule to that of the medium is greater than 20 then as the stress is increased the globule will become unstable when it reaches a critical shape. Instability in the globule may lead to breakdown of the oil.

The behaviour of water droplets suspended in dielectric liquids of various viscosities such as castor oil, paraffinic oil and the mixture of carbon tetrachloride with benzene (to obtain density equal to unity), under both direct and alternating field was studied by Skowronski (1967). It was found that the droplets ranging from a few microns to 100 microns were distorted, elongated and the polarized droplets at sufficiently high fields were pulverized into very fine suspension. For gaps less than 1 mm the water droplets bridged the gap but at larger gaps no proof of bridge formation by elongated droplets was found. Instead very fine droplets were observed to have been formed by bursting from the larger ones under the influence of the dielectric forces due to the difference in permittivities of oil and water (i.e. 80 : 23), and coulomb forces due to the induced charges or charges accumulated on the surface of the droplet having their origin in the moving ions in the liquid. These effects are illustrated in Fig 2.7. He found that the charged droplets moved at a very high speed along the field lines and often were reflected even before touching the electrode as a result of acquiring charges of opposite polarity. Breakdowns took place when the droplets of water were completely broken and dispersed in the medium.

2.2.3 The effect of solid impurities

Two kinds of forces act on the insoluble impurity particles in a liquid dielectric. They are electrophoresis and dielectrophoresis.
Fig 2.7
Electrophoresis - The electrophoretic effect in the liquid could be divided into two classes depending on whether the ions are injected by the applied field or are created by other processes. Typical of the former is the Injection Pumping Phenomenon which arises with the injection of charge into the fluid and the subsequent motion of the fluid due to the interaction with the injected charge which will move in the applied electric field. Electro-osmosis is typical of the latter. When a liquid is allowed to come in contact with a solid surface, there will be a partition of ions between the solid and the liquid. The result of this partition is to leave the liquid phase with a net charge and to establish an electric potential gradient ("zeta potential") within the liquid. Under the influence of this potential difference the liquid will flow and the phenomenon is called "electro-osmosis". The charge injection phenomenon varies as the square of the applied voltage while electro-osmosis has a linear dependence (Pickard, 1965).

Dielectrophoresis and bridge formation of non-conducting impurities

When an electric field is applied to a dielectric liquid it becomes polarized and the insoluble impurity particles of higher dielectric constant move into the region of highest stress. The phenomenon is readily observed in relatively coarse suspensions and high fields especially when a great difference between the dielectric constant of the liquid and suspended particles exists.

Middendorf et al (1958) as a result of their investigation divided the motion of the suspended particles into two groups, namely: co-field motion, the particles moving along the lines of the applied field and cross-field motion, the particles moving in the direction perpendicular to the field lines. Under the influence of the cross-field component of the force acting upon the particles, the particles having higher permittivity than that of the liquid drift towards the maximum stress region.
Von Hippel derived an expression for the cross-field force $F$ acting on a spherical particle in an insulating liquid in an inhomogeneous field $E$ in the following form:

$$F = 2\pi r^3 \varepsilon_1 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \nabla (E^2)$$

where:

- $r$ is the radius of the particle,
- $\varepsilon_2$ is the permittivity of the particle,
- $\varepsilon_1$ is the permittivity of the medium.

The force is directed towards the region of maximum stress when $\varepsilon_2 > \varepsilon_1$ and away from it when $\varepsilon_1 < \varepsilon_2$, as in the case of gas bubbles. However, when the bubbles are attached to the suspended particles having high permittivity than the liquid they can also move towards maximum stress region.

The insoluble impurity particles upon which the force $F$ may act could be divided into two groups: (1) those which are too small to be filtered out during the preparation of the liquid and (2) metal particles produced from electrodes by breakdowns. The small impurity particles may combine together to form larger aggregates. In an experiment with aqueous gold solution Kruyt and Vogel (1941) observed that particle sizes due to flocculation increased from $100\ \hat{A}$ to $5000\ \hat{A}$.

In the maximum stress region the particles may align themselves in so-called pearl-strings and form a bridge across the gap when a certain critical stress is reached. Bridge formation may lead to non-sustained sparks but sometimes also to a fully developed breakdown. Darveniza (1961) pointed out that fully developed sparks of sufficient duration may cause the operation of properly co-ordinated circuit breakers and protective relays. Kok in his book (1961) tried to correlate the break-
down strength of insulating oils and the sizes of impurity particles but it was found by many other authors that the breakdown strength of a liquid with much larger particles than those considered by Kok is higher than that estimated by him.

The effect of suspended particles on d.c. breakdown values was studied among others by Gindin (1951) who reported that application of a direct field to a suspension of particles ranging in diameter from 4 μm to 40 μm of Cu, Al and other metals in benzene, chlorobenzene and nitrobenzene results in breakdown when a certain critical field is applied to the liquid. The value of the critical field increases as the size of particles decreases. Gosling (1960) using transformer oil, filtered through a No. 5 sintered glass filter, observed motion of particles between electrodes along definite trajectories. At higher stresses particles were ejected from the gap which became clear after a period of 2-3 hours when nickel electrodes were used. Sletten (1960) proposed an explanation for this phenomenon assuming reduction of dielectric constant of the particles due to absorption of oxygen. Huq (1962), Nosseir (1964) and Megahed (1965) have since confirmed Gosling's observations. Khare (1969) using perspex enclosure around the electrodes restricted considerably the number and the activity of the particles in the gap.

Many authors differ in their opinion regarding the effect of particles on breakdown values. Schroter (1923) while neglecting non-self-sustained sparks concluded that solid bridges have no effect in moisture-free oil. Also Draeger (1924) found that the effect of bridges was relatively unimportant. On the other hand according to the results of Whitehead (1928) cotton and pressboard fibres reduce the breakdown strength of dry oil by 30% and 20% respectively. The effect of fibres was more marked when moisture was present, the reduction of strength being about 90%.
Particles are always produced when breakdown occurs. Bucklow and Drain (1964) reported that particles ranging in diameter from 200 Å to 500 Å were formed after breakdown in liquid argon. In a highly purified oil, Friese (1922) found that carbon particles produced as a result of breakdowns reduced the breakdown strength of the liquid.

Tests were also carried out to study the effects of known-size particles added to the insulating liquids. Vogel (1938) adding gold particles (100 - 200 Å) observed increased conductivity and formation of bridges. Kok also reported formation of parallel bridges between parallel-plate nickel electrodes after addition of aluminium, graphite, Fuller's earth and Al₂O₃ particles and relatively low values of breakdown strength. Higher values of breakdown voltage were obtained for dry oil.

Emulsions and dispersions when subjected to a.c. fields show also a peculiar behaviour of suspended particles. First observations have been reported by Cotton and Mouton (1906). They observed formation of stripes by particles which oscillated in tact with the applied alternating field.

Svedberg (1910) utilized this effect to estimate the speed of electrophoretic migration applying commutated d.c. voltage to obtain alternating voltage with a rectangular wave form.

In certain conditions and in alternating fields the suspended particles will form larger aggregates in the form of pearl-strings in the direction of the applied field. This phenomenon was noted by von E. Muth (1927) and Kruyt and Vogal (1941) who used diluted milk and aqueous solution of gold although the latter did not find the direct evidence of pearl-string formation of gold particles.
in aqueous solution of gold. It seems that formation of pearl-strings takes place only when greater particles are present in the liquid and therefore, this effect would not be observable in case of fine aqueous gold solution as shown by Kruyt and Vogel (1941).

E. Sach (1927) gave some explanation of the phenomenon assuming mutual displacement of charges of particles and their ion atmosphere. More detailed theory was given by Krasny and Ergen (1936) based on the force of attraction between dipoles produced by polarization.

Von J. Stauff who studied a number of different emulsions containing particles the sizes of which varied from 0.6 μm to 1.4 μm gave more detailed information regarding the formation of pearl-strings in alternating fields (30 - 500 Hz). He found that in the studied region of frequencies the amplitude of the particle oscillation was inversely proportional to the frequency of the applied field. Regarding the forces of attraction between particles in the direction of applied field which cause the formation of pearl-strings he found that the energies involved are proportional to the square of the field intensity, to the fifth power of the particles radii and that they decrease as the frequency is increased.

2.3 Electrical Breakdown

In order to find out the possible breakdown mechanism both pure hydrocarbons and commercial insulating liquids have been the subjects of extensive investigations in the last few decades. However it is acknowledged that the breakdown mechanism is a highly controversial topic.

2.3.1 Theories of breakdown

There are three breakdown theories on the basis of one or more of which all the investigators explain their results. The electronic theory
of breakdown of liquid dielectrics has been extended to liquid from gases by Lewis (1953), Goodwin and Macfadyen (1953) and later by Crowe et. al (1954)

This is based on the mechanism of electron emission and its subsequent multiplication due to ionizing collisions. In an electronic theory of breakdown it is assumed that, in a sufficiently high field, the electron will gain more energy than it loses in vibrational collisions with the atoms. The electrons are accelerated until they gain sufficient energy to ionize the liquid molecules and initiate an electron avalanche. This theory explains the gap dependence of breakdown strength, on the other hand it cannot explain satisfactorily the breakdown time lag data.

Kao and Higham (1951) showed that the breakdown strength of insulating liquids strongly depends upon the hydrostatic pressure even for the microsecond pulse range, which is a strong evidence in support of their cavitation or bubble theory. A bubble may form in the liquid due to gas pockets in the micro cavities on the electrode surfaces, dissociation of liquid molecules by high conduction current or local concentration or energy at the tip of the electrode asperity. The bubble once formed is distorted under the electrostatic forces or high fields until it bridges the gap resulting in the breakdown of the liquid. The cavitation theory is consistent with the observed variation of breakdown strength with pressure, temperature and boiling point.

A suspended particle theory was put forward by Kok and Corbey (1957). The solid impurity particles which are assumed to be polarizable spheres are invariably present in the insulating liquids. They usually have higher permittivities than that of the liquid and move into the maximum stress region under the influence of the dielectrophoretic force. There they form a bridge which subsequently leads to breakdown. There is little quantitative evidence in support of this theory although impurity particles often are the major contributing factor in the breakdown of insulating liquids.
None of these theories either explain all the experimental results or is generally accepted.

Salvage (1951), Lewis (1953, 1956), Crowe et al. (1953, 1954) and Sharbaugh et al. (1956) investigated the correlation between breakdown strength and molecular structure of liquid hydrocarbons. It was reported by Salvage and later by Kao (1965) that the electric strength of liquid straight-chain aliphatic hydrocarbons increased with increase in the chain length of the hydrocarbon molecules. Testing n-paraffins, pentane to decane, Lewis found that the breakdown strength increased slowly for shorter chain liquids and rapidly for longer chain liquids. Sharbaugh et al. (1956) confirmed that the breakdown strength of straight-chain liquid alkanes increased with molecular chain length. They further observed that introduction of branches in the hydrocarbon chain resulted in a reduction in strength.

2.3.2 Effect of gap setting

Lewis (1953), Watson (1953), Sharbaugh et al. (1955), Zein Eldine and Tropper (1956), Swan (1959) and Gosling (1960) investigated the effects of gap setting on the breakdown strength of insulating liquids. It is apparent from their results that the breakdown strength for gaps less than 50 μm increases rapidly as the gap is reduced for direct, alternating and pulse voltage tests. This dependence is less pronounced with the increase of the gap above 50 μm and at gaps above about 100 μm the breakdown strength was found to be almost independent of gap length (Kao, 1965). The only exceptions to these findings are the results of Darveniza (1959) and Khambanonda (1958) who used d.c. voltages and Hancox (1956) who used impulse voltage and found no gap dependence for transformer oil. Using coarsely filtered and finely filtered transformer oil Crawley and Angerer (1966) reported an interesting relationship between gap setting and breakdown strength.
For coarsely filtered oil the breakdown strength was found to increase with the increase of gap setting and to decrease for finely filtered oil. This effect is illustrated in Fig 2.8.

The presence of oxygen, nitrogen, sulphur hexafluoride and oxidized compounds such as azoxybenzene and benzophenone in insulating oil produced an apparent intercept when the d.c. breakdown voltage/gap setting characteristics were extrapolated to zero gap. These observations were made by Gosling (1964), Nosseir et. al. (1965) and Angerer (1965). This may indicate formation of surface layers on electrodes affecting the breakdown process.

Skowronski (1967) using both direct and alternating voltage investigated, using high speed camera, breakdown mechanism of dielectric liquids of commercial purity, i.e. containing small amount of suspended impurities such as dispersed water or solid particles, and found that it depends on electrode separation. At very small gaps (less than 1 mm) the bridge may be formed by the impurities and the breakdown could have typical bridge breakdown character; at medium gaps (between 1 mm and 10 mm) the effect of solid particles and dispersed water depends on the field configuration; and at larger gaps (greater than 10 mm) the influence of impurities suspended in the dielectric is small and very often insignificant. At larger gap and non-uniform field (point-point or point-plane electrode configuration) an electrical wind is created at the tip of the point electrode and no bridge formation is possible. The breakdown at these gaps develops from a streamer and is similar to that in gases.

Fallou and Galand (1968) studied the breakdown behaviour of liquid helium at 4.2°K with 50 Hz uniform field. They found that the breakdown strength varies non-linearly with electrode distance between 0.1 mm and 3 mm gaps. The breakdown strength at 0.1 mm gap was reported to be 450 kV/cm as against 220 kV/cm at 1 mm gap.
MEAN-BREAKDOWN-STRESS/GAP SETTING CHARACTERISTICS
RESULTS OBTAINED FOR FILTERED TRANSFORMER OIL,
USING DIRECT VOLTAGE AND SKOWRONSKI'S CUP-SPHERE GAP
a TRANSFORMER OIL AS RECEIVED
b,c TRANSFORMER OIL FILTERED THROUGH SINTERED-GLASS
FILTERS WITH POROSITIES OF 1.5 AND 0.8 MICRONS
RESPECTIVELY
d,e,f TRANSFORMER OIL FILTERED THROUGH PLASTIC FILTERS
WITH POROSITIES OF 0.45, 0.1 AND 0.05 MICRON
RESPECTIVELY (AFTER CRAWLEY AND ANGERER)
2.3.3 Effect of electrode material size, configuration and coating

Salvage (1951) using direct voltage showed that the breakdown strength of n-hexane depended on the metal from which the electrodes were made and that the electric strength increased with increasing photo-electric work function. On the other hand Lewis (1953) found very little dependence of breakdown strength on the material used for electrodes. While confirming the findings of Salvage that metals with high work function give high electric strength, Maksiejewski and Tropper (1954) however, concluded that the dependence on the work function is rather irregular because the effect could be destroyed by degassing the electrodes and the liquid.

Therefore no direct correlation between breakdown strength with that of the corresponding work function was possible. Zein Eldine and Tropper (1956) testing transformer oil with impulse voltages observed that the difference in breakdown strengths obtained from different metals was very small which is in striking contrast with the pronounced dependence with direct voltages. They suggested that the dependence on the electrode metal is a time dependent effect. This is in conformity with the results of Watson and Higham (1953). Using impulses of 4 milli.sec. duration they obtained electric strength values for electrodes made of Phosphor-bronze and steel respectively, which showed a percentage difference of 32% whereas the percentage difference in the electric strength for these electrodes was only 2.8% when impulses of 0.2 milli. second duration were used. Hancox and Tropper (1957) using cathode and anode of different materials have shown that the breakdown strength was dependent only upon the material of the cathode used. Gosling and Tropper (1960) using one aluminium and one nickel electrode found that the cathode metal had the greater influence on the breakdown strength but the shape of the breakdown strength/gap setting characteristic appeared to be influenced also by the metal of the anode. However, Sharbaugh et. al. (1958) did not find any dependence of breakdown strength on electrodes made of brass.
and stainless steel. All these investigations clearly indicate that the findings on the dependence of breakdown strength upon electrode material is far from conclusive.

Extensive tests were carried out by Maksiejewski and Tropper (1954) to study the effects of electrode geometry upon the breakdown strength. Spheres of various diameters and the plate electrodes regarded as spheres of infinite diameter did not show any variation in d.c. breakdown strength for the same gap spacing. With direct voltage of positive polarity Zein Eldine and Tropper (1956) obtained an increase in breakdown strength with decreasing size of electrodes although this dependence was not very marked. This was confirmed by Hancox and Tropper (1958) and Kao (1965) who used impulse voltages. The 60 cycle breakdown strength of good quality transformer oil has been shown by Weber and Endicott (1956) to depend upon electrode size. Sharbaugh et al. (1958) obtained 50% higher breakdown strength for 1 inch diameter hemispherical electrodes than with the same diameter of Rogowski electrodes at the same spacing.

The breakdown strength of transformer oil was investigated by Zaky et al. (1964) using plane-parallel electrodes of Bruce profiles and overall diameter 1 cm, coated with 0.25 mm thick polyether 'Penfon' insulating film. They found that coating either anode or cathode resulted in an increase of electric strength, but when both the electrodes were coated no further improvement in breakdown strength was obtained. The results were interpreted in terms of space charge which alter the normal field distribution. In a point plane electrode system Kao reported an increase in d.c. breakdown strength of carbon tetrachloride when the plane electrode was covered with a thin layer of glass. The negative point in such cases gave still higher breakdown voltage than the positive point (Kao 1964).
2.3.4 Effect of frequency on breakdown strength

While much work has been done on breakdown properties of liquid dielectrics under direct voltage conditions relatively little is known about their behaviour when subjected to high voltages at variable frequencies. At higher frequencies particle transit times may become significant, compared to the periodic time and hence breakdown strength may become sensitive to frequency.

As early as 1924 Draeger using spherical electrodes of 20 mm diameter found that breakdown strength of oil increased with frequency up to 400 Hz. Sorge (1924) observed that the breakdown strength of hexane increased with frequency up to 500 Hz. He used German mushroomshaped (VDE) electrodes and the test gap in hexane was 3 mm. Unfortunately both Draeger and Sorge obtained only three points for their characteristics. Walter and Inge (1932) reported that the breakdown strength (peak value) of filtered and degassed Xylo1 at 50 Hz was much higher than the corresponding direct voltage breakdown strength. This difference was found to be significantly reduced when higher purity Xylo1 was tested at a later date. On the other hand Toriyama did not find significant difference between breakdown strengths of purified transformer oil at 50 Hz alternating voltage and direct voltage. The information published by Koppleman (1935) and Volta and Inge (1929, 1939) has shown that from 0 to 60 Hz the breakdown strength of transformer oil increases with frequency by about 60-100%.

In the course of a review of previous work Shanavi (1958) reported that for the low range of frequencies the breakdown strength of commercially pure transformer oil increases with frequency. Table 1 shows some of the results reported therein.
These results are represented in Fig 2.9 and compared with the results for pure hexane. However this dependence was found to be less pronounced when the oil was better purified.

The reason for increase of breakdown strength at higher frequency has been ascribed to the instability in the chains and bridges by Whitehead (1928). He also suggested the possibility of the time interval in the actual discharge which must be completed within a half cycle. This being less at higher frequency the breakdown strength should be higher.

According to Draeger (1924) the breakdown strength does not vary much above 400 Hz. But Peek (1929) found that the breakdown strength at 90 kHz is smaller than at 60 Hz. In an attempt to explain Draeger's observation that the breakdown strength is independent of frequency above 400 Hz, Whitehead (1928) suggested correlation of anomalous conduction current which has less and less effect upon the permittivity with the increase of frequency. The decrease of breakdown strength at very high frequency could be ascribed to the losses in oil due to high local heating.

