CHAPTER III

BREAKDOWN OF AIR IN CROSSED RADIO-FREQUENCY AND D.C. ELECTRIC FIELD.

INTRODUCTION

Varela (1947) observed an increase of breakdown potential in a discharge excited by radio frequency source when a d.c. potential less than the radio frequency breakdown voltage was applied across the discharge tube. Similar results were also obtained earlier by Kirchner (1925, 1947) while studying the breakdown in gases by a radio frequency field in the presence of a d.c. potential. Varnerin and Brown (1950) theoretically calculated the distribution function of electrons in an ionized gas in the presence of both radio frequency and d.c. fields. The breakdown of a gas in a cavity occurs when the loss of electrons to the walls of the cavity are replaced by ionization in the body of the gas. When a radio frequency field alone is applied, the electrons are lost by diffusion. When a small d.c. sweeping field is applied electrons are lost both by diffusion and mobility. Varnerin and Brown have shown that the only difference between the breakdown condition in the radio frequency field in presence of d.c. field case and the pure radio frequency case is the substitution of a modified diffusion length in place of characteristic diffusion length where the modified diffusion length is a function of the applied d.c. field. That a greater breakdown field is necessary when the d.c. voltage is superimposed on the radio frequency field was further shown by Brown (1956) in the case of air at a pressure of 38 mm. Hg. where a d.c. field upto 200 Volts/cm. was applied.

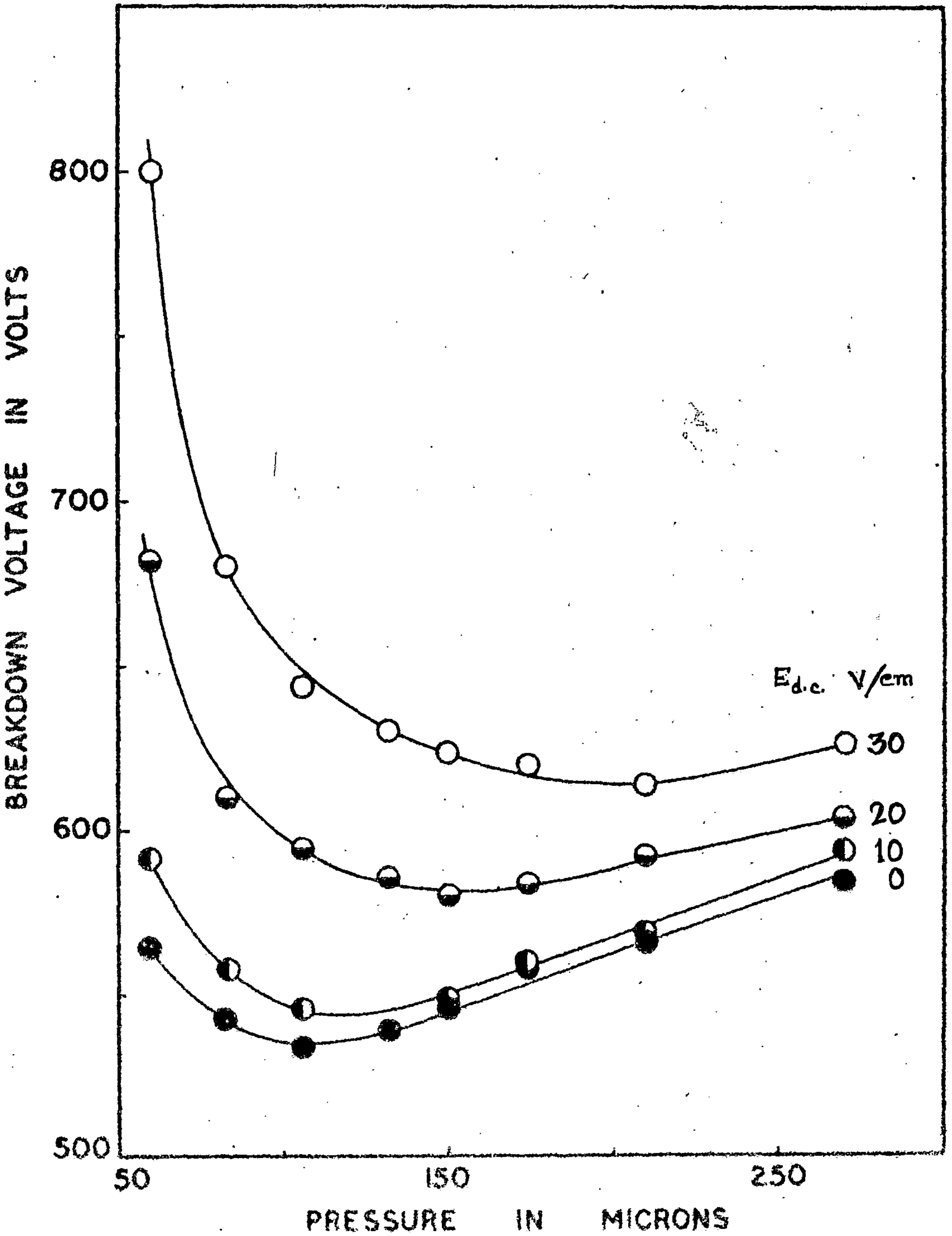
In a series of papers Sen and Bhattacharjee (1965, 1966, 1967) have shown that radio frequency breakdown potential of gases increases when d.c. field is simultaneously applied parallel to radio frequency field and for a sufficiently strong d.c. field, the d.c. ionization causes lowering of radio frequency breakdown potential. In order to extend the work further and to see whether a transverse d.c. potential can cause a change of radio frequency breakdown potential, it has been proposed to measure the radio frequency breakdown potential of electrodeless discharge of gases when a variable d.c. field is applied perpendicular to radio frequency field where the d.c. field is less than the radio frequency breakdown field. An attempt has been made to explain the results with the help of prevalent theories.

