## SUMMARY OF THE PRESENT WORK & CONCLUSION

In the present study some of the properties of ionised gases have been investigated under both transverse and longitudinal magnetic fields and following conclusions have been made. The ionised gases investigated are molecular gases such as hydrogen, oxygen, air ~~carbondioxide~~ and ammonia and both d.c. and radio frequency fields have been employed for excitation. The range of pressure has been varied from a few microns to a few torrs and the magnetic field employed lies between zero to 2000 gauss.

In chapter III a theoretical investigation of the radio frequency conductivity of ionised gases has been carried out under a transverse magnetic field taking into consideration the theoretical deduction of Beckman regarding the radial density distribution of charge carriers. It is concluded that if the magnetic field is varied then to have a measurable magnetic field at which the r.f. conductivity attains a maximum value the measuring field must have a frequency in either the ultrahigh frequency or in the microwave region. On the other hand if the pressure is gradually varied then a maximum in the pressure conductivity curve can be obtained in the radio frequency region. The theoretical deductions are verified experimentally in a satisfactory manner and the charge carrier density and the collision frequency have been obtained, In case of ionised gases such as hydrogen, oxygen, air and ammonia. The measurement of plasma conductivity in a magnetic field thus affords a reliable method for the measurement of plasma parameters. Beckman's calculation regarding the variation of radial electron density in a magnetic field has been verified while the other aspect namely the increase of the axial field need not be taken into consideration as the measurement of conductivity is made in a direction perpendicular to both the electric and magnetic fields. In all previous work the radial electron density has been assumed constant but here our calculations have taken into consideration the radial variation of electron density in a magnetic field.

In chapter IV momentum transfer collision cross section for slow electron in hydrogen and x oxygen in a transverse magnetic field varying from zero to 1850 gauss have been obtained by studying the variation of radio frequency conductivity of the ionised gas within the pressure range of a few microns to 6 torr. The momentum transfer cross section is g higher than that without field for the same range of electron energies. The results have been discussed in the light of the experimental breakdown voltage measurements in these gases. A suitable but accurate method of measurement of the momentum transfer cross section and its variations in a magnetic field has been suggested.

In chapter V the variation of current and voltage in a d.c. excited glow discharge has been studied in a longitudinal magnetic field varying from zero to 1600 gauss for values of pressure varying from 0.685 to 0.925 torr in air and hydrogen. The current gradually rises and the voltage gradually decreases up to 800 gauss and then both attain saturation values from these measurements the experimental values regarding the radial variation of charge carrier density with longitudinal magnetic field has been obtained. Starting from some basic postulates a detailed theoretical treatment of the problem regarding the radial variation of charge carrier density in the longitudinal magnetic field has been presented. The theoretical deductions are in very good agreement with experimental results. The results further indicate that the radial distribution of charge carriers can be well represented by a Bessal function in presence of magnetic field as well.

Chapter VI deals with the phenomena of breakdown in hydrogen, oxygen and air excited by a r.f. field in a longitudinal magnetic field varying from zero to 600 gauss, and over a range of pressure varying from a few ~~da~~ microns to a ~~frm~~ few torr. It is observed that the breakdown voltage decreases with the application of the magnetic field and the pressure at which the breakdown voltage becomes minimum always shifts to the lower pressure with the increase of the magnetic field. The object of this work is to ~~build~~ find the limitations of the diffusion theory of breakdown of the gas. The values of ( $\alpha/p$ ) where $\alpha$ is the Townsend's first ionization coefficient, has been calculated both from the theory of Brown (1949) and that of Kihara (1952) from the experimentally determined breakdown voltages and compared with the values of ( $\alpha/p$ ) published in literature. There is striking agreement between the two within the values of ( $E/p$ ) investigated and this establishes on a sound experimental basis the fact that within the range of pressure, dimension of the discharge tube and frequency of the applied field, ~~applied~~ the loss of electrons is mainly governed by the process of diffusion. Having established the fact that diffusion is the dominent loss mechanism the diffusion length as well as the pressure for minimum breakdown voltage have been calculated in presence of magnetic field and the agreement with the experimental results is very much satisfactory. The general conclusion has thus been drawn that not only in the case of gases excited by microwaves but also in case of radio frequencies the dominent loss mechanism of charge carrier in a discharge is governed by the process of diffusion.