<table>
<thead>
<tr>
<th>Frequency ( \text{Hz} )</th>
<th>( E_{bd} ), kV/cm</th>
<th>Transformer oil No. 1</th>
<th>Transformer oil No. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>380</td>
<td></td>
<td>480</td>
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<tr>
<td>150</td>
<td>430</td>
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<tr>
<td>225</td>
<td>470</td>
<td></td>
<td>570</td>
</tr>
<tr>
<td>800</td>
<td>-</td>
<td></td>
<td>610</td>
</tr>
</tbody>
</table>
2.3.5 Dependence of breakdown strength on the rate of increase of the applied voltage

No appreciable effect of the rate of increase of voltage upon the breakdown strength of liquid dielectrics was found by Sorge (1924) for the rates of increase of voltage between 6 and 78 kV/min. His results corresponded to very low frequencies, i.e. 0.01 Hz. According to Shanavi (1958) the rate of increase of applied voltage accounts for the increase of strength of commercially pure liquids as the frequency increases. Fig 2.10 shows the experimental results of different authors. Skanavi concluded that if the temperature of the liquid remains below the boiling point, there should be no increase of breakdown strength of a highly purified oil due to the increasing rate of raising of the applied voltage.

2.3.6 The effect of gap setting on breakdown strength at variable frequency

A gap dependence of the breakdown strength of turpentine oil at 50 Hz and 32 kHz was reported by Skanavi (1958). The 32 kHz breakdown strength between two parallel plate electrodes for gaps smaller than 3 mm was found to be greater than the corresponding strength at 50 Hz whereas for gaps bigger than 3 mm 32 kHz breakdown strength was smaller than that of the 50 Hz breakdown values (see Fig 2.11). At 32 kHz the particle transit time being longer than the periodic time of the applied voltage the breakdown strength at gaps less than 3 mm could be higher than that at 50 Hz where the particles could play an effective role and the breakdown be due to bridge formation. But for gaps larger than 3 mm, the particle size-gap ratio being very small, the particles could be ineffective and the mechanism of breakdown different and most probably of thermal character. The dissipation of energy in the form of heat at 32 kHz, when the applied stress is high, could be high enough to vaporise the liquid and subsequently the breakdown stress would be lower than that at 50 Hz.
Fig. 2-9 FREQUENCY DEPENDENCE OF ELECTRIC BREAKDOWN OF TRANSFORMER OIL
1. transformer oil no.1, 2. transformer oil no.2, 3. hexane

Fig. 2-10 DEPENDENCE OF BREAKDOWN STRENGTH OF DIELECTRIC LIQUIDS ON THE RATE OF RAISING THE APPLIED VOLTAGE
1. transformer oil no.2, 2. xylol, 3. trans. oil no.1, 4. benzene, 5. hexane
6. trans. oil

Fig. 2-11 DEPENDENCE OF BREAKDOWN VOLTAGE OF TURPENTINE OIL ON GAP SPACING OF ELECTRODES AT DIFFERENT FREQUENCIES
1. 50 Hz, 2. 32 kHz

(AFTER SKANAVI)
3. EXPERIMENTAL APPARATUS AND TEST PROCEDURE

3.1 Introduction

The design was based on the apparatus used by Gosling (1960), Angerer (1964) and Jones (1968). Modifications of the apparatus were subsequently made in order to study the effect of particle size on the breakdown and pre-breakdown phenomena in insulating oil. A gas system, a vacuum system and an oil system of which the test cell was an integral part, were three parts of the apparatus. The general arrangement is shown in Figures 3.1 and 3.2.

3.2 The Gas System

The gas was first fed through a number 4 filter \((A_1)\) and in order to dry the gas it was then passed through a silica gel column into a reservoir which also contained some silica gel. By manipulating the different stopcocks it was possible to admit the gas into any part of the system after it had passed through a number 5 filter \((B_1)\). Nitrogen, Oxygen and sulphur hexafluoride gases were used in the experiments and the gas system was evacuated to a pressure of \(10^{-2}\) torr and flushed with the desired gas several times before being admitted to the rest of the system. The gas pressure was measured with a mercury manometer between the gas cylinder and the number 4 filter \((A_1)\).

3.3 The Vacuum System

The vacuum system consisted of a rotary pump, a phosphorus pentoxide trap and a liquid nitrogen trap. By manipulating various stopcocks it was possible to pump down any part of the system and with the liquid nitrogen trap in operation a vacuum of \(10^{-3}\) torr could be obtained. The socket and the solid cone arrangements at the top and bottom of the main vacuum line made it possible to flush the vacuum system with hexane.
GENERAL ARRANGEMENT
OF
APPARATUS

gas system

TO N₂ CYLINDER

SILICA GEL COLUMN

PIRANI GAUGE HEAD

TO VACUUM PUMP

vacuum system

GAS RESERVOIR WITH SILICA GEL

REMovable COLUMN

OIL RESERVOIR

TEST CELL

LIQUID NITROGEN TRAP

COLLECTING FLASK

oil system

DEGASSING FLASK

Fig. 3-1
Fig 3.2 General Arrangement of Apparatus
3.4 The Oil System

The degassing flask of 1000 ml capacity was a part of the oil system and contained a magnetic stirring device. One side of the flask, having a B-19 socket, was connected to the vacuum line using a B-19 cone fitted to one end of a flexible nylon tube, the other end being connected to the vacuum line. The other side of the flask was connected to the filter column with a flexible nylon tube. The lengths and positions of the nylon tubes were arranged in such a way that the oil level in the degassing flask in its tilted position was about 2" below the oil outlet. Wherever movement was likely between parts of the system flexible nylon B-66 tubing was used. All the nylon-glass nipple joints were reinforced with araldite to prevent leakage and greaseless stopcocks with Viton-A diaphragms were used throughout the oil system. All the cone joints used in the apparatus were sealed with neoprene O-rings in the vacuum system and Viton-A O-rings in the oil system.

A removable column below the degassing flask enabled various filters to be used. It was fixed to the system using ground glass joints, details of which are shown in Fig 3.3. They were made vacuum tight with Viton-A O-rings pressed between the joints by clamps. The various filters in the column were connected by flexible nylon tubes. On replacing or removing filters dry and clean nitrogen was passed through stopcocks 9 and 10 in order to keep the system dry and clean. After filtering, the oil was collected in a 1000 ml reservoir and by controlling stopcock 11 the test cell could be filled by allowing the oil to flow under gravity.

3.5 The Test Cell

In order to reduce the possibility of field distortion in the gap due to charges on the inside surface of the cell, a relatively large test cell of 75 ml capacity (shown in Figs 3.4 and 3.5) was designed. The cell was
Fig. 3.3 details of interchangeable filter
Fig 3.5 TEST CELL
made of brass with two optically flat glass windows 3 mm thick, one for illuminating the cell and the other for microscopic observation of the gap. They were held in position by end plates and sealed by O-rings located in a groove. Two brass tubes with tapered ends were soldered on to the cell in order to make flexible nylon inlet and outlet connections.

The electrode assembly, which was at earth potential, consisted of a brass plug which was bored to take an insulated electrical connector. The connector consisted of a glass-metal seal with a 0.8 mm dia. Kovar wire (Cathodeon Limited, type 3124) and a 0.5 mm dia. wire which was fixed to the wire of the seal by a threaded sleeve. The seal was soft-soldered to the brass plug and an insulating tube prevented connection between the Kovar wire and the main body of the test cell.

The high voltage electrode shank was a 5 mm dia. solid stainless steel rod ending with a 0.8 mm dia. stem in order to mount a spherical electrode. The solid stainless steel rod was spring loaded and butted on to a ball bearing, which was against a micrometer anvil. A sufficiently strong spring was used to function against the vacuum pressure and O-ring friction. The high voltage electrode shank and the micrometer were insulated from the body of the cell by a plug of PTFE insulation.

The electrodes were 5 mm dia. spheres of spectroscopically pure nickel and were drilled along the diameter with a blank hole so that they could be fitted to a 0.8 mm dia. wire. They were secured in position by a 12 BA grub screw along a diameter perpendicular to the wire. The electrode also had a 12 BA tapped hole opposite the grub screw so that it could be handled using a special tool having a 12 BA threaded end piece.

The cell was made vacuum tight by means of the Viton-A O-rings fitted on to the end flanges of the brass or PTFE plugs, which could be removed with the electrodes. The plug on the low voltage side was attached to the cell by six 6 BA brass screws and the high voltage plug was attached by six 6 BA nylon screws.
3.6 Cleaning the oil System and the Test Cell

Before assembling the system all the glass parts of the apparatus and the test cell were cleaned with chromic acid and then washed with cold tap water and finally with distilled water. The water from the system was removed by rinsing with acetone followed by a rinsing in distilled hexane and drying with a hot air blower. The nylon tubes used in the system were rinsed with acetone followed by hexane and then dried with hot air.

When assembled the system was cleaned with distilled hexane. Before opening the system to the atmosphere it was filled with dry nitrogen to a pressure slightly greater than the atmospheric so that there was a constant flow of dry nitrogen into the atmosphere as soon as a part of it was opened. This was to prevent any impurity particles and moisture from the atmosphere entering into the apparatus. The oil system was also cleaned with hexane after each test. To clean the degassing flask hexane was shaken around it vigorously and then after raising the flask to its vertical position stopcock 9 was opened to allow the hexane to rush through the filter column to the reservoir and then finally through the cell to the collecting flask. In this way the whole line was thoroughly cleaned. The collecting flask was then replaced after removing the hexane. The whole process was repeated at least three times to make sure that the oil line was thoroughly cleaned.

Once the cleaning operation was complete the hexane vapour was removed from the system by pumping it for 24 hours. In this process all the hexane vapour was found to condense in the liquid nitrogen trap and was removed from time to time. The oil in the rotary pump was never contaminated due to the efficient functioning of the trap and after 24 hours the whole system was found to be completely free of any vapour. It was then ready for the introduction of the oil sample. The oil line was further cleaned by an oil sample processed in a way similar to that of the test sample to follow.
3.7 **Preparation of Electrodes**

The method of cleaning and polishing the electrodes was similar to that of Zaky (1959), Gosling (1960), Angerer (1962) and Megahed (1965). The electrodes were polished by buffing with a grade B high speed mop. A green chrome oxide polishing agent was used to remove carbon deposits and deep scars from the surfaces of the electrodes. From time to time the surface of the electrode was examined by a microscope (magnification 100), and when the surface was free from visible scratches the electrodes were finally polished with a clean mop. The clean electrodes were never touched by hand, they were either manipulated by a specially designed tool with 12 BA thread or when necessary, handled with Kleenex tissues wetted with distilled hexane. After cleaning, the electrodes were kept immersed in boiling hexane, for about 10 minutes in an effort to remove the last traces of green polishing compound.

Before opening the test cell dry nitrogen was allowed into the system at a pressure slightly higher than the atmospheric so that on opening the cell there was a steady outflow of dry nitrogen preventing the entry of moisture and dust particles. Then the electrodes were removed from the electrode holder, given a final spray of hexane and placed quickly in the test cell. The gas supply was then cut off and the whole system was evacuated for 24 hours with the liquid N$_2$ trap in operation, to remove gas and hexane vapour (see Section 3.6). Fig 3.6 shows a part of the electrodes before and after breakdown.

3.8 **Adjustment and Visual Observation of Gap**

The distance between the electrodes was adjusted by a spring loaded micrometer. One circular division of the micrometer corresponds to 10 microns and a Vernier made it possible to measure one tenth of this value. It is estimated that the gap was correct to ±1 micron. The zero gap setting
PART OF CLEANED ELECTRODE SURFACE
MAGNIFICATION X 3080

PART OF ANODE AFTER 300 BREAKDOWN SHOTS, MAGNIFICATION X 2925

PART OF CATHODE AFTER 300 BREAKDOWN SHOTS, MAGNIFICATION X 2925

Fig 3.6
of the electrodes was accurately obtained by placing the gap in the grid circuit of a triode valve which had a milli ammeter in its anode circuit (Lewis, 1953). Closure of the gap caused negative bias on the grid and anode current then fell to zero, thus giving a very sensitive indication of gap closure. The merit of this method is that practically no current flows on contact and little damage can be done to the electrodes. After zero adjustment the micrometer head was retracted to a distance corresponding to the required gap length.

Observation of the gap was possible by means of an ultra microscope which was fitted in front of the cell and illumination from a tungsten lamp at the rear of the cell. The magnification of the microscope was 100 using a (x4) objective and (x25) eyepiece but sometimes lower magnification (4x10) was employed to give a wider field of view.

3.9 Preparation of Test Liquid

The test liquid was Gulf transformer oil, B-30 commercial grade, supplied by Gulf Oil (Great Britain) Limited. After the cleaning of the oil system and test cell followed by pumping for 24 hours to remove hexane vapour and gas from the system as described in Section 3.6, dry nitrogen was introduced into the degassing flask at a pressure higher than the atmospheric. The cone and socket joint of the degassing flask was then disengaged and about 100 ml of transformer oil was transferred into the degassing flask in its clamped position on top of the magnetic stirrer. The cone was then replaced with its O-ring seal and the degassing of the liquid started by pumping down the degassing flask. After about half an hour the magnetic stirrer was set into motion first slowly and then vigorously with the help of a Variac. This delay was essential because otherwise, due to vigorous bubble formation in the initial stage of degassing, the oil would have overflowed the entrance
which had been sealed under vacuum was opened so as to bring the whole oil system under vacuum and degassing was continued for 20 to 24 hours. With the liquid nitrogen trap in operation the oil could be degassed to $10^{-3}$ torr. To ensure that the test liquid was degassed to this extent, the vacuum pump was disconnected from the system and the pirani gauge was observed after 15 minutes. If there was no appreciable change in the reading, then the sample was accepted as degassed.

Once the degassing was complete the stirrer was stopped and the degassing flask was tilted to a position so that the outlet was vertical and the liquid was allowed to flow to the collecting flask through the filter column. To hasten the filtering process dry nitrogen at approximately 1 atmospheric pressure was applied to the oil surface. The processed liquid was stored in the oil reservoir which was pumped so as to ensure the removal of any nitrogen which may have been absorbed by the oil. The top layer of oil in contact with nitrogen was not allowed into the reservoir. When the test cell and the oil reservoir showed a vacuum of $10^{-3}$ torr, 75 ml of the sample was allowed to flow into the cell under gravity. As soon as the cell was full, it was sealed and the rotary pump was switched off.

When a sample containing added particles was required, they were introduced into a metallic filter casing C (Fig 3.1) after removing the filter support. The inherent particles in the oil were removed by filtering the degassed sample through No. 4 ($A_2$) and No. 5 ($B_2$) filters.

3.10 The High Voltage Supply

3.10.1 D.C. supply and measurement

The d.c. high voltage source was a stabilised Brandenberg E.H.T. Generator, type S 0530, the output voltage of which could be adjusted
between 1 kV and 30 kV. Details of the d.c. supply and circuits are described
by Jones (1968). Measurement of the test voltage was by means of a 300 MΩ
high stability chain resistor in series with a 0-50 μA moving coil
meter. An electrostatic voltmeter was used to calibrate the ammeter.

3.10.2 D.C. diverter unit

Fig 3.7 shows the circuit similar to one devised by Saxe and Lewis
(1955). The 2D21 thyatron was fired by the breakdown current pulse across
the 100 kΩ cathode resistance. The thyatron discharges the 0.03 μF
capacitor through the 500 Ω cathode resistance triggering the XH16-20
hydrogen-filled thyatron and shorting the cell. This was achieved in
less than a micro second thereby minimising the effect of breakdown
damage on the electrodes and decomposition of the test liquid.

3.10.3 A.C. supply and measurement

An alternating high voltage up to 30 kV was obtained from a transformer
driven by a power amplifier (see Fig 3.2) which was controlled by a variable
frequency signal generator, Type LF 141 (Servomex Controls Limited). The
amplifier model PP1/2P (LTV Ling Altec Limited) was designed to give an
output of 1 kVA over a frequency range of 20 Hz to 5000 Hz. An input
signal of 1 volt r.m.s. was required for full output. The output waveform
was quite satisfactory and no significant distortion was observed even with
load impedance variations.

Distortion at 1 kVA output

20 to 1000 Hz - 1%
1000 to 5000 Hz - 2.5%

Hum and noise better than 70 dB below full output. Below 20 Hz the
output voltage fell proportionally with frequency down to 5 Hz.
FIG. 3-7 ELECTRICAL APPARATUS (D.C. TESTS)
A resistor chain of 5 MΩ made up of fifty 100 kΩ units was used in series with the cell to limit the breakdown current. These units were spirally wound on a 'Perspex' holder which was immersed in transformer oil contained in a perspex cylinder. Due to excessive capacitive loss at frequencies above 500 Hz, a limiting resistor chain of more than 5 MΩ could not be used.

All connecting cables were polythene insulated stranded high voltage cables. A soldered tag joint connected the cable to the transformer output terminal and the joint was covered with insulating wax (Apezion Q compound). The high voltage was connected to the cell with a rounded face spring-loaded brass rod of \( \frac{1}{4} \)" diameter so as to facilitate easy movement of the micrometer head for gap adjustment.

The voltage was measured with Pye Scalamp electrostatic meters (0-10, 0-18, and 0-40 kV). To measure voltages below 3 kV a sensitive valve voltmeter was used after calibration with Pye electrostatic meters. The reading accuracy of voltage was estimated to be within ±1%.

3.10.4 A.C. diverter unit

To minimise the damage to the electrode surfaces and the liquid decomposition, the breakdown energy was diverted with the help of an electronic circuit shown in Fig 3.8. The circuit worked as a flip-flop using a relay in the collector circuit of transistor \( T_1 \) to short circuit the input to the amplifier when switching took place. Initially the circuit was set by operating switch \( S_1 \) manually. This switched the transistor \( T_1 \) off and deactivated the reed relay which disengaged switch \( S_2 \) and made transistor \( T_1 \) conducting. When breakdown occurred in the cell, a positive potential from the breakdown spark at the base of transistor \( T_2 \) switched it off, which in turn switched transistor \( T_1 \) on. This activated the reed relay coil and switch \( S_2 \) was closed thereby
short-circuiting the input to the amplifier. The signal was then reduced to zero and the circuit was reset using switch $S_1$.

The operation of the relay was approximately 1 millisecond after the breakdown had occurred. Due to the transients of the amplifier circuit it was not possible to use a thyratron to make the operation faster. However, microscopic observation of the electrode surfaces after equal number of breakdowns with a d.c. diverter unit with hydrogen thyratron revealed that damage due to a.c. breakdown with the relay circuit in operation was less than that with d.c. breakdowns.

3.11 The test procedure

All the tests were carried out at room temperature. A pair of electrodes with fresh surfaces were used in each test and the gap was adjusted as described in Section 3.8. The test cell was filled with a sample, the preparation of which was been described in Section 3.9.

In the d.c. tests the gap was set at 125 microns and the test voltage was quickly raised to 7 kV. The liquid was stressed for two hours, following the procedure adopted by Gosling (1960), Angerer (1962), Nossier (1964) and Jones (1968), to remove particles from the gap and to obtain steady conduction and breakdown readings. Then the conduction current readings were taken for gaps in decreasing order. For each gap the readings were checked for increasing and decreasing voltages. The breakdown runs were commenced with the smallest gap of 28 microns. This avoided greater electrode damage for larger gaps. A run of 14 breakdowns were taken for each gap.