EXPERIMENTAL ARRANGEMENT.

The method of measurement of breakdown voltage is the same as was used by Sen and Ghosh (1963). The gas container is a glass rectangular parallelopiped of height (h) = 20 cm, length (l) = 2.5 cm, breadth (b) = 2.5 cm. and radio frequency field is applied along the height using two external electrodes whose cross section is much larger than that of the face of the tube. D.C. electric field is applied using two external electrodes along the length of the tube. The d.c. field was perpendicular to the radio frequency field and uniformity of d.c. field within the container is maintained along its whole length. Dried air free from dust and water vapour has been studied in the present investigation. The gas pressure is measured by an Edward Pirani Penning Vacuum Gauge. The radio frequency voltage is supplied from a Colpitts oscillator, the frequency of which is adjusted to a value 5.7 Mc/sec. for the present investigation. The experiment is repeated and the results are found to be reproducible. The d.c. field has been supplied from a stabilized variable voltage power supply.

RESULTS AND DISCUSSION.

The variation of ~~fx~~ radio frequency breakdown potential with pressure of the gas, when a steady value of d.c. field is applied perpendicular to the radio - frequency field has been plotted for different values of d.c. field in case of air as shown in Fig. 3.1. The variation of breakdown potential without d.c. field has been given for comparison.



BREAKDOWN VOLTAGE IN VOLTS
800
700
600
500
50
150
250
PRESSURE IN MICRONS
$E_{d.c.}$ V/cm
30
20
10
0

FIG. 3.1.

It is seen that for all the d.c. field applied, the general nature of the variation of radio frequency breakdown potential with pressure in presence of transverse d.c. field remains same as without d.c. field. Observations were limited to low values of d.c. field due to limitation of power from the radio frequency source. The pressure at which the breakdown potential becomes minimum in presence of transverse d.c. field is found to shift towards higher pressure with increase of d.c. field. The breakdown potential increases for all values of gas pressure at any transverse d.c. field.