In the a.c. tests the pre-breakdown activity, including bridge formation, were recorded without conditioning the liquid. In the a.c. breakdown tests the liquid was conditioned by breakdowns because it was found that even after stress conditioning a further increase in
strength due to breakdowns was observed (Details in Section 4). After conditioning a series of breakdown measurements were recorded at one minute intervals. A voltage of about 60% of the breakdown value was maintained between two successive measurements, from which the voltage was increased until breakdown occurred. After the breakdown the signal was turned down to zero, the reset switch of the diverter unit was operated and the voltage was immediately restored to 60% of breakdown value. Twenty breakdown values at each frequency, ten at increasing frequency and ten at decreasing frequency, were recorded. The average values of these twenty readings were plotted in the curves.
4. EXPERIMENTAL RESULTS

4.1 Introduction

The major part of the experimental work is concerned with the measurement of breakdown strength at variable frequency. The preliminary tests were designed to check the operation of the apparatus and to develop a standard test procedure which was adhered to during the remainder of the work. A few tests, reported in Section 4.2, have been carried out with direct voltage. This was to check that results similar to those of other workers could be obtained with the equipment used in this investigation. In section 4.3 preliminary tests with variable frequency alternating voltage and the effects of conditioning are reported. These preliminary measurements could not be compared with other workers because of the non-availability of published data in this respect. The variation of breakdown strength with number of measurements at a fixed frequency and breakdown measurements at various frequencies are given in section 4.4. However the most important aspects of the present work are dealt with in sections 4.5 and 4.6. Section 4.5 deals with the effect of inherent particles of the oil on the breakdown strength at variable frequency and the effect of introduced particles is shown in section 4.6. The particle bridge formation, stability and instability of the bridges and their effects on the strength of the oil are considered in section 4.7. The luminosity, a rather interesting aspect, observed under certain conditions is described in section 4.8. Breakdown and post-breakdown results are reported in sections 4.9 to 4.13.

The test liquid was B-30 transformer oil of Peruvian origin supplied by the Gulf Oil Company.

Gosling (1960), who separated the chemical constituents of Gulf B-30 transformer oil, found the following proportions by volume.
4.2 Preliminary Tests

4.2.1 D.C. breakdown measurements

In order to gain experience and become familiar with this type of work a few tests applying direct voltage were made by using similar apparatus used by Gosling and Angerer. The inclusion of a brass test cell designed to accommodate larger volume of test liquid compared with the cell used was the only modification made in the apparatus at this stage. When a degassed sample, filtered through a No. 5 sintered glass filter, was tested breakdown values of 1150 kV/cm were obtained for a gap of 51 microns. This value is in good agreement with those reported by Gosling (1960) and Angerer (1962). It signified that the oil samples and test procedures adopted were similar to those of the previous workers.

4.2.2 Non-degassed and non-filtered tests

When the test liquid was not stress conditioned, conduction current readings (shown in Fig 4.1) were observed to be unstable for 125 micron and 81 micron gaps. Although some fluctuations in current readings were found at all test gaps, comparatively stable currents were recorded in tests at gaps of 51 microns and 28 microns. With prestressed transformer oil the conduction current readings were found to be stable (see Fig 4.2). The breakdown values in both the cases were very nearly the same and are shown in Fig 4.3.

4.2.3 Degassed and filtered tests

When the transformer oil was degassed and filtered, stable and
FIG. 4-1  STEADY CURRENT - STRESS CHARACTERISTICS OF NON-FILTERED, NON-DEGassed, AND NON-PRESTRESSED TRANSFORMER OIL
Fig. 4.2 Steady current-stress characteristics of transformer oil, non-filtered and non-degassed but prestressed at 400 kV/cm.
FIG. 4-3  BREAKDOWN STRESS/GAP LENGTH CHARACTERISTICS OF TRANSFORMER OIL UNDER STEADY VOLTAGE
significantly smaller conduction current values were recorded (see Fig 4.4). The breakdown strengths were found to be higher than those of non-degassed and non-filtered transformer oil. Table 2 shows the relative breakdown strengths and their coefficients of variation.

TABLE 2

<table>
<thead>
<tr>
<th>Transformer Oil</th>
<th>Breakdown strength (kV/cm), average of 15 readings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28 μm</td>
</tr>
<tr>
<td>Degassed and filtered (No. 5)</td>
<td>1410</td>
</tr>
<tr>
<td>Degassed and filtered (No. 4)</td>
<td>1220</td>
</tr>
<tr>
<td>Non-degassed and non-filtered</td>
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</tr>
<tr>
<td>Non-degassed, non-filtered, non-prestressed</td>
<td>890</td>
</tr>
</tbody>
</table>

These results are given in Fig 4.3.

4.3 A.C. Tests

In order to study the effect of particle size in these tests the apparatus was redesigned to allow for the introduction of a replaceable filter column. Other basic features remained unchanged. From the preliminary tests both with direct voltage and alternating voltage it was apparent that in non-degassed oil, there was a large scatter in the breakdown stress readings. Also prolonged conditioning was necessary for non-degassed oil compared with a degassed sample. Therefore except for a few preliminary measurements the alternating voltage tests were carried out with degassed transformer oil.
FIG. 4-4 STEADY CURRENT-STRESS CHARACTERISTICS OF TRANSFORMER OIL DEGASED, FILTERED (NO. 5 FILTER), AND PRESTRESSED AT 600 KV/CM
4.4 Pre-breakdown Phenomena

In this section the activity of the solid impurity particles under the influence of variable frequency alternating stress in transformer oil is considered. The oil samples may be classified as follows:-

1. Those containing inherent particles (see section 4.5)
   (a) non-filtered
   (b) number 3 filter (porosity ≤ 25 microns)
   (c) number 4 filter (porosity ≤ 10 microns)
   (d) number 5 filter (porosity ≤ 1.63 microns)

2. Those filtered with a number 5 filter and non-metallic particles added (see section 4.6).
   (a) Selenium powder, (approx 1 m.g.m., diameter ≤ 45 microns)
   (b) Silicon powder, (approx 1/2 m.g.m., diameter ≤ 45 microns)

3. Those filtered with a number 5 filter and metallic particles added (see section 4.7)
   copper powder, (approx 1 m.g.m., diameter ≤ 1 micron)

4.5 Inherent Particles

On the application of an a.c. electric stress the particle impurities were often observed to form bigger complexes. Microscopic observation of the gap revealed that particles were set into motion in the liquid by the stress and that the particle oscillations were found to increase with increased voltage. At very low frequencies i.e. up to about 15-20 Hz, the particles were observed to follow the frequency of the applied voltage and the particle motion could be observed up to about 300 Hz, above which the particles appeared to remain stationary (see Fig 4.5). Due to pronounced activity of the particles at frequencies below 50 Hz the gap appeared to be in a turbulent state. It was also observed that the
LONGITUDINAL MOTION  
FREQUENCY < 150 Hz

CIRCULAR MOTION  
FREQUENCY 150 TO 300 Hz  
GAPS ≥ 150 MICRONS

DOUBLE CIRCULAR MOTION  
FREQUENCY 150 TO 300 Hz  
GAPS ≥ 150 MICRONS

STATIONARY PARTICLES  
FREQUENCY ≥ 300 Hz

Fig. 4.5 various motions of particles
amplitude of oscillation of the particles in an alternating field decreased with increasing frequency (see Fig 4.6).

Three types of particle motion were noticed when an alternating stress was applied to a test sample. One was along the field lines in which the particles were seen to oscillate and sometimes jump from one electrode to the other. Unlike the particles under d.c. field, most of the particles in this case either stuck to the surface of the electrode after jumping or were seen to move randomly over the surface, only a few jumped back to the other electrode. The second type of motion was perpendicular to the field lines. In this case the particles either moved towards the maximum stress region or away from it. This motion was found to be random and did not follow a definite trajectory. At frequencies between 150 Hz and 300 Hz and gap above 150 μm, a circular motion of the particles was noticed as can be seen in Fig 4.5. The behaviour of particles under a steady field, which was observed by Gosling (1960), is illustrated in Fig 4.7.

An interesting frequency effect of the particles was observed when the stress was kept constant, the value of which was above critical to maintain a steady bridge. It was found that by increasing the frequency of the applied voltage to 400 Hz or above, the particle impurities could be dragged into the maximum stress region. As the frequency increased the particle concentration increased and at 1000 Hz and above they formed a dark patch in the maximum stress region (see Fig 4.8). The region containing particles was observed to be darker and smaller at the higher frequencies. On decreasing the frequency from 1000 Hz, the particles spread out and at 500 Hz the particles started dispersing from the maximum stress region. At about 300 Hz all the particles moved away from the gap and below 300 Hz the gap remained clear of the particles. However, at frequencies 80 Hz and below, occasionally a few particles
Fig. 4.6 dependence of amplitude of oscillations of particle upon frequency
Fig. 4.7 particle behaviour under direct field (AFTER GOSLING, 1960)
gap 200µm, stress 200 kV/cm, particle size ≤ 25µm

20 c/s 80 c/s 300 c/s

→ particle moving

500 c/s 1000 c/s 1500 c/s

particle stationary

Fig. 4.8 particle behaviour at a fixed stress
were seen moving on the surfaces of the electrodes. In this process the particle activity on the anode was often observed to be greater than that on the cathode. The whole cycle of events could be repeated over and over again by increasing and decreasing the frequency while keeping the voltage constant. No bridges were seen during these observations.

For a fixed frequency it was found possible to clear the gap of particles by increasing the applied voltage. Clearing the gap in this way was much easier at the larger gaps i.e. in excess of 100 microns.

When the applied stress was increased or decreased slowly, the particles were found to flocculate and form a 'pearl-string' bridge at certain stresses. This bridge formation was also dependent on frequency and duration of the applied voltage. It was found that below a certain minimum stress and above an easily defined maximum stress the bridge formation was not possible at any gap. There was also a maximum gap length (1.5 mm) above which the particles were unable to form a bridge.

4.6 Bridge Formation Phenomena in Oil Containing Non-Metallic Particles

4.6.1 Frequency dependence of bridge formation

The particle bridge formation was found to be dependent upon frequency of the applied voltage. The stress needed to initiate the bridges increased with frequency (see Fig 4.9).

4.6.2 Gap dependence of bridge formation

For all sizes of impurity particles, whether inherent in the oil or introduced into it, a critical gap of 1.5 mm was found at and above which no bridge formation was possible in the frequency range of 20 Hz to 1000 Hz. Below the critical gap (less than 1.5 mm) the initial bridge formation stress was independent of the gap length. On the other hand the critical stress for a steady bridge depended upon the gap. The value of this
stress at all frequencies decreased with the increase of gap length. This effect is also illustrated in Fig 4.9.

4.6.3 Threshold stress to initiate bridge formation

The minimum stress necessary for bridge formation was independent of gap length (<1.5 μm) and particle size at all frequencies. On increasing the stress from zero value, the threshold stress was found to vary from 5 kV/cm at 20 Hz to 60 kV/cm at 1000 Hz. This is shown in Fig 4.9. When the stress was decreased from a higher value, similar minimum stresses were obtained for bridge stability. In this case the time interval needed to wait for the dispersal of the bridge was longer compared to the time necessary for bridge formation.

4.6.4 Critical stress for steady bridges

On increasing the stress slightly above the threshold value, the selenium and silicon particles were observed to form a number of parallel bridges. Further increase of stress made the bridges move slowly into the maximum stress region until at a certain stress they combined to form a single bridge. However, on decreasing the stress from this value no parallel bridges were formed. But if the stress was gradually increased to a value where the bridge was dispersed and after that quickly reduced to the value, where multiple parallel bridges were formed while increasing the stress, a few parallel bridges were again observed. Fig 4.10 illustrates this effect. No parallel bridges were found to have formed in case of samples containing inherent particles. If the stress was increased after the formation of a bridge it was found to remain stable at all frequencies up to a certain stress beyond which it broke up. The maximum stress beyond which the bridge could no longer exist will be called the critical stress. It was found to depend on frequency for all gap-settings and decrease with the increase of gap length (see Fig 4.9).
Fig. 4.10 multiple bridges with selenium particles

11 kV/cm
Gap 500 μm, 20 Hz

20 kV/cm

30 kV/cm

20 kV/cm

30 kV/cm

50 kV/cm
Gap 200 μm, 20 Hz
4.6.5 Effect of Particle Size

As already mentioned the threshold stress for bridge initiation did not depend upon the size of the particles but the critical stress to maintain a steady bridge was found to depend upon the size of the particles. This critical value was found to be the same for both increasing and decreasing stresses and the dependence for a 200 μm gap is illustrated in Fig 4.11

4.6.6 Gap clearance

When the stress was increased above the critical value for steady bridges violent motion of the particles was observed and it was no longer possible to maintain a bridge. A further increase of the stress slowly removed the particles away from the gap and above a certain stress the gap was found to be clear of all the particles. This gap clearing stress was found to increase with frequency and decrease with increase of the gap length (see Fig 4.8). For higher stresses the gap remained clear until the breakdown of the oil occurred.

4.6.7 Non-sustained breakdowns

The formation of a bridge was found to be accompanied by occasional bubble formation and spurious or non-sustained local breakdown sparks. The oil sample was observed for two minutes, one minute as the stress was increased, and one minute as the stress was decreased, in order to study the effect of spurious sparks at each frequency. After the formation of a bridge at the threshold stress no spurious sparks were observed at low frequencies but at 500 Hz and 1000 Hz one or two sparks were noticed. However, more spurious sparks were observed during the same time interval at the critical stress. Table 3 shows that the number of spurious sparks in two minutes ranged from 3 to 6 for a 100 micron gap as against 2 to 4 for a 200 micron gap (see Table 4).
Bridge formation characteristics of various particles at 200 μm gap

- **SELENIUM PARTICLES**
- **NO. 3 FILTER**
- **COPPER PARTICLES**
- **NO. 4 FILTER**
- **NO. 5 FILTER**
- **THRESHOLD STRESS**

**fig. 4-11**

- **applied stress, kV (p.m.s.)/cm**
- **frequency, Hz**
### TABLE 3
Selenium Particles 100 μm test

<table>
<thead>
<tr>
<th>Freq Hz</th>
<th>$kV/cm$ Threshold stress for bridge initiation</th>
<th>$kV/cm$ critical stress for steady bridge</th>
<th>$kV/cm$ No. of sparks in 2 mins</th>
<th>$kV/cm$ No. of sparks in 2 mins</th>
<th>$kV/cm$ No. of sparks in 2 mins</th>
<th>$kV/cm$ No. of sparks in 2 mins</th>
<th>$kV/cm$ No. of sparks in 2 mins</th>
</tr>
</thead>
<tbody>
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<td>120</td>
<td>2</td>
<td>350</td>
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<tr>
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<td>90</td>
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<td>130</td>
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<tr>
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<td>135</td>
<td>6</td>
<td>260</td>
<td>2</td>
<td>350</td>
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### TABLE 4
Selenium Particles 200 μm test

<table>
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<th>Freq Hz</th>
<th>$kV/cm$ Threshold stress for bridge initiation</th>
<th>$kV/cm$ No. of sparks in 2 mins</th>
<th>$kV/cm$ No. of sparks in 2 mins</th>
<th>$kV/cm$ No. of sparks in 2 mins</th>
<th>$kV/cm$ No. of sparks in 2 mins</th>
<th>$kV/cm$ No. of sparks in 2 mins</th>
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<td>1</td>
<td>120</td>
<td>4</td>
<td>200</td>
<td>2</td>
</tr>
</tbody>
</table>
4.7 Bridge Formation Phenomena in Oil Containing Metallic Particles

Tests were carried out by adding copper particles to the degassed transformer oil after filtering it through a number 5 filter to study the pre-breakdown effects of these particles with particular reference to bridge formation and its associated phenomena.

4.7.1 Frequency dependence of bridge formation

The bridge formation by copper particles like non-conducting particles was found to be frequency dependent and is shown in Fig 4.12.

4.7.2 Gap dependence of bridge formation

This dependence was observed to be similar to that of the non-conducting particle bridges. No bridge formation was possible at gaps of 1.5 mm or larger in the frequency range of 20 Hz to 1000 Hz. The threshold stress for bridge formation did not depend upon the gap length whereas the critical stress was gap dependent. This is also shown in Fig 4.12. Of all the introduced particles, copper particles showed the lowest critical stress for steady bridge for the same gap and frequency.

4.7.3 Threshold stress for bridge formation

Either increasing the stress from zero or decreasing from a higher value, a threshold stress could be found for all the frequencies at which the copper particle bridge initiated. In case of these particles the threshold stress was found to be similar to that found for silicon, selenium or particles inherent in the oil. This confirmed that neither particle size nor the nature of the particles had any effect on the threshold stress for bridge formation. This stress increased with frequency and was independent of gap length, below 1.5 mm at all frequencies (see Fig 4.12).
4.7.4 Critical stress for a steady bridge

When the stress was increased above the threshold value the copper particle bridge became thicker and thicker due to the particles in the surrounding volume joining the bridge. Unlike selenium and silicon particles, only a single bridge was found to form in this case. On increasing the stress further a value was reached beyond which the bridge broke up. Also when the stress was reduced again the bridge was found to reform. As in the non-conducting particle case this critical stress for a steady bridge increased with frequency for all gaps and decreased with gap at any frequency (see Fig 4.12). It was found that the critical stress values for copper particles were lower than those of selenium and silicon particles but higher than those found with particles naturally present in the oil filtered through No. 5 and No. 4 filters (see Fig 4.11).

4.7.5 Dependence of bridges on particle size

This dependence could not be studied as only one size of particle was used in the tests. However, a comparison is drawn between the effects of different sizes of non-conducting and conducting particles. As mentioned earlier, the size of the conducting and non-conducting particles had no effect on the threshold stress for bridge formation but the critical stress varied depending on the size of particle and a comparison of results taken at a gap of 200 μm is shown in Fig 4.11.

4.7.6 Gap clearance

The critical stress above which the gap would be clear of copper particles was found to be lower than the corresponding gap clearing stress for samples containing selenium and silicon particles. However, the behaviour of conducting particles is similar to that found for
non-conducting particles and the results are shown in Fig 4.12.

A comparatively higher stress was necessary to clear the gap of copper particles at higher frequencies.

4.7.7 Non-sustained breakdowns

At times when an oscillating copper particle hit an electrode in the maximum stress region, a bubble was observed to have formed. The bubble either dissolved in the neighbourhood of the electrode surface or disappeared into the surrounding liquid. This type of bubble formation very rarely destroyed the bridge, whereas a spurious spark initiated by a bubble almost invariably disrupted the bridge. The bridge would then be dispersed into many oscillatory particles which recombined later to form a new bridge - and the cycle of events would be repeated. Particle bridges sometimes contributed to spurious sparks in the oil and occasionally they led to a fully developed breakdown. A large oscillatory particle in the maximum stress region was more often found to cause a breakdown rather than a bridge formed by particles.

Similar to non-metallic particles, the number of spurious sparks observed in two minutes was noted. At the threshold stress only one or two sparks were noticed at high frequency and there were no sparks at low frequency. When the critical stress for a steady bridge was applied the number of sparks observed in 2 minutes ranged from 3 to 7 for 100 µm gap and 2 to 5 for 200 µm gap. The number decreased to between 1 and 3 when the gap clearing stress was applied for the same period. However, no sparks were observed at a stress of 300 kV/cm, a stress well within the clear gap region. These results may be referred to in tables § and 6. It is clear from these tables that the number of spurious sparks with conducting particles in oil were more than that with non-conducting particles for the same period of time.
Figure 4.12: Effect of copper particles (sizes ≤ 1 μm)
### Copper Particles

**100 µm Gap**

**Table 5**

<table>
<thead>
<tr>
<th>Freq in Hz</th>
<th>kV/cm threshold stress for bridge initiation</th>
<th>No. of spurious sparks in 2 min.</th>
<th>Critical stress for stable bridge kV/cm</th>
<th>No. of sparks</th>
<th>Gap clearing stress kV/cm</th>
<th>No. of sparks in 2 min.</th>
<th>Stress in clear region kV/cm</th>
<th>No. of sparks in 2 min</th>
<th>b.d. stress kV/cm</th>
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<tbody>
<tr>
<td>2</td>
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**200 µm Gap**

**Table 6**

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<th>Freq in Hz</th>
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<th>No. of sparks in 2 mins</th>
<th>Steady bridge critical stress kV/cm</th>
<th>No. of sparks in 2 min</th>
<th>Gap clearing stress kV/cm</th>
<th>No. of sparks in 2 min</th>
<th>Stress in clear region kV/cm</th>
<th>No. of sparks in 2 min</th>
<th>b.d. stress kV/cm</th>
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4.8 **Surface Motion of Dielectric Liquid Under an Alternating Stress**

In the present investigation only a few preliminary observations were made regarding the surface motion of transformer oil and hexane under an alternating stress at variable frequency. When the test cell was not full, but the electrodes were well below (≥ 1 cm) the surface of the liquid, ripples on the surface were noticed at low frequencies. The surface motion was observed above 1 Hz, the lowest frequency which could be applied to the amplifier, and was first found to increase for a fixed stress up to 7.5 Hz and then decrease gradually until about 30 Hz for transformer oil and 50 Hz for hexane the motion could no longer be observed. For a fixed frequency in the region of 1 Hz to 50 Hz, the amplitude of the ripples was found to be directly proportional to the applied stress and for a fixed stress above 7.5 Hz, the amplitude was inversely proportional to the frequency. After the disappearance of the motion only two small depressions in the liquid, one on top of each electrode, were noticed. At very low field no surface motion was observed. It is interesting to note that the periodic motion did not follow the frequency of the applied voltage.

It seems likely that the surface motion of a liquid dielectric is dependent on electric stress and frequency of the applied voltage as well as other parameters such as electrode spacing and diameter, depth of penetration of the electrodes in the liquid and viscosity of the liquid.

4.9 **Breakdown Phenomenon**

4.9.1 **The time interval between breakdowns**

Khambanonda (1950) and Naksiejewski and Tropper (1954) recommended a time interval of 1 minute to 5 minutes between successive breakdowns. Darveniza (1959) found that one-minute interval gave the same breakdown strength as for periods up to 10 minutes. The effect of time interval between breakdowns was also studied by Salvage and Gibbons (1960).
An interval of one minute was suggested by them. Gosling (1960) found that a voltage of about 75% of breakdown value could be maintained between successive shots at one minute intervals with only rare breakdowns. This interval was found to be enough to bring breakdown deposits and particles to a stable state so that breakdowns and conduction could be measured under similar conditions.

In the present investigation with alternating voltage it was found in the preliminary experiments that a minimum of one minute interval between successive breakdowns was needed for obtaining a steady state in the test liquid. The scatter of the breakdown values was found to be more for half a minute interval than that of one minute interval or more - indicating a minimum time interval needed for a stable state of the liquid to be achieved after a breakdown. Therefore a time interval of one minute was adopted between successive breakdowns for all the subsequent tests.

4.9.2 Conditioning of samples (breakdown conditioning)

The cleaning effect mentioned in section 4.5 could probably be termed as stress conditioning although in variable frequency tests it took only a few minutes to clear the gap of particles as against prolonged period of two hours or more for stress conditioning with direct voltage. It was discussed in chapter 2 that stress conditioning was not enough for obtaining reproducible breakdown strength values of a liquid dielectric. Breakdown strengths of two samples of transformer oil, one non-degassed, non-filtered (fig 4.13 and 4.14) and the other degassed, non-filtered (Fig 4.15) were recorded after two hours of stress conditioning. It can be seen from the figures that conditioning shots of about 80 were needed for obtaining reproducible breakdown values, which confirmed the view that stress conditioning was not enough
Fig. 4.13 Conditioning behaviour of transformer oil, non-degassed, non-filtered, but prestressed at 250 kV/cm for 2 hours, gap 5 microns, frequency 1000 Hz.
Fig. 4.14 Conditioning Behaviour of Transformer Oil

(Oil non-degassed, non-filtered, gap 51 microns, frequency 1000 Hz, prestressed for 2 hours at 250 microns gap applying 200 kV/cm)
fig. 4.15  CONDITIONING BEHAVIOUR OF TRANSFORMER OIL

(OIL  DEGASSED, NON-FILTERED, GAP 51 MICRONS, FREQUENCY 1000 HZ,
PRESTRESSED FOR 2 HOURS AT 250 MICRONS GAP APPLYING 300 KV/CM)
(see section 2.1). Therefore before recording the breakdown strength of the transformer oil samples they were subjected to breakdown conditioning.

The number of conditioning shots for obtaining reproducible breakdown values was found to vary with the treatment of the oil sample and the electrode separation. For testing at a gap of 51 microns, 80 shots for non-degassed and non-filtered (see fig 4.14), 80 shots for non-degassed but filtered (see fig 4.16), 50 shots for degassed but non-filtered (see fig 4.15) and 40 shots for degassed and filtered (see fig 4.17) transformer oil was found to be necessary for conditioning. During the conditioning as much as 100% increase in breakdown values was obtained (see fig 4.14). The frequency of occurrence of the breakdown values obtained in the tests with non-degassed, non-filtered (fig 4.14), degassed but non-filtered (fig 4.15); and degassed and filtered transformer oil are shown in figures 4.18, 4.19 and 4.20 respectively. It is clear from the figures that the chances of occurrence of the breakdown values very near the mean value is highest in case of a degassed and filtered oil sample.

4.10 A.C. Breakdown Strength

4.10.1 Breakdowns without diverter unit

Fig 4.21 shows the relationship between breakdown strength and frequency for non-degassed and non-filtered transformer oil tested at various gaps. It can be seen that the frequency appeared to have little effect on breakdown strength of the oil. Degassing of the liquid improved the breakdown strength. A frequency dependence of breakdown strength at gaps of 125 µm and less could be seen from fig 4.22. For the degassed but non-filtered sample. However, no frequency dependence was found for 500 µm gap. Further improvement of the breakdown strength was obtained when the transformer oil was degassed and filtered through a no. 5 filter.
Figure 4.16 Conditioning Behaviour of Transformer Oil

(Oil non-degassed, filtered (No. 4), gap 125 microns, frequency 40 Hz.)
fig. 4.17 CONDITIONING BEHAVIOUR OF TRANSFORMER OIL

(OIL DEGASSED, FILTERED (NO. 4), GAP 51 MICRONS, FREQUENCY 1000 HZ.)
MEAN BREAKDOWN STRESS = 541 KV/CM

**FIG. 4.18 HISTOGRAM OF BREAKDOWN STRESS**

(TRANSFORMER OIL NON-DEGASSED AND NON-FILTERED)

GAP 51 MICRONS, FREQUENCY 1000 Hz
**FIG. 4-19** HISTOGRAM OF BREAKDOWN STRESS

(TRANSFORMER OIL DEGASSED, NON-FILTERED, GAP 51 MICRONS, FREQUENCY 1000 HZ.)
MEAN BREAKDOWN STRESS = 626 KV/CM

FIG. 4.20 HISTOGRAM OF BREAKDOWN STRESS

(TRANSFORMER OIL, DEGASSED, FILTERED, GAP 51 MICRONS, FREQUENCY 1000 HZ.)
Fig. 4.21  Breakdown stress as a function of frequency for transformer oil non-degassed and non-filtered (without diverter unit)
Fig. 4.22  BREAKDOWN STRESS AS A FUNCTION OF FREQUENCY FOR NON-FILTERED BUT DEGASED TRANSFORMER OIL (WITHOUT DIVERTER UNIT)
The results are represented in Fig 4.23. In this case the frequency
dependence of breakdown strength was found to be greater at the smaller
gaps.

A very interesting result was obtained when two samples, one degassed
but non-filtered and the other degassed and filtered, were subjected
to breakdown strength measurements 20 shots each at 40 Hz and 1000 Hz.
alternately. In each case the test gap was 51 µm. When the oil was
not filtered the breakdown values at 40 Hz were found to be higher than
that at 1000 Hz. But filtration of the liquid through a number 4
filter not only improved the general breakdown strength but also 40 Hz
breakdown values in that case were found to be lower than the corresponding
1000 Hz values. These results are represented in Figs 4.24 and 4.25
respectively.

4.10.2 A.C. breakdown strength with diverter unit

So far the tests were carried out without the use of any electronic
circuitry to divert the breakdown energy and minimise the damage both
to the electrodes and the oil when breakdown occurred. Although
diverter units were used by earlier investigators in tests with direct
voltage and 50 Hz alternating voltage, they were unsuitable for variable
frequency alternating voltage tests. Due to high capacitive currents
at frequencies 500 Hz and above, a series resistance of more than
1 MΩ could not be used. However at this stage it was decided to limit
breakdown test gap to 250 µm instead of 500 µm and therefore it was
possible to put a series resistance of 5 MΩ to limit the current to the
cell. Also the second and by far the most important improvement in
the electrical equipment was the design of an electronic circuit to
divert the breakdown energy. This was achieved by short-circuiting the
input to the amplifier with the help of a reed relay, the operation of
which was about 1 milli-second. Details of the diverter unit are
given in chapter 3.
Fig. 4.23  Breakdown stress as a function of frequency for degassed and filtered (No. 5) transformer oil (without diverter unit)
Fig. 4.24  TESTS AT ALTERNATE FREQUENCIES
Fig. 4.25  TESTS AT ALTERNATE FREQUENCIES
The use of this diverter unit and a higher series resistance gave a marked improvement in the breakdown strength particularly at larger gaps at which the damage to the electrodes and the liquid were significant after a few breakdowns. For example, the breakdown strength of a degassed and filtered (No. 4) sample of transformer oil at 250 μm gap was found to be 300 kV/cm before and 558 kV/cm after (shown in Fig 4.32) the use of the electronic diverter unit.

4.10.3 Breakdown Conditioning

About 70 to 80 breakdown shots were necessary for conditioning a sample of degassed and filtered (No. 4) transformer oil when tested at 200 μm gap, 40 Hz (shown in Fig 4.26).

It is clear from the breakdown conditioning so far that 40 to 80 breakdown shots were needed for conditioning of degassed transformer oil under various conditions. Therefore for uniformity in all tests the first 80 shots were regarded as sufficient to condition all the samples.

4.10.4 Time effect on breakdown strength

The time effect on the breakdown values was studied for a degassed and filtered (No. 4) sample at 51 μm gap. The frequency of the applied voltage was 1000 Hz. After 140 breakdown shots the test was abandoned and resumed once again after 17 hours. The average of 60 breakdown shots after conditioning in the first case was 623 kV/cm and the average of 60 breakdowns taken on the next day without further conditioning was 637 kV/cm. This indicates that once the electrodes and the liquid were conditioned no further conditioning was necessary even after waiting several hours. Fig 4.27 explain this effect.
Breakdown conditioning at 0.2 mm gap, 40 Hz
TRANSFORMER OIL DEGASSSED AND FILTERED (NO. 4)
test continued after 17 hours

mean 623 kV/cm

mean 637 kV/cm

fig. 4.27  TIME EFFECT ON BREAKDOWN STRESS
Although it is not directly relevant to this section it is worth noting that three oil samples, degassed and filtered (No. 4) were tested on 17 August 1969 (Fig 4.28), 25 November 1969 (Fig 4.29) and 31 December 1969 (Fig 4.30). The test gap was 51 μm and the frequency of the test voltage was 40 Hz in each case. The average breakdown values were 703 kV/cm, 717 kV/cm and 705 kV/cm respectively. These results show a consistency in sample preparation and test procedures.

4.10.5 Extended tests at fixed frequencies

No effect of frequency of the applied voltage on breakdown strength was found for a gap of 250 μm. The liquid in all the cases was degassed and filtered (No. 4). Figures 4.31, 4.32, and 4.33 illustrate this effect. The average breakdown values at 40 Hz, 200 Hz and 1000 Hz were 550 kV/cm, 565 kV/cm and 535 kV/cm respectively.

An interesting effect of frequency on the breakdown strength was found for 51 μm test for similarly treated oil. In Fig 4.34 each point is the average of 60 breakdown values and represents an individual test carried out at that frequency. The breakdown strength was found to increase from 20 Hz to 300 Hz and then decrease to 1000 Hz to a similar value as that at 20 Hz. The peak value at 300 Hz showed an increase of about 300 kV/cm over 20 Hz and 1000 Hz breakdown values.

4.10.6 Breakdown strength at various frequencies

Each curve reported in the next few sections showing breakdown strength measurement at variable frequency under various conditions represents a complete test run. The breakdown strength at each frequency represented by the corresponding point is an average of 20 breakdown strength values, 10 recorded in tests in which the subsequent test was at a higher and 10 in which it was at a lower frequency.
fig. 4.31 BREAKDOWN OF TRANSFORMER OIL
Breakdown stress, kV (r.m.s.)/cm

Mean Value: 558 kV/cm

Number of breakdowns

Fig. 4.32 Breakdown of Transformer Oil
fig. 4.33  BREAKDOWN OF TRANSFORMER OIL
Fig. 4.34 Breakdown of transformer oil as a function of frequency
(oil degassed, filtered (No. 4), gap 51 microns, frequency 40 Hz)

Each point is the mean of 60 breakdown measurements.
4.11 Effect of Conditioning

In an attempt to find out the influence of conditioning on the variable frequency breakdown strength of transformer oil, the test liquid was subjected to breakdown conditioning at various gaps and tested at different gaps. All the samples were degassed and filtered through a No. 4 filter.

4.11.1 Effect of conditioning at various frequencies

The effect of conditioning at various gaps on the breakdown strength/frequency relationship for a 51 μm gap is shown in Fig 4.35. When the liquid was conditioned at 100 μm, the highest breakdown values were obtained. The frequency dependence was also found to be highest in this case followed by 51 μm and 200 μm conditioning respectively. Conditioning at 51 μm showed the lowest breakdown strength.

4.11.2 Effect of conditioning at a fixed frequency

Figure 4.36 shows the breakdown strength as a function of frequency for various samples conditioned at 200 μm and tested at different gaps. It appears that the frequency dependence of the breakdown strength was less when the liquid was conditioned at a larger gap. Higher breakdown values were obtained for smaller gaps. For a 200 μm gap the breakdown strength was found to increase up to 300 Hz and then decrease.

4.11.3 Effect of conditioning and testing at the same gap

It can be seen from Fig 4.37 that a significant frequency dependence of breakdown strength was obtained when the oil was conditioned and tested at the same gap. This dependence was highest for conditioning and testing at 51 μm. Lowest dependence was found for 200 μm gap, which was the largest test gap in this case. However 100 μm conditioning and test
Fig. 4.35 Breakdown strength as a function of frequency for a 51 microns gap conditioned at different gaps.
fig. 4.36 Breakdown stress as a function of frequency for various gaps conditioned at 200 microns gap.
BREAKDOWN STRENGTH AS A FUNCTION OF FREQUENCY FOR VARIOUS GAPS
SAMPLES CONDITIONED AND TESTED AT SAME GAP

fig. 4.37
showed highest breakdown strength at all frequencies followed by 51 \( \mu m \) and 200 \( \mu m \) respectively.

4.12 Effect of Particles

4.12.1 Effect of inherent particles

The breakdown strength of transformer oil was found to be dependent on the size of impurity particles present in it at the time of testing. Finer filtration showed higher breakdown strength. Figure 4.38 shows that frequency dependence of breakdown strength is related to the nature of filtration of the test liquid. Less dependence was found for finely filtered oil. When the oil was filtered through a No. 5 (1.45 \( \mu m \) porosity) and a Metricel filter (0.45 \( \mu m \) porosity), there was virtually no frequency dependence of breakdown strength. On the other hand frequency dependence was found when the oil was filtered through No. 4 (7.5 \( \mu m \) porosity) and No. 3 (25 \( \mu m \) porosity) filters, showing the effect of particle size on variable frequency breakdowns. All these tests were carried out at 51 \( \mu m \) after conditioning the liquid at the same gap.

4.12.2 Effect of non-conducting particles

The breakdown values were found to be reduced by the introduction of these particles. Almost similar breakdown values were obtained with both silicon and selenium powders. The reduction was more for the smaller gaps than for larger gaps. It was also found that the frequency dependence was negligible in both cases (see Figs 4.39 and 4.40).

4.12.3 Effect of conducting particles

The introduction of conducting copper particles greatly reduced the breakdown strength of the oil when tested at 100 \( \mu m \) gap. Although
**fig. 4.38**  BREAKDOWN STRENGTH AS A FUNCTION OF FREQUENCY FOR NATURALLY PRESENT PARTICLES IN THE OIL, GAP 51 MICRONS
Breakdown Strength as a Function of Frequency for Samples Containing Added Particles, Gap 200 Microns.
the copper particles were small compared to the selenium or silicon particles, similar breakdown values were obtained in all the cases. For instance, when the liquid was filtered through No. 4 filter (7.5 μm porosity) without the introduction of particles, 100 μm testing showed a breakdown strength of over 800 kV/cm reduced to about 500kV/cm for the same gap testing with introduced < 1 μm copper powders, < 45 μm selenium or silicon powders. This indicates that the conducting particles were more effective in lowering the breakdown strength than the non-conducting ones, when due consideration is given to the particle sizes. Tests at 200 μm gaps showed that the particle sizes under investigation were less effective at larger gaps. Without the introduced particles the breakdown strength of a transformer oil sample, degassed and filtered through No. 4 filter, was found to be 550 kV/cm, whereas the breakdown strength with copper or selenium particles was 500 kV/cm and with silicon powders was 430 kV/cm. The frequency dependence in all these cases was negligible.

4.13 Variable Frequency Glow-discharge

In tests with degassed transformer oil, a glow was observed after a few breakdowns at gaps bigger than 200 μm. The glow was visible to the naked eye and a high current (4 - 6 mA) was measured during continuous discharge which was triggered by the breakdown spark. It appeared right across the gap, slightly above the centre line of the electrodes and was accompanied by a continuous bubble formation. When viewed through a microscope it was found that the central part of the glow was green surrounded by deep blue, and it was interesting to find that the definitions of the two colours varied with frequency. At higher frequencies the colours of the glow became more brilliant and well defined (see Fig 4.41). The glow could be maintained for about a minute
Fig 4.41 GLOW DISCHARGES (Gap 500 μm, Applied stress 200 kV/cm)
or so by increasing the output from the variable frequency generator (i.e. the current in the glow) immediately after the process had been triggered by breakdown. It should be noted that the glow did not appear when a direct voltage was applied to the sample under the same conditions.

As soon as the glow started the electrostatic voltmeter across the cell showed a considerable decrease of voltage from the breakdown value to approximately 1 - 2 kV during the glow. Obviously the current was found to increase. By measuring the peak voltage across a resistance in series with the cell (see Fig 4.42) it was found that the current (r.m.s.) during the glow was about 4 mA. A hot wire ammeter, a thermo-couple meter and an Avometer were also used but care had to be taken because strong electric fields can effect the accuracy of the meter readings.

The salient features about the glow could be summarised as follows:-

1. Basic requirements for the glow to appear were - transformer oil, degassed (10^-3 torr), gaps larger than 200 μm and frequency higher than 200 hz.