Holstein (1956) and later Varnerin and Brown (1950) obtained the solution of energy distribution function of electrons in a gas and showed a very close ~~m~~ similarity between the distribution function under the action of radio frequency and d.c. fields.

The gas in a cavity will breakdown when the losses of electrons to the walls of the cavity are replaced by ionization in the body of the gas. When the radio frequency field alone is applied electrons are lost by diffusion and in presence of a superimposed d.c. field electrons are lost by mobility also.

The d.c. flow of electrons $\vec{\Gamma}$ is given by

$$\vec{\Gamma} = -n\mu\vec{E}_{d.c.} - D\nabla n \qquad \text{.... (3.1)}$$

where 'D' and μ are the diffusion and mobility coefficients respectively of electrons having number density 'n' and $\vec{E}_{d.c.}$ is the uniform d.c. electric field applied along the x-axis. When the electrons that are lost are replaced by new ones resulting from ionization, we have

$$\nabla \cdot \vec{\Gamma} = \nu_i n \qquad \ldots (3.2)$$

or,

$$\nabla \cdot \left(-n\mu \vec{E}_{d.c.} - D\nabla n\right) = \nu_i n$$

or,

$$D\nabla^2 n + \mu \vec{E}_{d.c.} \nabla n + \nu_i n = 0 \qquad \ldots (3.3)$$

where ν_i is the frequency of ionization. Assuming the radio frequency field along the y-axis, the solution of eqn. (3.3) is

$$n = A \cos(k_1 z) \cos(k_2 y) \times$$

$$\cos\left[\left\{\frac{\nu_i}{D} - k_1^2 - k_2^2 - \left(\frac{\mu E_{d.c.}}{2D}\right)^2\right\} x\right] \exp\left(-\frac{\mu E_{d.c.} x}{2D}\right) \ldots (3.4)$$

where 'A' is any constant and 'l', 'b', and 'h' denote the length, breadth, and height of the discharge tube. The boundary condition that $n = 0$ at $x = \pm \frac{l}{2}$, $y = \pm \frac{h}{2}$ and $z = \pm \frac{b}{2}$ requires that

$$k_1^2 = \left(\frac{\pi}{b}\right)^2 \qquad \ldots (3.5a)$$

$$k_2^2 = \frac{\pi^2}{h^2} \qquad \text{... (3.5b)}$$

and

$$\frac{\nu_i}{D} - k_1^2 - k_2^2 - \left(\frac{\mu E_{d.c.}}{2D}\right)^2 = \frac{\pi^2}{l^2} \qquad \text{... (3.5c)}$$

Combining (3.5a), (3.5b) and (3.5c) we get the desired breakdown condition as

$$\frac{\nu_i}{D} = \pi^2\left(\frac{1}{h^2}+\frac{1}{b^2}+\frac{1}{l^2}\right) + \left(\frac{\mu E_{d.c}}{2D}\right)^2 \qquad \text{... (3.6)}$$

So, the modified diffusion length $\Lambda_{d.c.}$ is given by

$$\frac{1}{\Lambda_{d.c.}^2} = \pi^2\left(\frac{1}{h^2}+\frac{1}{b^2}+\frac{1}{l^2}\right) + \left(\frac{\mu E_{d.c.}}{2D}\right)^2$$

$$= \frac{1}{\Lambda^2} + \left(\frac{\mu E_{d.c.}}{2D}\right)^2 \qquad \text{... (3.7)}$$

where Λ is the characteristic diffusion length given by

$$\frac{1}{\Lambda^2} = \pi^2\left(\frac{1}{h^2}+\frac{1}{b^2}+\frac{1}{l^2}\right) \qquad \text{... (3.7a)}$$

Sen and Bhattacharjee (1969) have deduced that

$$\frac{\nu_i}{D} = A_0 \cdot \frac{p^2}{\nu} \cdot \exp\left(-\frac{B_0 p}{E_{rd}}\right) \qquad \text{... (3.8)}$$

where A_o and B_o are Townsend's coefficients, 'p' being the pressure of the gas, E_{rd} is the radio frequency breakdown field in presence of transverse d.c. field and $r = L/R^{1/2} = L/\left(\frac{2m}{M}\right)^{1/2}$, 'L' being the free path of electrons at a pressure of 1 torr. and 'm' and 'M' are the masses of electrons and ions respectively.