2. In a fresh sample the glow appeared after a few breakdowns.

3. Continuous bubble formation was noticed during the glow.

4. The higher the frequency, the more brilliant was the colour.

5. The boundaries of the green and blue regions of the glow were found to vary with frequency and current in the glow.

6. There was no glow with degassed transformer oil, after the admixture of oxygen or SF₆ and direct current conditions.

7. The glow was found to move continuously.
fig. 4-42

- 5 MΩ test. cell
- electrostatic voltmeter
- rectifier diode
- 1 μF
- 10 kΩ
- valve voltmeter

20 Hz to 1.5 kHz
30 kV transformer
8. If during the glow a resistance was placed in parallel with the cell it was found that for a test gap of 500 μm the glow would disappear unless the resistance was 2 MΩ or greater.

9. Continuous pumping of the liquid did not effect the glow provided the test cell was full. If the test cell was half-filled a glow could be maintained in the vapour above the liquid.

10. Without the 5 MΩ series resistance in the circuit the glow started at 5 - 6 kV for a gap of 200 μm rather than at 7 - 8 kV with the resistance.

11. The glow could be recovered by opening the switch of the parallel path without further breakdowns.

12. When the oil sample was replaced by a new one without replacing the electrodes, no further breakdown was necessary to initiate the glow, which indicated that it was an electrode effect.
5. DISCUSSION OF RESULTS

5.1 Introduction

While examining the results presented in Section 4 it will be helpful to bear in mind the testing conditions under which they were obtained. Due to limitation of the variable frequency power supply that was available, a small scale testing technique was adopted with a test cell volume of 80 cm$^3$ and electrodes of 5 mm diameter. The effects of both introduced and inherent impurity particles on the prebreakdown and breakdown phenomena were studied.

Unfortunately there is little published literature on these topics, particularly on the prebreakdown phenomena of bridge initiation and the critical stresses for steady bridges and the gap clearance under variable frequency high field conditions. No comparison being available, these aspects will, therefore, have to be judged on their own merit.

The impurity particles may move in a liquid dielectric under the influence of one or more of the following forces:

(1) Gravitation forces always acting vertically downwards for the particles of specific density greater than that of the liquid and upwards for particles having specific density lower than that of the liquid.

(2) When the electric field is applied to the liquid the uncharged particles of higher permittivity than that of the liquid will move into the region of higher stress due to the dielectrophoretic force and particles of lower permittivity will move away from the high stress region.

(3) Charged particles without an ion atmosphere surrounding them will move along field lines due to the coulomb force.

The problem how the suspended particles acquire an electric charge will not be discussed because the information obtained in this work is insufficient for such a study.
Formation of bridges in d.c. and a.c. (50 Hz) fields has been reported by many authors. In this study formation of bridges was observed for fields of variable frequency from 20 Hz to 1000 Hz. For d.c. fields the uncharged particles were considered to be polarized, swept into the region of higher stress, aligned along the field lines thus forming so-called pearl-strings and finally, crossing the gap in a form of a bridge.

There is a good reason to postulate similar process when an a.c. field is applied to a dielectric liquid containing suspended impurities. The dipoles formed change their sign in phase with the frequency of the applied field but always orient themselves in such a way that the positive charge of one dipole is facing the negative charge of the neighbouring dipole. The only difference is that in the case of a.c. fields mean values of dipole moments and effective values of field strength should be considered.

The experimental results in this work indicated that the process of bridge formation in a.c. fields is independent of particle size but depends on the frequency of the applied field as the voltage required to initiate the process increased with the frequency.

It was also found that there was a critical length of the gap in which the bridge could be formed. For gaps greater than the critical size it was impossible to initiate a bridge no matter what value of applied voltage was used.

5.2 Prebreakdown Phenomena

The threshold stress to initiate formation of the bridges was found to be independent of particle size for gaps smaller than the critical gap (see Figures 4.9, 4.11 and 4.12). It was also observed
that the pearl-strings were formed by the tiny particles at very low stresses. No clear dependence of threshold voltage on the gap length was found.

However, a clear dependence of the threshold voltage on the frequency of the applied field was found in all tests. This voltage increased with frequency.

At low frequencies some of the particles were found to oscillate in phase with the frequency of the applied field and hence in the process of oscillation once they came into the maximum stress region also contributed to the bridge formation. On the other hand at higher frequency (above 300 Hz) these particles appeared to be stationary, most probably because the amplitude of oscillations was too small to be noted by visual observation through a microscope with 1:100 magnification. This would confirm Stauff findings that the product of (oscillation amplitude) x (frequency) is constant (1955).

The results obtained in this work are in contradiction to the findings and theoretical considerations presented by Krasny-Ergen (1936) who claimed that formation of pearl-string depends on size of particles and is independent of frequency. On the other hand they are in agreement at least in one aspect (frequency dependence) with the results published by Stauff (1955).

5.2.1 Critical voltage for steady bridges

Visual observations through a microscope also showed that after the bridge was formed at a threshold voltage it remained stationary even when the applied voltage was increased. But, a critical voltage was found to exist, and when a voltage, higher than critical value, was applied it resulted in the destruction of the bridge. For non-conducting particles, whether inherent or admixed in the oil the value of the critical voltage was found to depend on the size of particle.
(As only one type of sample containing conducting particles was tested in this investigation, the effect of conducting particle size cannot be discussed.) The value of the critical stress increased with the increase of particle size as shown in Figure 4.11.

For the same size of particles the critical stress was found to decrease with increased gap setting. The critical stress was also frequency dependent, increasing with frequency, but the dependence was less pronounced than for the threshold stress. These effects are clearly shown in Figures 4.9 and 4.12.

When copper particles of about 0.1 μm diameter were admixed in the oil bridge formation was also observed at the same threshold stress as for non-conducting particles but the critical stress was found to be lower than that for other particles.

Replotting characteristics shown in Figure 4.9 for a fixed value of frequency the critical stress - gap characteristic are obtained. This characteristic indicates that there is a critical gap length for which critical stress and the threshold stress may be of the same value thus indicating that for such a gap and larger gaps bridge formation cannot be achieved. Such a critical gap was reported by Skowronski who found that for spherical electrodes with 0.625 cm radius it was impossible to obtain a bridge for gaps larger than 1 mm. (1967). In this work using electrodes of 5 mm. diameter the critical gap was found to be less than 1 mm, but it was impossible to define an exact value for this critical gap setting.

5.2.2 Gap clearance

At stresses higher than critical the particle bridges could no longer be maintained and a further increase of the stress resulted in clearing the gap from impurity particles as shown in Figures 4.9 and 4.12.
Fig 5.1 Critical and threshold stresses for bridge formation of gap at various frequencies
During the clearing process two phenomena were observed through a microscope with magnification of 100. Some particles detached from the bridge vigorously oscillated from one electrode to the other and doing so moved away from the gap axis assuming new trajectories. Finally they were ejected from the gap. To explain this effect one must assume that these particles left the bridge with some net charge and thus were subject to coulomb forces. Oscillating between two electrodes they were also subject to the centrifugal forces which when sufficiently high may result in ejection of the particle from the gap. This process was postulated by Gosling (1960).

The other phenomenon observed was the formation of pearl-strings at right angles to the axis of the electrodes. After some oscillation perpendicular to the fields the pearl-strings were formed and also ejected from the gap region. This phenomenon could be accounted by invoking the Bjerknes' hydrodynamic forces (1915) and its theory according to which two particles oscillating in phase with the frequency of the applied field repel each other in the direction of the field and attract in the direction perpendicular to their oscillation. If so, up to critical stresses, the Bjerknes' forces were smaller than that of dielectrophoretic force, gravitation and coulomb forces. When the stress was increased and consequently vibration of particles more vigorous, the Bjerknes' forces may become predominant and take part in the process of the destruction of the bridge. It would also explain the relative reduction of critical stress when frequency was increased.

5.2.3 Non-sustained breakdowns

When the particles were concentrated in the region of higher stress between electrodes, irrespective of whether or not bridges were formed, a number of spurious sparks were observed at various gaps and frequencies. The number of sparks in a certain fixed time were observed
to increase with the increase of the frequency of the field and density of impurity content, as shown in Tables 1, 2, 3 and 4. Also, as it would be expected, the number of sparks with conducting particles under identical conditions were found to be greater than with non-conducting particles. Although these sparks more than often did not lead to fully developed breakdowns, if taken into account, would no doubt reduce the estimated breakdown strength of the oil.

5.3 Breakdown Phenomena

5.3.1 Breakdown conditioning of samples

All samples tested for breakdown values were conditioned by a number of breakdowns. This method was adopted because stress conditioned samples still showed some increase in breakdown values for a number of preliminary breakdowns.

It has been found that the breakdown conditioning of the samples did not depend upon the frequency of the applied field as shown in Figures 4.31, 4.32 and 4.33 but depended on the gap setting adopted for conditioning process, as shown in Figure 4.35. When a sample was conditioned at a larger gap and tested at a smaller gap, the breakdown values were usually higher than that obtained when the sample was conditioned and tested for the same gap setting. The explanation for this would appear to be that at the larger gap a greater surface area of the electrodes were exposed for conditioning. Moreover, a greater number of particles in the intervening space between electrodes could be disintegrated and destroyed during the breakdown conditioning.

Conditioning as such may be regarded as the removal of gases from the microcavities of the electrode surfaces and disintegration of particles by sparking. Usually 50-80 breakdown shots were necessary for conditioning. The number of breakdowns required decreased with improved filtration of the liquid i.e. increased purity of the liquid.
However, one exception was found when the samples filtered were through a number 4 sintered glass filter. The breakdown values obtained at 51 μm gap setting were higher for samples conditioned at 100 μm than that conditioned at 200 μm gap. It would appear that the removal by sparking of 7.5 μm size particles (maximum particle size for No. 4 filter) was more effective when conditioning was made at 100 μm gap due to the favourable particle size/gap length ratio, compared to that at larger gap settings.

5.3.2 Breakdown strength at variable frequency a.c. fields

The effects of frequency on the breakdown strength of transformer oil due to the presence of particle impurities have been clearly demonstrated by the experiments illustrated in Figures 4.24 and 4.25. For degassed but not filtered oil the 1000 Hz breakdown values were lower than those for the same sample tested at 40 Hz. On the other hand, when the oil was filtered through a No. 4 sintered glass filter in addition to degassing, the breakdown strength at 1000 Hz was higher than that at 40 Hz.

As it is evident from Figures 4.35, 4.36 and 4.37 the breakdown of transformer oil, degassed and filtered, increased slightly with frequency. Referring to Figure 4.38 it is clear that the frequency dependence of breakdown strength decreases with improved filtration of the liquid. There was almost no frequency dependence observable for samples filtered through a metalicel filter with a porosity of 0.45 μm. It may, therefore, be assumed that if the concentration of particles is low and their size reduced by filtration, they will not affect the breakdown strength of the liquid for frequencies ranging from 20 Hz to 1000 Hz.

The frequency dependence of the breakdown strength was found to decrease for larger gaps. This was observed for inherent particles as well as for added impurities.
Addition of foreign particles to the degassed and filtered test samples gave a reduction of the breakdown values depending on frequency for all frequencies from 20 Hz to 1000 Hz as shown in Figures 4.39 and 4.40. This proves again that frequency dependence of breakdown values depends on purity of tested liquid.

Figure 5.2 shows the results obtained during tests in which the conditioning frequency was the same as the frequency at which the breakdown value was determined. Visual observation of the gap was also carried out during these tests. The gap settings used were 51 µm, 100 µm and 200 µm. Samples were filtered through No. 4 and No. 3 sintered glass filters.

The curve showing the results obtained for a 51 µm gap and oil filtered through No. 4 filter of porosity 7.5 µm shows an increase of breakdown values up to 350 Hz and for higher frequencies a decrease giving the breakdown strength at 1000 Hz nearly equal to that at 40 Hz. This effect was less pronounced for oil filtered through a No. 3 filter at 51 µm gap and was not observable for larger gap settings even when selenium powder was added to the oil. Visual observations revealed that at lower frequencies some particles were present in the gap and oscillated between the electrodes. When frequency was increased, a clearance effect was observed and at 350 Hz the gap appeared free of particles. Further increase of frequency was followed by reappearance of a few particles in the gap.

The results presented in this work agree with those published by other workers. Skanavi in his appraisal of the variable (low) frequency results presented by some authors (1958) concluded that all of them found, for lower range frequencies, the electric strength of commercially pure liquids to increase when the frequency is increased.
Fig. 5.2 Breakdown stress as a function of frequency for various gaps
However, they also reported that the increase in breakdown stress with increasing frequency was greatly reduced as the degree of liquid purification was increased. Toryama (1958) did not find, in purified transformer oil, any significant difference between the magnitude of breakdown stress at 50 Hz and the value found in d.c. tests.

Some investigators have shown (1958) that variation of frequency gives different effects on the breakdown value for different gap settings. For example it was found that for gap settings less than 3 mm between two parallel plates the breakdown values of turpentine oil at higher frequency (32 kHz) was higher than that at 50 Hz and for gap settings greater than 3 mm opposite effects were observed, i.e. the breakdown values at 50 Hz were greater than at higher frequencies. It was impossible to check these findings in the work presented here because of limitations imposed by the variable frequency power supply. In a series of tests up to a gap setting of 0.7 mm it was found that the breakdown stress decreases when the length of the gap is increased for all the frequencies applied from 20 Hz up to 1000 Hz. This is illustrated in Figure 5.3 by curves showing the relationship between breakdown stress and gap setting for different frequencies.

None of the previous investigators who have reported on tests using variable frequency a.c. fields have mentioned the method of conditioning the test samples. The conditioning appears to be one of the most important factors not only regarding the reproducibility of the test results but also the results obtained for different frequencies. In addition, selection of the gap setting for conditioning process is of great importance. Different results could be obtained for the same testing gap when the sample was conditioned at larger gaps.
Fig 5.3 Breakdown stress as a function of gap at various frequencies
6. ANALYSIS OF THE BRIDGE FORMATION PROCESSES

6.1 General Considerations

In the following a study will be made on the behaviour of suspended impurities in dielectric liquids subjected to high electrical stresses. Motion of the particles will be considered as an effect of different forces acting upon them. Attention will be paid especially to their trajectories along which they will move, the definition of so-called sweeping region of the field produced by two metal spherical electrodes and the definition of high field region where the particles will flocculate and become elements in the process of pearl-string formation. Also an attempt will be made to explain the process of bridge formation in a.c. fields, by non-conducting and conducting particles in the region of high stress between two electrodes.

In both parts of this study the calculations will be limited to spherical particles under an assumption that for other shapes of particles essentially the same results would be obtained. The suspended particles will be considered as induced dipoles and acted upon by dielectrophoretic force, gravitation force and subject to viscous drag when moving in viscous liquid. Additional coulomb force will be considered in case of charged particles.

The analysis of formation of pearl-string in d.c. fields is given in Appendix 2. Formation of pearl-strings and bridges in a.c. fields is analysed in more detail in the second part of this chapter and based on the same principles as in d.c. field analysis with the only difference that for a.c. fields a mean dipole moment and r.m.s. values of field strength will be considered. The same assumption is made in the study of motion of particles in a.c. fields. The analysis showed that assuming a relaxation time of the ion atmosphere of the polarized particle it is possible to explain the dependence of threshold
voltage for initiation of pearl-string formation on the frequency of the applied field found in the experimental work.

6.2 Motion of non-conducting Particles in non-uniform Electrical Fields

6.2.1 Introduction

Non-conducting and conducting particles suspended in a dielectric liquid will move under the action of an electric field and flocculate in the region of higher stress. When the concentration of the impurities becomes sufficiently high pearl-strings may be formed which can cross the gap in the form of a bridge.

The phenomena associated with bridge formation have been studied for a long time but still many factors governing the process of particles flocculation and formation of pearl-strings are not well understood. In the following an attempt will be made not only to define the speed of moving particles and the trajectories along which the particles move into the region of higher stress, but also to define so-called "sweeping region" from which the particles may contribute to the formation of a bridge.

For testing of dielectric strength of insulating liquids a vessel must be used in which a system of metal electrodes is set with a certain gap spacing. It is important theoretically as well as from a practical point of view to find out the effect of the dimensions of the vessel (volume of the liquid tested) on the results obtained. In other words it is of interest to find out the region in the liquid from which the suspended particles could participate in the process of bridge formation. The time required for particles to migrate into the gap region would reveal the effect of time and give information regarding the test procedure to be adopted.
A typical system of electrodes used for testing of dielectric liquids, which also has been used in the work presented here is shown in Fig 6.1. It consists of two metal spheres separated by a fixed gap setting and immersed in insulating liquid.

Examining the conditions shown in Fig 6.1 it is easy to see that there are two distinct regions in the liquid - one from which the suspended particles, in stationary liquid, have a chance of moving due to the action of electrical and gravitation fields to migrate to the region of higher stress and become elements in the process of pearl-string formation and the other from which the suspended particles will never reach the gap region and therefore will not contribute to the formation of the bridge.

The electric field produced by two metal spheres separated by a certain gap setting is non-uniform. The larger the gap setting the more non-uniform the field results. The behaviour of suspended particles must therefore be studied under the action of non-uniform field. To simplify the calculations the actual field produced by the two metal spheres will be represented by the field produced by two point image charges.

The liquid is assumed to be stationary and this assumption is justified by the fact that the observed threshold stresses for initiation of the bridge formation never exceeded 60 kV/cm and higher stresses were required to induce turbulent motion of the liquid.

Also, it will be assumed that in the liquid the particles are uniformly distributed and have dimensions small when compared with the dimensions of the metal spheres and the gap setting. Small dimensions of the suspended particles result that their motion due to gravitation is slow but not negligible. After application of electrical field the particles are under the action of two fields - electrical and gravitation field. When they move in a viscous liquid they will be subjected to viscous drag and its effect must also be taken into account.
FIG. 6-1

SWEEPING REGION
of sphere–sphere spark gap in liquid
Fig 6.2 Maximum voltage gradient, equal spheres (after Carter and Loh).
6.2.2 Electrical field between two spherical metal electrodes

The problem of calculating the electric field produced by two metal spheres to which a voltage is applied may be solved by an infinite series of image point charges. The mathematical treatment of this method was given by J. H. Jeans (1951). The process of image point charges is in fact non-terminating but the successive images diminish so that a finite number of terms is giving sufficient approximation to the field.

G. W. Carter and S. C. Loh (1959) presented their results for unsymmetrical gap (one electrode at zero potential) and symmetrical gap (one electrode at \( \frac{V}{2} \) and the other at \( -\frac{V}{2} \) in the form of graphs which will be used in this work to determine the position of image point charges replacing the sphere electrodes. The graph presenting for two identical spheres the ratio of maximum stress to average stress in terms of the ratio sphere spacing to sphere diameter is shown in Fig 6.2. Therefore, with reasonable accuracy, the actual field produced by two metal spheres can be represented by two point image charges the magnitude and separation of which can easily be determined with the help of curves shown in Fig 6.2.

![Diagram of two spherical metal electrodes with image charges](image_url)
The potential at a point A (see Fig 6.3) can be defined by the equation
\[ V_p = \frac{q}{4\pi\epsilon_d} \left( \frac{1}{r^+} - \frac{1}{r^-} \right) \]
and the equipotential surfaces coinciding with the front part of the actual surfaces of the electrode can be defined by the functions \( f^+ \) and \( f^- \) of the form:
\[ f = \frac{1}{|x - d|} - \frac{1}{|x + d|} \]
for two identical metal spheres:
\[ f^+ = - f^- \]
If the field is produced by two surfaces represented by the equations \( f^+ \) and \( f^- \) then the image charge can be calculated from the equation:
\[ q = \frac{\epsilon_d V}{f^+ - f^-} \]
where \( V \) is the voltage applied to the two spheres. For identical electrodes
\[ q = \frac{\epsilon_d V}{2f} \]
Some calculations of equipotential surface functions are shown in Appendix 3.

The calculations of electric field intensity will be limited to that existing in the plane of symmetry of the system as shown in Fig 6.4. They are also less accurate as they do not take into account the effect of the supports of the electrodes which is more pronounced when planes considered are closer to the position of point charges.
Electric field intensity at a point A lying on the plane of symmetry of the system is assumed to be equivalent to that produced by two point image charges +q and -q situated at a distance +d and -d from the plane of symmetry. The magnitude of the charges which depends on the applied voltage V, the diameter of the electrodes and the gap setting can be determined with the help of the graphs given by Carter and Loh.

For the plane of symmetry

\[ [E^+_{(A)}] = [E^-_{(A)}] \]

and

\[ [E_{(A)}] = 2[E^+_{(A)}] \cos \phi \]

and is at right angles to the plane.

\[ E^+_{(A)} = \frac{q}{4\pi \varepsilon_d} \frac{1}{(x^2 + d^2)} \]

and

\[ \cos \phi = \frac{d}{\sqrt{(x^2 + d^2)}} \]
so the electric field intensity at point A is

\[ E_A = \frac{2q}{4\pi \varepsilon_d} \frac{d}{(r^2 + d^2)^{3/2}} \]

6.2.3 Polarization of non-conducting particle suspended in the liquid

If suspended, non-conducting impurity has permittivity different from that of the liquid it will be polarized due to the action of electric field and become an induced dipole having a dipole moment proportional to the electric field intensity \( E \). Assuming that suspended particles are of spherical shape of radius "a" and permittivity \( \varepsilon_a \) to be in suspension in the dielectric liquid of permittivity \( \varepsilon_d \), then the dipole moment of the polarized particle is:

\[ p = \frac{(\varepsilon_a - \varepsilon_d)}{2\varepsilon_d + \varepsilon_a} a^3 E \left(\frac{4\pi \varepsilon_d}{d}\right) \]

(The expression has been deduced using uniqueness theorem as shown in Appendix 1.)

where: \( a \) = radius of spherical particle,
\( E \) = electric field intensity at the point where the particle is located.

6.2.4 Force acting upon polarized particle in non-uniform field

In a non-uniform field the force acting upon a polarized particle is directed towards the region of higher stress if the permittivity of the particle material is greater than that of the liquid (\( \varepsilon_a > \varepsilon_d \)) and has opposite direction in case when the permittivity of the suspended impurity has lower value than that of the liquid (\( \varepsilon_a < \varepsilon_d \)) (see Fig 6.5). In case of gas bubbles, however, contamination at the gas-liquid interface may make the overall permittivity greater than that of the liquid and the contaminated gas bubble may drift also towards the region of higher stress.
Fig 6.5 Polarization of spherical particles with permittivity (A) $\varepsilon_a > \varepsilon_d$ and (B) $\varepsilon_a < \varepsilon_d$ where $\varepsilon_a$ and $\varepsilon_d$ are the permittivities of the spherical particle and the oil respectively (after Kok).

Fig 6.6 Speed of the particle as a function of $z$ ($z = \frac{|r|}{d}$) (after Skowronski).
The transverse component of the force acting upon the polarized particle in non-uniform field, such as produced by two spherical electrodes can be calculated from the expression:

\[ F = p \cdot \text{grad} \ E \]

The force acting upon the dipole "p" is therefore

\[ F(A) = \frac{(\varepsilon_a - \varepsilon_d)}{2\varepsilon_a + \varepsilon_d} a^3 E(A) \text{grad} E(A) \left(4\pi\varepsilon_d\right) \]

or

\[ F(A) = \frac{(\varepsilon_a - \varepsilon_d)}{2\varepsilon_a + \varepsilon_d} a^3 \frac{1}{2} \pi \text{grad} \left[\varepsilon_d^2 \right] \left(4\pi\varepsilon_d\right) \]

Now taking \( E(A) \) as:

\[ E(A) = 2 \frac{q}{4\pi\varepsilon_d} \frac{d}{(d^2 + r^2)^{3/2}} \]

\[ \frac{1}{2} \text{grad} E^2(A) = \frac{12 q^2 d^2 r}{16\pi^2 \varepsilon_d^2 (d^2 + r^2)^4} \]

and the force acting upon polarized particle is:

\[ F(A) = \frac{12 (\varepsilon_a - \varepsilon_d) a^3 q^2 d^2 r}{16\pi^2 \varepsilon_d (2\varepsilon_d + \varepsilon_a) (d^2 + r^2)^4} i_r \]

where:

\( i_r \) is the unit vector indicating the direction of force.

The expression for force may be someway simplified taking the ratio of magnitudes of \( d \) and \( r \):

\[ \frac{|r|}{d} = z \]

\[ F(A) = \frac{12 (\varepsilon_a - \varepsilon_d) a^3 q^2}{16\pi^2 \varepsilon_d (2\varepsilon_d + \varepsilon_a) d^5} \frac{z}{(i + z^2)^4} i_r \]
or
\[
F(A) = -\frac{12 (\varepsilon_a - \varepsilon_d) a^3 q^2}{16\pi^2 \varepsilon_d (2\varepsilon_d + \varepsilon_a) d^5} f(z) i_r
\]

where:
\[
f(z) = \frac{z}{(1 + z^2)^4}
\]

and
\(i_r\) unit vector indicating the direction of force.

For fixed gap setting and constant applied voltage the value of the force will depend on the value of the function \(f(z)\) which has a maximum for \(z = \sqrt{\frac{r}{r}} = 0.378\) as shown in Fig 6.6.

Replacing now the charge "q" in the expression for force by applied voltage across two electrodes
\[
q = \frac{4\pi \varepsilon_d}{2\varepsilon} V
\]

the expression for force in terms of applied voltage has the form:
\[
F(A) = -\frac{12\varepsilon_d (\varepsilon_a - \varepsilon_d) a^3 V^2}{(2\varepsilon_d + \varepsilon_a)(2\varepsilon)^2 d^5} f(z) i_r
\]

6.2.5 Force due to gravitation

If there is a difference between specific densities of the liquid and the material of the suspended particles then in addition to the electric force acting upon the polarized particle there will be a gravitation force of magnitude:
\[
H(A) = g \frac{a^3}{3} (\gamma_a - \gamma_d) \frac{q}{g}
\]

where:
- \(g\) - acceleration due to gravity,
- \(a\) - radius of the spherical particle,
- \(\gamma_a\) - density of the material of the particle,
- \(\gamma_d\) - density of the liquid,
- \(i_g\) - unit vector always vertical and directed downwards.
6.2.6 **Viscous drag**

A moving particle in a viscous liquid is subjected to a viscous resistance or drag which for slow uniform velocities according to Stokes can be calculated using formula:

\[ F(A) = -6\pi\eta a \, v(A) \]

where

- \( \eta \) - viscosity of the liquid,
- \( a \) - radius of the moving particle,
- \( v(A) \) - velocity of the particle at a point \( A \).

6.2.7 **Balance of forces**

Neglecting inertia of the particle and the liquid, the balance of forces may be established for uniform motion. Large frictional forces accompanied with motion of small particles in a viscous liquid justify this assumption.

\[ F(A) + H(A) + F(A) = 0. \]

6.2.8 **Velocity of non-conducting particles**

Substituting expressions for individual forces:

\[ -6\pi\eta a \, v(A) + g \frac{4\pi}{3} a^3 (\gamma_a - \gamma_d) \frac{i}{g} \frac{12\varepsilon_d (\varepsilon_a - \varepsilon_d) a^2 \, v^2}{(6\eta \pi (2\varepsilon_d + \varepsilon_a) (2f)^2 d^5 f(z) i_r} = 0 \]

from which the velocity of the particle is:

\[ v(A) = \frac{4\pi}{18\pi\eta} \frac{a^2 \, g (\gamma_a - \gamma_d)}{g} \frac{i}{g} \frac{12\varepsilon_d (\varepsilon_a - \varepsilon_d) v^2 a^2}{\pi g (\gamma_a - \gamma_d) (2\varepsilon_d + \varepsilon_a) (2f)^2 d^5 f(z) i_r} \]

\[ v(A) = \frac{2a^2 (\gamma_a - \gamma_d)}{g} \frac{i}{g} \frac{g \varepsilon_d (\varepsilon_a - \varepsilon_d) v^2}{\pi g (\gamma_a - \gamma_d) (2\varepsilon_d + \varepsilon_a) (2f)^2 d^5 f(z) i_r} \]
Now taking 
\[ h = \frac{2 a^2 (\gamma_a - \gamma_d) g}{9n} \]
as the speed due to gravitation only, and defining the material coefficient as 
\[ \omega = \frac{3 (\varepsilon_a - \varepsilon_d) \gamma_d}{(2\varepsilon_d + \varepsilon_a)(\gamma_a - \gamma_d)} \]
the expression for speed has the form:
\[
V(A) = h \left( \frac{i g - \omega \frac{3\varepsilon_d v^2}{\gamma_d g \pi (2f)^2 d^5} f(z) r}{i} \right)
\]
or
\[
V(A) = h i g - c h f(z) i r
\]
where:
\[ c = \omega \frac{3\varepsilon_d v^2}{\gamma_d g \pi (2f)^2 d^5} \]

When the applied voltage is an alternating voltage the speed equation gives approximately the mean value of the speed for the RMS value of the electric field intensity.

6.2.9 Motion of charged particles

If a spherical particle situated at point A in electric field of a potential \( V_A \) and has a charge Q then another force acting upon such a particle will appear the magnitude of which can be calculated from the expression:
\[ S(A) = Q \cdot E(A) \]
and its direction is tangent to the field lines. The equation for balance of forces will then be:
\[ P(A) + H(A) + F(A) + S(A) = 0 \]
and the component of the resultant speed vector due to the force acting upon charged particles will have the form:

$$\frac{Q}{6\pi\eta a} E(A)$$

so the complete expression for speed will be:

$$v(A) = \frac{a^2}{\eta} \left[ \frac{2}{\beta} (\gamma_a - \gamma_c) g \frac{i g}{g} + \frac{e_d}{12\pi} \frac{(e_a - e_d)}{(2e_d + e_a)} v (E(A))^2 \right]$$

$$+ \frac{Q}{6\pi\eta a} E(A)$$

6.3 Analysis of the Speed Equation

Analysis of speed equation gives an opportunity to define the so-called "sweeping region" from which particles migrate to the space between electrodes by establishing trajectories of the moving particles, and also the boundaries of the space between electrodes where particles flocculate providing condition for formation of pearl-strings.

For this purpose the vector representing the speed of the particle will be resolved into two components - "m" a radial component along the line connecting the centre of the moving particle and the midpoint between two electrodes, and the component "n" at the right angle to "m" as shown in Fig 6.7. Denoting the angle between the radial component "m" and the vertical line passing through the centre of the particle by $\phi$ we obtain the values of "m" and "n".

$$m = v(Ar) = h \cos\phi - c h f(z)$$

and

$$n = v(At) = h \sin\phi$$
The sweeping region will then be defined by the trajectories of these particles which are not swept by the field into the space between two electrodes and not removed by gravitation force, but remain stationary at the so called bottom of the sweeping region.

For particles of specific density higher than that of the liquid i.e. \((\gamma_a - \gamma_d) > 0\) the point on the vertical axis of the system defining the space in which the particles will flocculate will lie below the axis of the two electrodes and for particles having specific density lower than that of the liquid i.e., \((\gamma_a - \gamma_d) < 0\) above the axis of the electrodes as shown in Fig 6.8.
These two points which could be called as the bottoms of the sweeping region can be easily established from the condition that for these two points $\phi = 0$ and $\phi = 180^\circ$, so if for (a) and (b)

$$h - h c f(z) = 0$$

the particles will remain in suspension not being swept by the field into the space between electrodes or removed by the action of the gravitation. This condition will be satisfied when

$$c f(z) = 1$$

or

$$c = \frac{1}{f(z)}$$
where:

\[ f(z) = \frac{z}{(1 + z^2)^4} \]

and can be determined from the graph given in Fig 6.6. The boundaries of the space in which the particles will be gathered are determined by the maximum speed due to the electric field action. From the graph representing \( f(z) \) as a function of \( z \) the maximum speed due to the electric field action appears when

\[ z_0 = \frac{1}{\sqrt{7}} = 0.378 \]

and decreases to zero very rapidly, so the time for the particles to reach the axis of the electrodes becomes very long. Also the action of the electric field in this region changes its character. Therefore, assuming that the region in which the particles are gathered by the action of electric field could be defined as a cylinder of a radius \( r_0 \) and the length approximately equal to the gap length, the volume of the region can be calculated using formula:

\[ V_0 = \frac{\pi z_0^2 \cdot g}{\rho} \]

and \( r_0 \) calculated from

\[ r_0 = z_0 \cdot d \]

where "d" is the distance of point image charge from the centre of the system. The critical value for the "c" coefficient is therefore:

\[ c_{cr} = \frac{1}{f(z_0)} = 4.5 \]

as the value of the function \( f(z) = 0.222 \) for \( z_0 = 0.378 \).

For values of \( |c| < 4.5 \) the region in the plane of symmetry can be divided into two parts:
(a) a region from which suspended impurities are drawn into and gathered in space between two electrodes and which could be defined as the sweeping region of two spherical electrodes,

and

(b) the region from which suspended particles will never reach the space between two electrodes.

For values of $|c| > 4.5$ sweeping region cannot be produced and all particles will flow through the gap not being trapped in the space between electrodes.

The trajectories of the moving particles do not depend on the diameter of the particles but on the material coefficient $\omega$ and the coefficient $c$, the value of which depends on the applied voltage and the geometry of the spark gap, i.e., the diameter of the spherical electrodes and the setting of the gap. Fig 6.9 trajectories of the particles are shown for a spark gap having two metal spheres each of 0.625 cm radius and gap setting of 0.3 cm after Skowronski (1962).

Critical value of coefficient $c$ can be determined experimentally, for low grade oils, by observation of the gap in which a separation of impurities takes place after application of voltage. Denoting the distance of the separation line from the axis of the electrodes by $r$

$$ z = \frac{x}{d} $$

and

$$ c = \frac{1}{f(z)} $$

where the value of $f(z)$ can be found from the graph given in Fig 6.6.

6.4 Volume of the Sweeping Region and Flocculation Coefficient

Calculations carried out for two spherical electrodes are approximate not only because of representing the actual field by the field produced
FIG. 6.9 Boundary trajectories defining sweeping regions for different "C" coefficients (after Skowroński)

\[ C = \frac{\omega 3 d V^2}{\pi g f d^2 d^5} \]

FIG. 6.10
by two image point charges but also due to the fact that the effect of shanks supporting the two electrodes was neglected. This effect becomes more pronounced when the planes considered approach the supports. (The calculations are shown in Appendix 3). Therefore, for calculation of the volume of the sweeping region further assumptions must be made, as shown in Fig 6.10.

The boundaries of the sweeping region above the centre line of the electrodes is determined by two vertical planes passing through the points where the two image charges are located and two vertical planes a distance \( r \) from the centre line. Below the centre line the sweeping region is given by a half-cylinder of the radius "r" and length 2d.

The volume of half-cylinder of the radius \( r \) and length 2d is:

\[
2\pi r^2 \frac{d}{2}
\]

and the volume of the remaining part is approximately:

\[
4 r d h_d
\]

so the total volume of the sweeping region is:

\[
V_s = 2d(2rh_d + \frac{r^2\pi}{2}) \text{ cm}^3
\]

The volume of the space between electrodes into which the particles are drawn is that of the cylinder of a radius \( r_0 \) and the length equal to the gap length.

\[
V_o = r_0^2\pi l_g
\]

and the "floculation factor" can be defined as the ratio \( V_s/V_o \) if all the particles are swept from the sweeping region into the space between two electrodes. Thus,

\[
\frac{V_s}{V_o} = \frac{2d(2rh_d + \frac{r^2\pi}{2})}{r_0^2\pi l_g}
\]
Some calculations on flocculation coefficient are shown in Appendix 3.

6.5 Sweeping Time

The time required for the particle to travel from a point \( z_1 \) to \( z_2 \) (\( z_1 > z_2 \)) when particle moves towards electrodes can be estimated in the following way:

\[
v(r) = \frac{dr}{dt} = hc\left\{\frac{1}{c} - f(z)\right\}
\]

where

\[
z = \frac{r}{d}, \quad \frac{dz}{dt} = \left(\frac{1}{d}\right)\frac{dr}{dt}
\]

and so,

\[
d\left(\frac{dz}{dt}\right) = hc\left\{\frac{1}{c} - f(z)\right\}
\]

and substituting

\[
t = \frac{d}{hc} \int_{z_1}^{z_2} \frac{dz}{\left\{\frac{1}{c} - f(z)\right\}}
\]

where

\[
f(z) = \frac{z}{(1 + z^2)^4}
\]

The expression for time needed for particle to reach space between electrodes indicates that the time may be infinitely long for those particles which are moving along the trajectories forming the boundaries of the sweeping region. For other particles inside the sweeping region the time needed to reach the boundary of the space between the electrodes (where \( f(z) \) reaches its maximum) may be calculated from the expression:

\[
\tau_0 = \frac{d}{ch} \int_{z}^{z_0} \frac{dz}{f(z) - \frac{1}{c}}
\]
6.6 Formation of pearl strings and bridges in alternating fields

In the following an attempt will be made to calculate the attraction potential of two dipoles in an alternating field. For simplicity charged, particles, surrounded by ion atmosphere which neutralises completely the charge of the particle in the absence of the field, will be considered.

The same basic concept, as in d.c. fields (see Appendix 2), will be adhered to, in that when an alternating field is applied to the liquid containing suspended particles, the ion atmospheres of the particles will be polarized.

The polarization will change with frequency so that in the case of two neighbouring dipoles always a positively charged particle will face a negatively charged ion atmosphere or vice versa.

The resultant potential, therefore, can be calculated in a simple way as that of two dipoles in line arranged successively, as shown below.

The attraction energy between the dipoles is given by

$$U = -\frac{2 \cdot (qx)^2}{4\pi\varepsilon_0 r^3} = \frac{p^2}{2\pi\varepsilon_d r^3}$$  \hspace{1cm} (1)

where

- \(q\) = charge
- \(x\) = distance between the charges of the dipole.
- \(r\) = distance between the centres of two dipoles.
- \(p\) = dipole moment
- \(\varepsilon_d\) = permittivity of the liquid

The dipole moment is not constant but changes in phase with the applied field. It will be assumed that to estimate the potential energy the time average value of the dipole moments will be sufficiently accurate.
The polarization of the ion atmosphere may have some effect only when it is capable to exist for a definite time and does not collapse in very short time due to Brownian movement. When the particle moves in one direction (say positive), its ion atmosphere moves in opposite direction (negative) and its effect after time "t" will drop down by the amount $e^{-t/\tau}$ so that for the time $t = \tau$ (relaxation time), the effect will drop $e$-times. To find the time average of this effect it is necessary to integrate all effects and divide it by the integral of time function.

In the case under consideration the dipoles undergo periodic changes, therefore the studied effects are also periodic and the time function representing them must include a factor which takes this periodicity into account. Time constant "$\tau$" can be defined as the time required for the dipole moment of the polarized particles to revert practically to a random distribution after the removal of the field.