Assuming the electrons having Maxwellian distribution of energy in the present experimental condition, we can write

$$\frac{D}{\mu} = \frac{kT_e}{e}$$

where 'k' is the Boltzmann constant, 'e' is the electronic charge and T_e be the electron temperature. A mathematical expression involving T_e and the reduced field has been deduced by von Engel (1955) and is given by

$$\frac{kT_e}{e} = r\left(\frac{E_{rd}}{p}\right)$$

Therefore,

$$\frac{D}{\mu} = r\left(\frac{E_{rd}}{p}\right) \qquad \ldots (3.9)$$

Combining eqns. (3.6), (3.8) and (3.9) we get,

$$A_o \exp\left(-\frac{B_o p}{E_{rd}}\right) \cdot \frac{p^2}{r} = \frac{1}{\Lambda^2} + \left(\frac{pE_{d.c.}}{2rE_{rd}}\right)^2 \qquad \ldots (3.10)$$

In absence of the transverse d.c. field, the breakdown condition becomes

$$A_o \exp\left(-\frac{B_o p}{E_r}\right) \cdot \frac{p^2}{r} = \frac{1}{\Lambda^2} \qquad \ldots (3.11)$$

for the same pressure 'p' and E_r represents the breakdown potential without the transverse d.c. field. From eqns. (3.10) and (3.11) we get,

$$\exp\left[B_o p \left(\frac{E_{rd} - E_r}{E_{rd} E_r}\right)\right] = 1 + \Lambda^2 \left(\frac{p E_{d.c.}}{2 \gamma E_{rd}}\right)^2$$

or

$$B_o p \left(\frac{E_{rd} - E_r}{E_{rd} E_r}\right) = \log_e \left[1 + \Lambda^2 \left(\frac{p E_{d.c.}}{2 \gamma E_{rd}}\right)^2\right] \ldots \quad (3.12)$$

Eqn. (3.12) shows that for all values of 'p' and $E_{d.c.}$ the radio frequency breakdown potential in presence of d.c. field is greater than radio frequency breakdown field in absence of d.c. field.

To obtain p_{min}, the pressure at which the breakdown field E_{rd} becomes minimum, we differentiate eqn. (3.10), w.r.t. 'p' and putting $\frac{d E_{rd}}{dp} = 0$, we get

$$A_o \cdot \frac{2p}{\gamma} \cdot \exp\left(-\frac{B_o p}{E_{rd}}\right) - A_o \frac{p^2}{\gamma} \cdot \exp\left(-\frac{B_o p}{E_{rd}}\right) \cdot \frac{B_o}{E_{rd}} = \frac{p E_{d.c.}^2}{2 \gamma E_{rd}^2}$$

or,

$$2 - \frac{B_o p}{E_{rd}} = \frac{E_{d.c.}^2}{2 A_o \gamma E_{rd}^2} \cdot \exp\left(\frac{B_o p}{E_{rd}}\right)$$

Now, assuming $A_o = \frac{1}{L}$ as with Townsend (1947) we get,

$$\frac{B_o p}{E_{rd}} = 2 - \frac{1}{2} \cdot R^{1/2} \left(\frac{E_{d.c.}^2}{E_{rd}^2}\right) \exp\left(\frac{B_o p}{E_{rd}}\right) \quad \ldots (3.13)$$

For the highest value of d.c. field applied, and taking some representative values of E_{rd} and p the second expression

$$\frac{1}{2} \cdot R^{1/2} \left(\frac{E_{d.c}}{E_{rd}}\right)^{2} \cdot \exp\left(\frac{B_o p}{E_{rd}}\right)$$

assumes the value $\approx$ 0.04 which can be neglected compared to 2. Therefore, from eqn. (3.13) the pressure at which the breakdown field E_{rd} in presence of transverse d.c. field becomes minimum is given by

$$p_{min} = 2\,(E_{rd})_{min} / B_o \qquad \ldots (3.14)$$

As $(E_{rd})_{min}$ increases with the increase of d.c. field, so p_{min} shifts towards higher pressure with the increase of transverse d.c. field.