The intensity of the applied alternating field is represented by a sine function as

$$E_t = E_0 \sin \omega t$$

where $E_t$ is the instantaneous value of the applied field, and $E_0$ is maximum value of the applied field.

This field induces an alternating dipole moment "$p$" which acts in the direction of the field

$$p = q \cdot x$$

Assuming the velocity of the ion atmosphere with respect to the moving particle as

$$v_x = v_{ox} \cos \omega t$$  \hspace{1cm} (2)
the expression for the distance between the centre of the ion atmosphere and the centre of the particle will be

\[ x = \int v_x \, dt = \frac{v_{ox}}{\omega} \sin \omega t \]  \hspace{1cm} (3)

and the time

\[ t = \frac{1}{\omega} \sin^{-1} \frac{x_0}{v_{ox}} \]  \hspace{1cm} (4)

To calculate the average value of the dipole moment the following expression will be used applying Boltzmann's theorem. Let us assume that the distribution function of the dipole moments in an altering electric field is

\[ f = p \, e^{-j \omega t} \, e^{-t/\tau} \]  \hspace{1cm} (5)

where \( p \) is the dipole moment

and \( \tau \) is the "relaxation time, as defined before.

Therefore, the average value of the dipole moment will be given by

\[ p_{\text{av}} = \frac{\int_0^\infty p \, e^{-j \omega t} \, e^{-t/\tau} \, dx}{\int_0^\infty e^{-j \omega t} \, e^{-t/\tau} \, dx} \]  \hspace{1cm} (6)

where \( p = qx \)

and \( x \) is a function of time given by equation (3).

So,

\[ p_{\text{av}} = \frac{\int_0^\infty qx \, e^{-j \omega t} \, e^{-t/\tau} \, dx}{\int_0^\infty e^{-j \omega t} \, e^{-t/\tau} \, dx} \]

\[ = \frac{\int_0^\infty qx \, e^{-t(j \omega + 1/\tau)} \, dx}{\int_0^\infty e^{-t(j \omega + 1/\tau)} \, dx} \]  \hspace{1cm} (7)

where

\[ t = \frac{1}{\omega} \sin^{-1} \frac{x_0}{v_{ox}} \]
For integration a linear relationship between $x$ and $t$ can be obtained using average value of the speed $v_x$

$$v_{ox} = \frac{2}{\pi} v_{ox}$$  \hspace{1cm} (8)

and assuming that

$$x = v_{ox} t$$

from which

$$t = \frac{x}{v_{ox}}$$  \hspace{1cm} (9)

Substituting so calculated value of $t$ into equation (7) we get

$$p_{av} = \int_{0}^{\infty} q x e^{-ax} \frac{e^{-x(v_{ox}(j\omega + \frac{1}{\tau}))}}{e^{-x(v_{ox}(j\omega + \frac{1}{\tau}))}} dx$$  \hspace{1cm} (10)

Putting $a = (j\omega + \frac{1}{\tau})$ \hspace{.5cm} $\frac{1}{v_{ox}}$

We get from (10)

$$p_{av} = \frac{\int_{0}^{\infty} q x e^{-ax} dx}{\int_{0}^{\infty} e^{-ax} dx}$$

$$= \frac{q \frac{1}{a^2} [e^{-ax}]_{0}^{\infty}}{\frac{1}{a} [e^{-ax}]_{0}^{\infty}}$$

$$= \frac{q/a^2}{1/a} = \frac{q}{a} = \frac{q v_{ox}}{j\omega + 1/\tau}$$  \hspace{1cm} (11)

Rationalizing (11), we get

$$p_{av} = \frac{q v_{ox} (\frac{1}{\tau} - j\omega)}{(\frac{1}{\tau})^2 + \omega^2}$$
\[
p_{av} = q \frac{V_{ox} \left( \frac{1}{\tau^2} + \omega \right)^{\frac{1}{2}} e^{-j\alpha}}{\left( \frac{1}{\tau^2} + \omega \right)^{\frac{1}{2}}}
\]

\[
= \frac{q V_{ox} e^{-j\alpha}}{\left( \frac{1}{\tau^2} + \omega \right)^{\frac{1}{2}}}
\]

\[
= \frac{q r V_{ox} e^{-j\alpha}}{(1 + \omega^2 \tau^2)^{\frac{1}{2}}}
\]

(12)

where \( \tan \alpha = -\omega \tau \).

The expression for alternating dipole can be obtained by multiplying the expression (12) by \( e^{j\omega t} \), and replacing \( V_{ox} \) by \( v_{ox} \).

\[
P_t = \frac{q r V_{ox} e^{-j\alpha} e^{j\omega t}}{(1 + \omega^2 \tau^2)^{\frac{1}{2}}}
\]

\[
= \frac{q r V_{ox} e^{j(\omega t - \alpha)}}{(1 + \omega^2 \tau^2)^{\frac{1}{2}}}
\]

(13)

where \( \alpha \) is the phase angle between the field intensity and polarization accompanied by energy absorption.

The energy of two dipoles in line as shown in Fig 6.11 is therefore

\[
U = 2 \left( \frac{-p^2}{4\pi \varepsilon_0 r^3} \right) \quad \text{From expression (1)}
\]

\[
= \frac{-2 q^2 \tau^2 v_{ox}^2 e^{j2(\omega t - \alpha)}}{4\pi \varepsilon_0 r^3 (1 + \omega^2 \tau^2)}
\]

(14)

Fig 6.11
The real part of (14) is

\[ U_r = -\frac{q^2 \tau^2 \nu_{ox}^2 \cos^2 (\omega t - \alpha)}{2\pi\varepsilon_0 r^3 (1 + \omega^2 \tau^2)} \]

For cyclic processes the time average value of \( \cos^2 (\omega t - \alpha) = \frac{1}{2} \), therefore the time average value for energy is

\[ U_{av} = -\frac{q^2 \tau^2 \nu_{ox}^2}{4\pi\varepsilon_0 r^3 (1 + \omega^2 \tau^2)} \]  

(15)

Now assuming that

\[ \nu_{ox} = \mu_o E_0, \]

where \( \mu_o \) is the mobility of the ion atmosphere.

The expression for energy, therefore, may be written as

\[ U_{av} = -\frac{q^2 \tau^2 \mu_o^2 E_0^2}{4\pi\varepsilon_d r^3 (1 + \omega^2 \tau^2)} \]

\[ = -\frac{q^2 \tau^2 \mu_o^2}{4\pi\varepsilon_d r^3} \cdot \frac{E_0^2}{1 + \omega^2 \tau^2} \]

\[ \frac{u_{av}}{\mu_o^2} = -\frac{q^2 \mu_o^2 (E_{RMS} \sqrt{2})^2 \tau^2}{4\pi\varepsilon_d r^3 (1 + \omega^2 \tau^2)} \]

\[ = -\frac{q^2 \mu_o^2 E^2}{2\pi\varepsilon_d r^3} \cdot \frac{\tau^2}{(1 + \omega^2 \tau^2)} \]  

(16)

for d.c. field \( \omega = 0 \) so

\[ U_{av}^{dc} = -\frac{q^2 \mu_o^2 E_{dc}^2}{2\pi\varepsilon_d r^3} \cdot \tau^2 \]

or \( U_{av}^{dc} = -K \tau^2 \)
where \( K = \frac{q^2 \mu_0^2}{2\pi \varepsilon_0^2} E_{dc}^2 \)

so for a.c. fields

\[
U_{av} = -K \frac{\tau^2}{(1 + \omega^2 \tau^2)}
\]

(17)

It is interesting to note that for \( \omega = \frac{1}{\tau} \), the energy is half of that for d.c. field of the same intensity (see Fig 6.12).

To compare the threshold stress values obtained in experimental work the average energy associated with bridge formation was plotted against frequency (see Fig 6.12) based on expression for the energy

\[
U_{av} = - \frac{A \tau^2 E^2}{1 + \omega^2 \tau^2}
\]

where \( E \) is the r.m.s. value of the stress.

Approximate values of the time constants of particles of various sizes were given by Stauff (1955), few of which are listed below.

\[ \tau = 1.67 \times 10^{-4} \text{ seconds for particles of diameter 0.63 \( \mu \text{m} \).} \]

\[ \tau = 2.6 \times 10^{-4} \text{ seconds for particles of diameter 0.83 \( \mu \text{m} \).} \]

\[ \tau = 4.5 \times 10^{-4} \text{ seconds for particles of diameter 1.00 \( \mu \text{m} \).} \]

\[ \tau = 7.8 \times 10^{-4} \text{ seconds for particles of diameter 1.3 \( \mu \text{m} \).} \]

Considering particles of 1.3 \( \mu \text{m} \) size, which corresponds to No. 5 sintered glass filter, the following results were obtained

\[ \omega = \frac{1}{\tau} = 2\pi f \]

so,

\[ f = \frac{1}{2\pi \tau} = \frac{10^4}{2\pi \times 7.8} \approx 200 \text{ Hz.} \]
The value of $E_{dc}^*$ has been established by extrapolation of threshold stress/frequency characteristic obtained in experimental work. For comparison the values of threshold alternating stress ($E_{ac}$) at various frequencies are also shown in Figure 6.12.

Because of the different sizes of particles present in the liquid, the maximum size being limited by the filter No. 5 in this particular case under consideration, one should not expect a close agreement between the threshold stress/frequency characteristic and the experimental results. However, the comparison shows that the frequency dependence of threshold stress is well explained by the model assumed in this work.

<table>
<thead>
<tr>
<th>$\omega$</th>
<th>0</th>
<th>$\frac{1}{4\tau}$</th>
<th>$\frac{1}{2\tau}$</th>
<th>$\frac{1}{\tau}$</th>
<th>$\frac{2}{\tau}$</th>
<th>$\frac{3}{\tau}$</th>
<th>$\frac{4}{\tau}$</th>
<th>$\frac{5}{\tau}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>0</td>
<td>50</td>
<td>100</td>
<td>200</td>
<td>400</td>
<td>600</td>
<td>800</td>
<td>1600</td>
</tr>
<tr>
<td>$\frac{U_{ac}}{U_{dc}}$</td>
<td>1</td>
<td>0.93</td>
<td>0.8</td>
<td>0.5</td>
<td>0.2</td>
<td>0.1</td>
<td>0.059</td>
<td>0.0385</td>
</tr>
<tr>
<td>$\frac{U_{dc}}{U_{ac}}$</td>
<td>1</td>
<td>1.04</td>
<td>1.25</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>17</td>
<td>27</td>
</tr>
<tr>
<td>$\sqrt{\frac{U_{dc}}{U_{ac}}}$</td>
<td>1</td>
<td>1.02</td>
<td>1.11</td>
<td>1.41</td>
<td>2.23</td>
<td>3.16</td>
<td>4.12</td>
<td>5.19</td>
</tr>
<tr>
<td>$E_{ac}$ [kV/cm]</td>
<td>7.5</td>
<td>10</td>
<td>17</td>
<td>25</td>
<td>39</td>
<td>48</td>
<td>55</td>
<td>60</td>
</tr>
</tbody>
</table>

$E_{dc} = E_{ac}$ and kept constant
7. **CONCLUSIONS**

Explanation of the process of pearl-string and bridge formation by suspended particles in dielectric liquids subjected to alternating fields of variable frequency given by previous workers and in particular by Muth (1927) and Krasny-Ergen (1936) may be proved to be essentially correct. However, they considered the particles as conducting spheres and thus obtained expression for the bounding energy of dipoles in alternating fields to be proportional to the cube of the particle radius and to the square of the effective value of the applied field strength, but independent of the frequency of the applied alternating field.

Stauff (1955), on the other hand, who also used alternating fields of variable frequency (30 Hz - 500 Hz) in his study of various emulsions found frequency dependence of the pearl-string formation phenomenon. He also found that the process depends on the size of particles and the energies proportional to the fifth power of the particle radius. As far as the frequency is concerned Stauff findings were confirmed in the work presented here. Both, the threshold voltage required to initiate the process of bridge formation, as well as the critical voltage at which disruption of already formed bridge is initiated were found to depend on frequency. But the threshold voltage was found to be independent of particle size and the kind of particles, being the same for conducting and non-conducting particles. However, critical voltage for bridge disruption was found to depend on particle material and size.

It was also possible, considering dipoles to be formed by charged particles surrounded by an ion atmosphere which neutralize in effect the particle charge in the absence of electric field, and assuming that the polarization effect does not collapse immediately when the field is removed to deduce the bounding energy of the two dipoles. The
expression thus obtained showed clearly frequency dependence of the required stress to form the pearl-string of similar dipoles. The required stress increases with frequency and the results obtained from theoretical considerations shown in Fig 5.3 agree fairly with those obtained experimentally.

The mechanism of pearl-string and bridge formation between two spherical electrodes can be described as follows: the impurity particles having permittivity greater than that of the dielectric liquid are drawn into a small volume between electrodes so that the density of particles in this region increases considerably. Due to the action of the field in this region, the particles align themselves in the form of pearl-strings and form the bridge when crossing the gap. Visual observations and photographs taken confirmed this effect for certain conditions. The liquid must be stationary and the impurities do not become charged even when touching electrodes. These conditions may not prevail at higher stresses as then there is a possibility that motion of the liquid may be induced, and the particles may acquire some net charge. It was found in this work that such a critical voltage exists and when higher voltages than critical were applied bridges were destroyed. The value of critical voltage depended on gap length, frequency and particle size.

At stresses higher than critical a process of clearing the gap was observed. Some particles detached from the bridge and oscillated between electrodes assuming larger and larger trajectories until they were finally rejected from the gap. Formation of pearl-strings at right angle to the field direction was also observed. Such pearl-string also oscillated but perpendicularly to the field and finally they were rejected from the gap. The first effect could be explained by invoking centrifugal forces acting upon vigorously oscillating charged particles. Formation of vertically aligned pearl-strings could be accounted by invoking Bjerknes' (1915) induced hydrodynamic forces between two particles.
It was also found that for a given system of electrodes there was a critical gap setting for which bridges could not be formed. For gaps larger than critical formation of pearl-strings was observed, but their length was much shorter than the gap setting, and never resulted in the formation of a bridge across the gap. This phenomenon was reported by Skowronski (1962) and confirmed in this study. The critical gap setting for electrodes of 5 mm diameter used in this work was found to be less than 1 mm but it was impossible to define its exact value.

The study of the motion of the suspended particles in dielectric liquid due to the action of gravitational and electric field revealed that the particles move into the region of higher stress along trajectories determined by material coefficient which takes into account densities and permittivities of the suspended impurities and the liquid on a coefficient depending on the geometry of the spark gap and the applied voltage. The sweeping region, from which particles may be drawn into the region of higher stress depends critically on the product of the two coefficients. When the value of this product is greater than a critical value no sweeping region could be produced and all particles will flow through the gap without being trapped in the space between electrodes.

The coefficient of flocculation which defines the increased density of the particles gathered in the region of high stress depends on gap setting. For larger gaps the density of particles may become too low to enable formation of bridges and it was confirmed in this work that a critical gap length exists.

The analysis of the process of bridge formation leads to the following conclusions. In a system such as a spherical spark-gap the sweeping region cannot be defined precisely as it depends on the properties of the suspended particles, gap setting and the applied voltage.
If the voltage is gradually increased larger and larger volume of liquid tested may contribute to the process of flocculation of particles in high stress region and formation of pearl-strings. During this time a segregation of particles may also take place, some particles being acted upon by larger forces as for example droplets of water while the other as dry solid particles will be acted upon by smaller forces. The gas bubbles would be rejected from the region of high stress.

The dependence of the sweeping region on the applied voltage brings about the dependence of breakdown values on the time of voltage application or on the rate at which the voltage is increased. This is in agreement with experimental results. Estimation of the time required for all the particles to migrate into the region of higher stress is theoretically impossible. Therefore it is also impossible to determine theoretically the procedure for testing of samples which could only be established by experiments.

Finally the analysis showed that a comparison of the test results obtained using different spark-gaps is in fact impossible.

As far as the breakdown of the liquid containing impurities is concerned the results obtained in this work suggest that breakdown stress and its dependence on the frequency of the applied a.c. fields will greatly depend on the purification of the test samples. Oils of commercial purity will show some frequency dependence of dielectric strength and higher values of the strength may be obtained for higher frequencies. The frequency dependence of breakdown strength is less pronounced for larger gap settings and even less for purified oils. Frequency dependence is greatly reduced by careful purification of the test samples. For very fine filters (0.45 μm porosity) no frequency dependence of breakdown values was observed and therefore it could be concluded that there should be no frequency dependence for perfectly
purified oil. Finally it was found that the characteristics showing
dependence of breakdown values on the gap setting are similar to that
usually obtained in d.c. tests, i.e. the breakdown stress decreases
when the gap setting is increased for the frequencies used in this work.
7.1 Suggestions for Future Work

In the light of the present work it is felt that the following topics are worth investigation.

(a) Conduction current or dielectric loss measurements at various frequencies and gap settings with an emphasis on special filtering techniques.

(b) A more detailed study of bridge formation with conducting and non-conducting particles in order to assess the importance of particle conductivity.

(c) Measurements involving accurate control of the particle size with perhaps a larger test cell and electrodes.

(d) A photographic study of bridge formation should provide useful information of the pre-breakdown, breakdown and post-breakdown processes involved.

(e) The post-breakdown glow-discharge, which has been observed in this work at variable frequency, needs further investigation.

(f) These phenomena can also be studied in simple hydrocarbon liquids such as hexane, acetone, etc.
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ADDENDUM


POLARISATION OF DIELECTRIC SPHERE IN ELECTRIC FIELD

The problem of polarization of dielectric sphere placed in electric field $E$ whose direction may be taken parallel to the $x$-axis of a system of Cartesian axes may be solved by uniqueness theorem. Assuming that the centre of the sphere is placed at the origin "0" of this system of axes the potential of electric field at any point in the absence of the sphere can be defined as:

$$V = -E.x = -E.r\cos\theta$$

where "$r$" and "$\theta$" are polar co-ordinates defined by

$$x = r\cos\theta$$

and

$$x^2 + y^2 + z^2 = r^2$$

Let us assume that the potential inside the sphere is given by:

$$V_i = A.r\cos\theta$$

and that outside the sphere:

$$V_0 = -E.r\cos\theta + \frac{B\cos\theta}{4\pi\varepsilon_d r^2}$$

where $A$ and $B$ are constants. The second term represents the effect of the presence of dielectric sphere in the field.