In Table-3.1, p_{min} calculated from eqn. (3.14) taking the experimental values of $(E_{rd})_{min}$ from Fig. 3.1 and is compared with the observed p_{min} for different d.c. field applied.

TABLE-3.1

$E_{d.c.}$ volts/cm.	$(E_{rd})_{min}$ volts/cm.	Observed p_{min} * mm.Hg.	p_{min} from eqn. (3.14) mm.Hg.
0	26.0	0.12	0.142
10	27.5	0.13	0.150
20	31.0	0.16	0.169
30	32.0	0.20	0.176

* Deviation ± 0.01

The discrepancy between the two sets of values of p_{min} may be attributed to the uncertainties in the values of different parameters used. Also the approximation in eqns. (3.8) and (3.9) and the assumption that most of the collisions are elastic, which is approximately true in the present experimental condition may be responsible for the discrepancy between the two sets of values of p_{min}. The attachment loss of electrons and ionization due to d.c. field which have not been taken in to consideration may have some influence on the theoretical values of p_{min}.

Thus it can be concluded that the effect of application of small d.c. electric field transverse to radio frequency field, in gas breakdown mechanism, is equivalent to reduction of effective diffusion length. There is also possible contribution of d.c. field to production of electrons, beside the loss due to attachment.

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Breakdown Potential of Air Column with Crossed rf & dc Electric Fields

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The breakdown potential in air (pressure range 50-300 μ) under the simultaneous action of an rf (5·7 MHz) and a variable transverse dc field (0-30 V/cm) has been studied. It has been observed that the breakdown potential is always higher than that in the absence of dc field for all values of pressure and the pressure at which the breakdown voltage becomes minimum always shifts to higher pressures with the increase in the dc field. Following S. C. Brown [*Handb. Phys.*, Vol. 22 edited by S. Flugge (Springer-Verlag, Berlin), 1956, 531-75]. It is assumed that the electrons are lost not only by diffusion but also due to mobility due to application of dc field. The theoretical rf breakdown voltages calculated explain the increase in breakdown voltage for all values of pressure when a dc field is applied. The shift of pressure for minimum breakdown voltage specially for low dc field is explained satisfactorily. The observed discrepancy has been attributed to some approximations made in the theoretical calculations regarding the mechanism of production and loss of electrons and the uncertainties in the values of different parameters used.

1. Introduction

VARELA[1] observed an increase in the breakdown potential in a discharge excited by an rf source when a dc potential less than the rf breakdown voltage was applied across the discharge tube. Similar results were also obtained earlier by Kirchner[2,3] while studying the breakdown in gases by an rf field in the presence of a dc potential. Varnerin and Brown[4] theoretically calculated the distribution function of electrons in an ionized gas in presence of both the rf and dc electric fields and concluded that the only difference between the breakdown condition in the ac-dc case and the pure ac case is the substitution of a modified diffusion length in place of characteristic diffusion length where the modified diffusion length is a function of the applied dc field. The observation that a greater breakdown field is necessary when the dc voltage is superimposed on the rf field was reported by Brown[5] in the case of air at a pressure of 38 mm mercury where a dc field upto 200 V/cm was applied.

In a series of papers, Sen and Bhattacharjee[6-8] have shown for different gases that when a variable dc field is simultaneously applied parallel to rf exciting field the rf breakdown potential increases and shows a maximum when the dc field is continuously increased keeping the pressure of the gas constant. The maximum rf breakdown potential and the corresponding dc field are functions of the pressure and the nature of the gas and the cause of lowering of rf breakdown potential after attaining the maximum is attributed to dc ionization at high dc fields.

In order to extend the work further and to see whether a transverse dc potential can cause a change in rf breakdown potential, it has been proposed to measure the rf breakdown potential of electrodeless discharge of gases when a variable dc field is applied perpendicular to rf field where the dc field is less than the rf breakdown potential. An attempt has been made to explain the results with the help of prevalent theories.

2. Experimental Arrangements

The method of measurement of rf breakdown voltage is the same as was used by Sen and Ghosh[9]. The schematic arrangement of the discharge vessel is shown in Fig. 1 (not according to scale). The discharge vessel is a rectangular parallelopiped made of glass [height (h)=20 cm, length (l)=2·5 cm and breadth (b)=2·5 cm]. The two rectangular electrodes each of area 25 × 5 sq cm are used to supply uniform dc electric field. The exciting rf field is applied perpendicular to dc field using two rectangular elec-

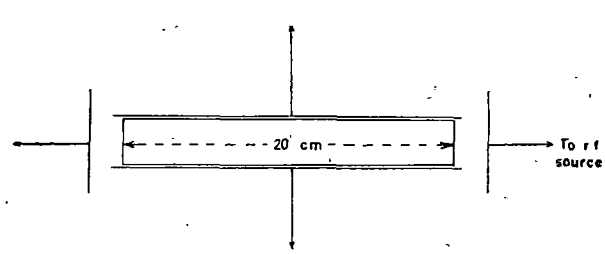

Fig. 1—Schematic diagram of the discharge vessel arrangement

trodes, each of area 10×10 sq. cm. Dried air free from dust and water vapour has been studied in the present investigation. The gas pressure has been measured by a Pirani gauge which is calibrated by using a Maclead gauge for air. The rf voltage was supplied from a tuned-plate tuned-grid oscillator, the frequency of which is adjusted at a value 5·7 Mc/s for the present experiment. The experiments were repeated and the results were found to be consistent. The dc field has been supplied from an electronically stabilized variable voltage power supply and uniformity of the field has been maintained throughout the length of the discharge tube.

3. Results and Discussion

The variation of rf breakdown potential with pressure of the gas when a steady value of dc field is applied perpendicular to rf field, is shown for different values of dc field in case of air in Fig. 2 where the variation of breakdown potential without the dc field is also given for comparison.

It is seen that the general nature of variation of rf breakdown potential with pressure remains the same for all values of dc field studied and the breakdown potential increases for all values of pressure

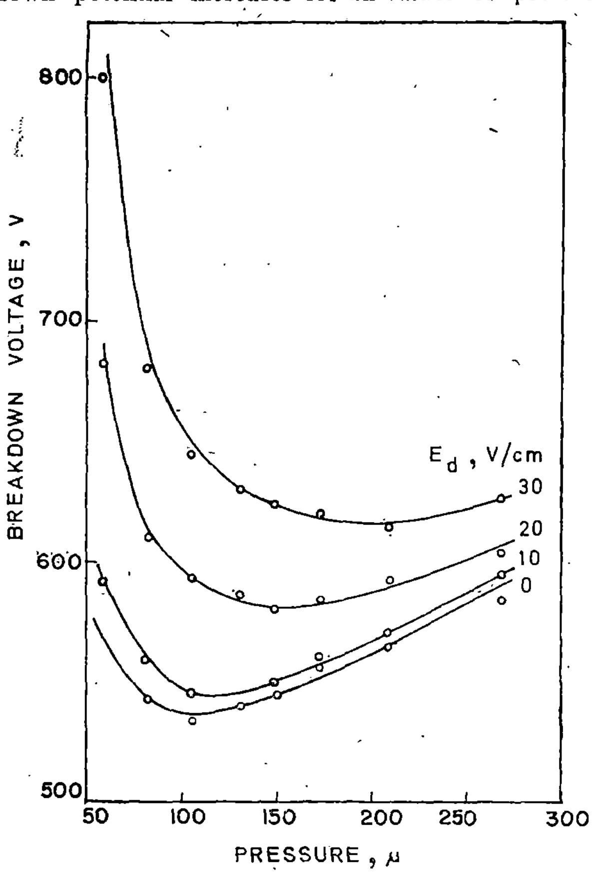

Fig. 2—Variation of breakdown potentials with pressure for different values of steady dc fields (E_d) applied perpendicular to the rf field