The boundary conditions to be satisfied are the continuity of the potential and the normal flux density at the surface of the sphere, namely:

$\theta = 0$, and $V_i = V_0$ at $r = a$
and
\[ E_d \frac{dV_0}{dr} = \varepsilon_a \frac{dV_i}{dr} \] at \( r = a \)

where \( \varepsilon_d \) and \( \varepsilon_a \) are the permittivities of the medium and the dielectric sphere respectively.

and
\[ -E.a + \frac{B}{4\pi\varepsilon_d a^2} = A.a \]

\[ \varepsilon_d \left( -E + \frac{2B}{4\pi\varepsilon_d a^3} \right) = \varepsilon_a A \]

from which:

\[ B = \frac{(\varepsilon_a - \varepsilon_d)4\pi\varepsilon_d a^3 E}{2\varepsilon_d + \varepsilon_a} \quad \text{and} \quad A = \frac{3\varepsilon_d}{2\varepsilon_d + \varepsilon_a}E \]

Assuming that the potential outside the sphere is defined by the expression
\[ V_0 = -E_z r \cos \theta + \frac{B \cos \theta}{4\pi\varepsilon_d a^2} \]

it is obvious that the second term represents the potential of an electric dipole of dipole moment \( B \), so the dipole moment of the polarized sphere is

\[ p = \frac{(\varepsilon_a - \varepsilon_d)4\pi\varepsilon_d a^3 E}{2\varepsilon_d + \varepsilon_a} \]
The following symbols will be used in the theoretical calculations:

- **E**  Electric field strength.
- **P**  Dipole moment.
- $\varepsilon_d$  Permittivity of dielectric liquid.
- **r**  Horizontal distance between centres of two dipoles.
- **$\theta$**  Angle between the direction of the field and the line connecting the centres of two particles.
- **$\alpha$**  Polarizability.
- **t**  Time.
- $\tau$  Relaxation time of the ion atmosphere.
- **F**  Force between the dipoles.
- **U**  Work done or energy of attraction.
- **$\omega$**  Angular velocity.
- **j**  Square root of $-1$.
- **x, y, z**  Co-ordinate system, the origin of which is situated at the centre of the particle, the x-axis coincides with the centre of the particle spheres. The x-y plane is determined by the direction if the field and the axis.
- **q**  Charge.
- **K**  Constant.
- **v**  Velocity of the ion atmosphere with respect to the moving particle.
- $V_{ox}$  Average velocity of the ion atmosphere with respect to the moving particle.
Let us first of all consider a case when a homogeneous d.c. field is applied to the dielectric liquid.

According to field theory, the potential around a point dipole \( P \) in vacuum is given by

\[
V(r, \theta) = \frac{1}{4\pi \varepsilon_0} \frac{P \cos \theta}{r^2}
\]

where \( r \) is the distance between \( P \) and the point \( L \) and \( \theta \) is the angle between \( P \) and \( r \).

The field around a dipole, therefore, has two components given by

\[
E_r = -\frac{\delta V}{\delta r} = \frac{1}{4\pi \varepsilon_0} \frac{2P \cos \theta}{r^3}
\]

and

\[
E_\theta = -\frac{1}{r} \frac{\delta V}{\delta \theta} = \frac{1}{4\pi \varepsilon_0} \frac{P \sin \theta}{r^3}
\]

when \( \theta = 0 \), \( E_\theta = 0 \)

and

\[
E_r = \frac{2P}{4\pi \varepsilon_0 r^3}
\]

and when \( \theta = 90^\circ \),

\[
E_r = 0
\]

and

\[
E_\theta = \frac{P}{4\pi \varepsilon_0 r^3}
\]
When the particle dipoles are as shown above, the field at B due to \( A = \frac{2P}{4\pi\varepsilon_0 r^3} \). Therefore the total field = \( E_i = E + \frac{2P}{4\pi\varepsilon_0 r^3} \).

Let \( P = \alpha E \), where \( \alpha \) is the polarizability, then

\[
E_i = E + \frac{2\alpha E}{4\pi\varepsilon_0 r^3}
\]

or

\[
E = E_i (1 - \frac{2\alpha}{4\pi\varepsilon_0 r^3}) \quad (5)
\]

Let \( P_1 \) be the dipole moment with single dipole, and \( P_2 \) be the dipole moment of each dipole with two dipoles, then

\[
P_1 = \alpha E \quad (6)
\]

and \( P_2 = \alpha E_i = \alpha \left( \frac{E}{1 - \frac{2\alpha}{4\pi\varepsilon_0 r^3}} \right) \quad (7)\)

Total dipole moment = \( 2P_2 \).

Case 2

When the dipoles are as shown.

Field at B due to \( A = \frac{P}{4\pi\varepsilon_0 r^3} \)

so, \( E_i = E + \frac{\alpha E}{4\pi\varepsilon_0 r^3} \)

or \( E = E_i (1 - \frac{\alpha}{4\pi\varepsilon_0 r^3}) \)
and \( P_2 = \alpha E \) = \( \frac{\alpha E}{1 - \frac{a}{4\pi \varepsilon_d r^3}} \) 

For interaction of two dipoles.

To find out the force responsible for bridge formation

\[
F = \frac{-q_1^2}{4\pi \varepsilon_d r^2} + \frac{q_2^2}{4\pi \varepsilon_d (r+x)^2} + \frac{q_2^2}{4\pi \varepsilon_d (r-x)^2} - \frac{q_2^2}{4\pi \varepsilon_d r^2}
\]

\[
= \frac{-q_1^2}{4\pi \varepsilon_d} \cdot \frac{-2 (r+x)^2 (r-x)^2 + r^2 (r+x)^2 + r^2 (r-x)^2}{r^2 (r+x)^2 (r-x)^2}
\]

\[
= \frac{-q_1^2}{4\pi \varepsilon_d} \cdot \frac{6 r^2 x^2 - 2x^4}{r^2 (r+x)^2 (r-x)^2}
\]

If \( r \gg x \)

\[
F = \frac{-q_1^2}{4\pi \varepsilon_d} \cdot \frac{6 r^2 x^2}{r^6} = \frac{6 q_1^2 x^2}{4\pi \varepsilon_d r^6}
\]

\[
= \frac{6P^2}{4\pi \varepsilon_d r^6}
\]

where \( P = \alpha q \).

The work done in pulling one of the charges by a distance \( dr \) is

\[
U_{\alpha} = \int_{r}^{r} \frac{6P^2}{4\pi \varepsilon_d r^6} \cdot \frac{1}{r^4} \, dr
\]

\[
= -\frac{1}{3} \left[ \frac{6P^2}{4\pi \varepsilon_d r^3} \right]_{r}^{\infty}
\]
Case 2

The force of attraction between the two dipoles in the position shown above will be:

\[ F = \frac{-2q^2}{4\pi \varepsilon_d r^2} + \frac{2q^2}{4\pi \varepsilon_d (r^2 + x^2)} \cos \theta \]

\[ = \frac{-2q^2}{4\pi \varepsilon_d r^2} + \frac{2q^2}{4\pi \varepsilon_d (r^2 + x^2)} \frac{r}{\sqrt{r^2 + x^2}} \]

If \( r \gg x \), \( \theta = 0 \), i.e. \( \cos \theta = 1 \).

\[ F = \frac{2q^2}{4\pi \varepsilon_d} \left[ \frac{1}{r^2} - \frac{1}{r^2 + x^2} \right] \]

\[ = \frac{2q^2}{4\pi \varepsilon_d} \left[ \frac{r^2 - r^2 - x^2}{r^4 + r^2 x^2} \right] \]

\[ = - \frac{2q^2}{4\pi \varepsilon_d} \frac{x^2}{(r^4 + r^2 x^2)} \]

\[ = - \frac{2p^2}{4\pi \varepsilon_d r^4} \]
Therefore the work done, that is to say the energy of attraction in this case, will be given by

\[
U = \int_{r_1}^{\infty} \frac{r^2 P^2}{4\pi\varepsilon_0 r^4} \, dr
\]

\[
= \frac{1}{3} \frac{2 P^2}{4\pi\varepsilon_0 r^3}
\]

\[
= \frac{P^2}{6\pi\varepsilon_0 r^3}
\]

(10)

However, in the above two cases, while finding the average value of the force the polarizability of the dipole was not taken into account, hence a modification will be necessary of the energy calculated so far.

**Case 1**

\[
F = \frac{6 P^2}{4\pi\varepsilon_0 r^4}
\]

From expression (7)

\[
P = \frac{\alpha E}{1 - \frac{2\alpha}{4\pi\varepsilon_0 r^3}}
\]

Hence, \( F = \frac{6 \alpha^2 P^2}{4\pi\varepsilon_0 r^4 \left(1 - \frac{2\alpha}{4\pi\varepsilon_0 r^3}\right)^2} \)
On simplification,

\[ F = \ \frac{6 a^2 E^2}{4 \pi \varepsilon_d r^4 \left\{ 1 - \frac{4a}{4 \pi \varepsilon_d r^3} + \frac{4a^2}{16 \pi^2 \varepsilon_d^2 r^6} \right\}} \]

\[ = \ \frac{6a^2 E^2}{4 \pi \varepsilon_d r^4 - 4a^2 + \frac{a^2}{\varepsilon_d r^2}} \]

\[ = \ 6a^2 E^2 \left\{ \frac{\pi \varepsilon_d x^2}{4 \pi^2 \varepsilon_d^2 r^6 - 4 \pi \varepsilon_d \alpha r^3 + a^2} \right\} \]

Therefore energy = \[ \int_0^r F \, dr \]

\[ = 6 \pi \varepsilon_d a^2 E^2 \int_0^r \frac{r^2 \, dr}{4 \pi^2 \varepsilon_d^2 r^6 - 4 \pi \varepsilon_d \alpha r^3 - a^2} \]

Let us put \( x = r^3 \), so \( \frac{dx}{dr} = 3r^2 \), or \( r^2 \, dr = \frac{1}{3} \, dx \).

Hence \[ \int_0^{3\sqrt{x}} \frac{dx}{3 \left( 4 \pi^2 \varepsilon_d^2 x^2 - 4 \pi \varepsilon_d x + a^2 \right)} \]

\[ = \int_0^{3\sqrt{x}} \frac{dx}{3 \left( 2 \pi \varepsilon_d x - a \right)^2} \]

\[ = \ \frac{1}{3} \left\{ - \frac{1}{2 \pi \varepsilon_d} \left( 2 \pi \varepsilon_d x - a \right)^{-1} \right\}^{3\sqrt{x}}_0 \]

\[ = - \ \frac{1}{6 \pi \varepsilon_d} \left[ \frac{1}{2 \pi \varepsilon_d r^3 - a} \right]^r_0 \]

\[ = - \ \frac{1}{6 \pi \varepsilon_d (2 \pi \varepsilon_d r^3 - a)} \]
So from (11), we get

\[ U_{\rightarrow} = \frac{-6\pi \epsilon_0 \alpha^2 E^2}{6\pi \epsilon_0 (2\pi \epsilon_0 r^3 - \alpha)} \]

\[ = \frac{-\alpha^2 E^2}{2\pi \epsilon_0 r^3 - \alpha} \]

Hence with interaction with the polarized dipoles,

\[ U_{\rightarrow} = \frac{-\alpha^2 E^2}{2\pi \epsilon_0 r^3 - \alpha} \]  \hspace{1cm} (13)

For no interaction \( \alpha \ll 2\pi \epsilon_0 r^3 \)

so \[ U_{\rightarrow} = \frac{-\alpha^2 E^2}{2\pi \epsilon_0 r^3} = \frac{-p^2}{2\pi \epsilon_0 r^3} \]  \hspace{1cm} (14)

same as expression (9).

Case 2

Similarly we can find the work done, i.e. the energy between the dipoles for the second case,

where \( F = \frac{-2}{4\pi \epsilon_0 r^4} \) from expression (9)

\[ = \frac{-2 \alpha^2 E^2}{4\pi \epsilon_0 r^4 (1 - \frac{\alpha}{4\pi \epsilon_0 r^3})^2} \]  \hspace{1cm} (15)

substituting the value of \( P \) from expression (8).
Therefore the energy of attraction is given by

\[ U_{\pm\pm} = \int_0^r F dr = \int_0^r \frac{-2a^2E^2}{4\pi\epsilon_d r^4 (1 - \frac{a}{4\pi\epsilon_d r^3})^2} dr \]

\[ = \frac{-2a^2E^2}{4\pi\epsilon_d r^4 (1 - \frac{2a}{4\pi\epsilon_d r^3} + \frac{a^2}{16\pi^2 \epsilon_d^2 r^6})} \]

\[ = \frac{-2a^2E^2}{16\pi^2 \epsilon_d^2 r^6 - 8\pi\epsilon_d a r^3 + a^2} \]

\[ = -8\pi\epsilon_d a^2E^2 \int_0^r \frac{r^2 dr}{(4\pi\epsilon_d r^3 - a)^2} \quad (16) \]

Let us put \( r^3 = x \), i.e. \( r^2 dr = \frac{dx}{3} \)

So, \( \int_0^r \frac{r^2 dr}{(4\pi\epsilon_d r^3 - a)^2} = \int_0^{3\sqrt{x}} \frac{dx}{3 (4\pi\epsilon_d x - a)^2} \)

\[ = \frac{1}{3} \int_0^{3\sqrt{x}} \frac{1}{4\pi\epsilon_d} \left[ \frac{1}{4\pi\epsilon_d x - a} \right]^{3\sqrt{x}} = \frac{1}{3} \int_0^{3\sqrt{x}} \frac{-1}{4\pi\epsilon_d} \left[ \frac{4\pi\epsilon_d r^3 - a}{4\pi\epsilon_d} \right]^{3\sqrt{x}} \]

\[ = \frac{-1}{12\pi\epsilon_d (4\pi\epsilon_d r^3 - a)} \quad (17) \]

So from (16) and (17), we get

\[ U_{\pm\pm} = -8\pi\epsilon_d a^2E^2 \cdot \frac{-1}{12\pi\epsilon_d (4\pi\epsilon_d r^3 - a)} \]
So, \[
U_{\parallel \parallel} = \frac{2 \alpha^2 E^2}{3 (4\pi \varepsilon_d x^3 - \alpha)}
\]

\[
= \frac{2 p^2}{(12\pi \varepsilon_d x^3 - 3\alpha)}
\] (18)

When there is no interaction with other polarized particles,
\( \alpha \ll 12\pi \varepsilon_d x^3 \) so,

\[
U_{\parallel \parallel} = \frac{2 p^2}{12\pi \varepsilon_d x^3} = \frac{p^2}{6\pi \varepsilon_d x^3}
\]

same as expression (10)

For case I the expression (13) can be written as

\[
U_{\parallel \parallel} = \frac{-\alpha^2}{2\pi \varepsilon_d x^3 - \alpha} = \frac{2 p^2}{4\pi \varepsilon_d x^3 - 2\alpha}
\] (19)

Let us now consider a more general case when the external field is at an angle \( \theta \) to the dipoles.
The energy of attraction for case (1) is

\[ U_{\leftrightarrow} = \frac{-2 \pi^2}{4\pi\epsilon_0 r^3 - 2\alpha} \cos^2 \theta \]  

(20)

This follows from expression (19).

Similarly, the energy of attraction for case (2) will be

\[ U_{\leftrightarrow} = \frac{2 \pi^2}{12\pi\epsilon_0 r^3 - 3\alpha} \sin^2 \theta \]  

(21)

This follows from expression (18).

Therefore the total energy of attraction will be given by addition of (20) and (21), i.e.

\[ U_{\leftrightarrow \leftrightarrow} = \text{sum of the components of } U_{\leftrightarrow} \text{ and } U_{\leftrightarrow \leftrightarrow} \]

\[ = \frac{-2 \pi^2 \cos^2 \theta}{4\pi\epsilon_0 r^3 - 2\alpha} + \frac{2 \pi^2 \sin^2 \theta}{12\pi\epsilon_0 r^3 - 3\alpha} \]

\[ = 2 \pi^2 \left\{ \frac{\sin^2 \theta}{12\pi\epsilon_0 r^3 - 3\alpha} - \frac{\cos^2 \theta}{4\pi\epsilon_0 r^3 - 2\alpha} \right\} \]  

(22)

For \( \theta = 0 \), \( U_{\leftrightarrow \leftrightarrow} = \frac{-2 \pi^2}{4\pi\epsilon_0 r^3 - 2\alpha} \)  

(23)

the energy is negative and for \( \theta = 90^\circ \),

\[ U_{\leftrightarrow \leftrightarrow} = \frac{2 \pi^2}{12\pi\epsilon_0 r^3 - 3\alpha} \]  

(24)

the energy is positive.
When the axis connecting the centres of two polarized particles is parallel to the direction of the field, the energy is always negative. Therefore to attain minimum energy, the spheres will always arrange themselves in the field in such a way that the line connecting their centres is parallel to the field lines.

When a third particle comes nearer, it will also arrange itself with the nearest particle in such a way that the line connecting their centres is parallel to the direction of the applied field. The fourth particle will behave in a similar way and so on. In this manner a whole chain of particles, or so-called "pearl-string" will be formed. Such "pearl-string" bridges were observed by many workers both in steady as well as in alternating fields.
APPENDIX 3

SAMPLES OF CALCULATIONS

1. Equipotential surfaces of two point charges representing the metal surfaces of two spherical electrodes

It is assumed that the external field produced by two metal spheres to which a potential difference \( V \) is applied could be represented, with sufficient accuracy, by the field produced by two equivalent image charges. The actual metal surfaces would then be represented by these equipotential surfaces of the two image charges which are passing through the nearest points of the actual electrodes on the axis connecting their centres and also through the points on the intersection circle of the metal spheres and the plane perpendicular to the axis of the electrodes passing through the points where the image charges are located as shown in Fig 1.

The potential at any point on the axis connecting the centres of the metal electrodes can be calculated from the formula:

\[
V_x = \frac{q}{4\pi\varepsilon_d} \left[ \frac{1}{|x - d|} - \frac{1}{|x + d|} \right]
\]

The functions defining equipotential surfaces are therefore of the form

\[
f = \frac{1}{|x - d|} - \frac{1}{|x + d|}
\]
and in general, for a pair of metal spheres of different diameters, there will be two functions, $f_1$ and $-f_2$. For two identical spheres however:

$$f_1 = -f_2$$

So, if a potential difference $V$ is maintained between such surfaces, the equivalent image charges could be calculated using the formula:

$$q = \frac{4\varepsilon_0 \cdot V}{f_1 - f_2}$$

or

$$q = \frac{4\varepsilon_0 \cdot V}{2f}$$

for two identical spheres.

The values of equipotential surfaces defining equations will depend on the size of electrodes and the gap setting. In this work 5 mm diameter electrodes were used and the gap setting varied from 28 µm to 1000 µm. In the following calculations are shown for 50 µm gap setting.

$$\xi_g = 0.05 \text{ cm gap setting}$$

$$D = 0.5 \text{ cm diameter of the sphere}$$

$$\text{ratio} \quad \frac{\xi_g}{D} = \frac{0.05}{0.5} = 0.1$$

From Clark and Loh graph, the ratio of $E_{\text{max}}/E_{\text{mean}} = 1.15$

and the distance between two image charges

$$2d = \frac{0.5 + 0.05}{1.15} = 0.478 \text{ cm}$$
For
\[ x = \frac{\lambda_g}{2} = \frac{0.05}{2} = 0.025 \text{ cm.} \]
\[ d = \frac{0.478}{2} = 0.239 \text{ cm.} \]

the function defining equivalent equipotential surfaces is therefore,

\[ f = \frac{1}{\left| 0.025 - 0.239 \right|} - \frac{1}{\left| 0.025 + 0.239 \right|} \]
\[ = \frac{1}{0.264} - \frac{1}{0.214} = \frac{0.264 - 0.214}{0.264 \times 0.214} \]
\[ = 0.885 \text{ m}^{-3}. \]

2. Flocculation Region

The high stress region in which particles flocculate has been defined as cylinder of radius \( r_o \) and the length equal to \( l_g \), as shown in Fig. 6.10.

The value of \( r_o \) depends on gap setting and the calculations are given for the gap setting of 500 \( \mu \)m.

\[ z_o = \frac{r_o}{d} \]

and \( z_o = 0.378 \) as found in Chapter 6, so:

\[ r_o = 0.239 \times 0.378 = 0.09 \text{ cm.} \]

The volume of flocculation region is therefore,

\[ r_o^2 \pi l_g = 0.09^2 \times 3.14 \times 0.05 = 1.2 \times 10^{-3} \text{ cm}^3. \]
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