with the increase in dc field. As the rf breakdown potential increases with the increase in dc field, it is evident that beyond a certain dc field the power obtained from an rf source may not be sufficient enough to cause breakdown. Hence the present experiment has been performed for low dc fields only. The minimum rf breakdown potential of each curve for a fixed dc potential is found to shift towards higher pressure with increase in dc field.

The gas in a cavity will breakdown when the losses of electrons to the walls of the cavity are replaced by ionization in the body of the gas. When an ac field alone is applied, electrons are lost by diffusion and when in addition dc field is also applied, electrons are lost by mobility also. This loss is compensated by the ionization produced by rf and applied dc fields. If we neglect the contribution to ionization made by the dc field which will evidently be small specially for low dc fields then

$$D \nabla^2 n + \mu E_d \nabla n + \nu_i n = 0 \qquad \ldots(1)$$

where D and μ are diffusion and dc mobility coefficients, respectively, of electrons whose number density is n; ν_i is the coefficient of ionization and E_d is the dc electric potential applied along x-axis. High frequency field is assumed along y-axis. The solution of Eq. (1) is

$$n = A \cos(k_1 z) \cos(k_2 y) \cos\left\{\frac{\nu_i}{D} - k_1^2 - k_2^2 - \left(\frac{\mu E_d}{2D}\right)^2\right\}^{1/2} x \exp(-\mu E_d x/2D) \quad \ldots(2)$$

with the conditions

(i) $k_1^2 = \pi^2/b^2$; (ii) $k_2^2 = \pi^2/h^2$;

and

(iii) $\pi^2/l^2 = \frac{\nu_i}{D} - k_1^2 - k_2^2 - \left(\frac{\mu E_d}{2D}\right)^2$

In Eq. (2) A is a constant and l, b, h denote the length, breadth and height of the discharge tube. Combining (i), (ii) and (iii), we get,

$$\frac{\nu_i}{D} = \pi^2\left(\frac{1}{h^2} + \frac{1}{b^2} + \frac{1}{l^2}\right) + \left(\frac{\mu E_d}{2D}\right)^2 \qquad \ldots(3)$$

Eq. (3) gives the desired breakdown condition. Sen and Bhattacharjee[7] have already deduced that

$$\frac{\nu_i}{D} = A_0 \exp(-B_0 P/E_{rd}) P^2/r \qquad \ldots(4)$$

where E_{rd} = rf breakdown potential with dc field on; A_0 and B_0 are Townsend's constants introduced in his theory of breakdown of gases and $r = L/(2m/M)^{1/2}$

where L is the mean free path of the electron at a pressure of 1 torr and m and M are masses of electron and ion respectively.

Assuming the electrons to have a Maxwellian distribution in the present experimental condition, we can write

$$D/\mu = kT_e/e = r\, E_{rd}/P \quad \ldots(4a)$$

where T_e is the electron temperature and k = Boltzmann'sc onstant. Combining Eqs. (3), (4) and (4a) we get,

$$A_0 \exp\left(-B_0P/E_{rd}\right) P^2/r = \frac{1}{\Lambda^2} + \left(\frac{P\,E_d}{2r\,E_{rd}}\right)^2 \quad \ldots(5)$$

where

$$\frac{1}{\Lambda^2} = \pi^2\left(\frac{1}{h^2} + \frac{1}{b^2} + \frac{1}{l^2}\right)$$

When dc field is absent, the breakdown condition becomes

$$A_0 \exp\left(-B_0P/E_r\right) P^2/r = 1/\Lambda^2 \quad \ldots(6)$$

for the same pressure P where E_r is the rf breakdown potential without dc field.

From Eqs. (5) and (6)

$$\exp B_0P\left[\frac{E_{rd} - E_r}{E_{rd}\,E_r}\right] = 1 + \Lambda^2\left(\frac{P\,E_d}{2\,r\,E_{rd}}\right)^2$$

or

$$B_0P\left(\frac{E_{rd} - E_r}{E_{rd}\,E_r}\right) = \ln\{1+\Lambda^2\,(PE_d/2r\,E_{rd})^2\} \quad \ldots(7)$$

Eq. (7) shows that for all values of P and E_d, the rf breakdown potential with dc field on, is always greater than the rf breakdown potential without dc field.

Maximizing E_{rd} with P from Eq. (5) and as $L=1/A_0$ where A_0 is the constant in Townsend's[11] theory of breakdown of gases, we get,

$$B_0\,P/E_{rd} = 2 - \tfrac{1}{2}\,R^{1/2}\left(\frac{E_d}{E_{rd}}\right)^2 \exp\left(B_0\,P/E_{rd}\right) \quad \ldots(8)$$

where $R = 2m/M$

For the strongest dc field applied, and taking some representative values of E_{rd} and P, the expression becomes,

$\tfrac{1}{2}\,R^{1/2}\,(E_d/E_{rd})^2 \exp\,(B_0P/E_{rd}) \approx 0{\cdot}04$

The value on RHS can be neglected as compared to 2. Therefore, from Eq. (8) the pressure $P_{\min}$ at which breakdown potential E_{rd} is minimum is given by

$$P_{\min} = 2\,(E_{rd})_{\min}/B_0 \quad \ldots(9)$$

where $(E_{rd})_{\min}$ = Minimum breakdown potential.

As $(E_{rd})_{\min}$ increases with increase of dc field, so $P_{\min}$ shifts towards higher pressure with increase of dc field.

In Table 1, the values of $P_{\min}$ as calculated from Eq. (9) taking the experimental value of $(E_{rd})_{\min}$ from Fig. 2 are compared with those observed with different dc fields applied.

Table 1—Comparison Between the Observed and Calculated Values of $P_{\min}$

E_d (V/cm)	$(E_{rd})_{\min}$* (V/cm)	obs†	$P_{\min}$ (in mm of Hg) from Eq. (9)
0	26	0·12	0·14
10	27·5	0·13	0·15
20	31	0·16	0·17
30	32	0·20	0·18

* Values taken from Fig. 2; † deviation = ± 0·01.

The discrepancy between the two sets of values of $P_{\min}$ may be attributed to the uncertainties in the values of different parameters used. Also the approximations in Eqs. (4) and (8) and the assumption that most of the collisions are elastic, which is only approximately true in the present experimental condition, may be responsible for the discrepancy between two sets of values of $P_{\min}$. The attachment loss of electrons and ionization due to dc field which have not been taken into consideration may have some influence on the theoretical values of $P_{\min}$, because it has been observed previously[8] that the variation of rf breakdown voltage with dc field applied parallel to rf field and the existence of a maximum for the rf breakdown voltage can be satisfactorily explained by assuming contribution by dc ionization and attachment loss. So it can be concluded that for a more rigorous treatment of the problem, the attachment as well as ionization by the dc field should be taken into consideration. Experimental work is in progress with highly attaching and non-attaching gases so that a rigorous theory may be worked out incorporating the ionization and attachment factors which will enable us to understand the mechanism operating in discharges excited by the crossed rf and dc fields.

4. Conclusion

As a preliminary observation, it can be stated that the effect of application of small dc field transverse to rf field, in gas breakdown mechanism, is equivalent to reduction of effective diffusion length. Besides the loss due to attachment, there is also a possible contribution of dc field to production of electrons by ionization as well.

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