In order to verify by direct experimental determination the mechanism of loss processes due to diffusion in a magnetic field, the diffusion coefficient (or diffusion length) in the magnetic field has been obtained by measuring the d.c. conductivity of the ionised gases. When the magnetic field is applied and the results are incorporated in chapter VII. The conductivity shows a maximum at a certain value of the magnetic field and a detailed mathematical treatment has been provided to explain the occurance of this maxima; quantitative agreement between experimental and theoretical results has been obtained. The experimental results regarding the variation of diffusion length in a magnetic field indicates that for values of (H/P) used here the normal diffusion process takes place and the coefficient varies inversely as $H^2$ according to Townsend and Gill's theory. No evidence of anomalous diffusion has been obtained.

In the last chapter, the variation of electron temperature and charge carrier density in ionised gases have been determined by the Langmuir single probe method when magnetic field is either transverse of longitudinal. This has brought out clearly the fact that the alignment of magnetic field with the undisturbed flow of current in a plasma interacts in different manner in the variation of plasma parameters. Whereas in case of a transverse magnetic field the electron temperature increases and radial electron density distribution decreases in case of a longitudinal magnetic field the electron temperature decreases whereas the radial electron density increases. The experimental results support the quantitative derivations deduced earlier.

The present work thus has provided experimental data and their theoretical interpretation regarding the various properties of ionised gases and their interactions with transverse and longitudinal magnetic fields.

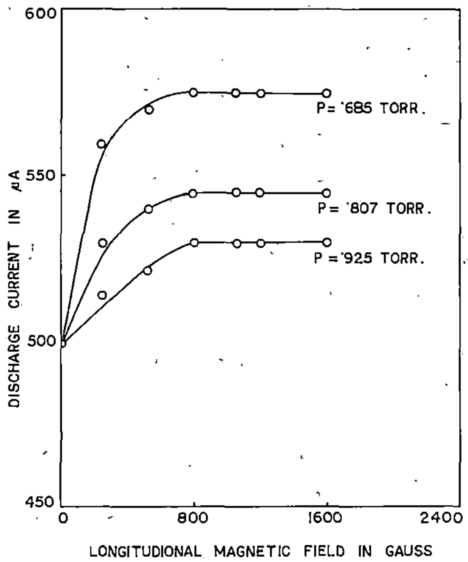


Fig. 2. Variation of discharge current in magnetic field.

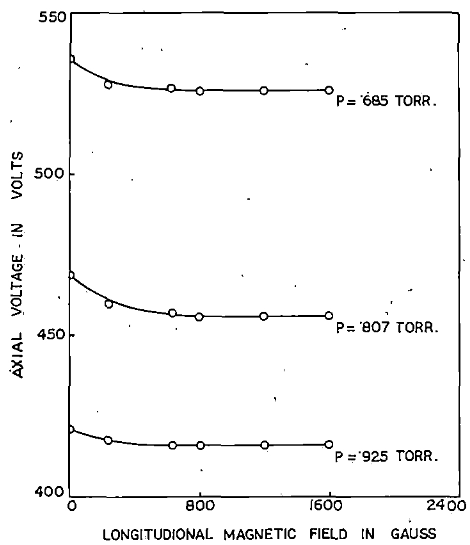


Fig. 3. Variation of voltage across the tube in magnetic field.

volume and $\nu_c$ is the collision frequency for momentum transfer; then

$$j=\frac{ne^2\lambda_e E}{mv_r},$$

where $\lambda_e$ is the mean free path of the electron and $v_r$ the random velocity. Hence

$$j=\frac{ne^2\lambda_e E}{\sqrt{3mkT_e}},$$

where $T_e$ is the electron temperature.

$V_0$ is the supply voltage from the stabilizer, $V_c$ and $V_A$ are the cathode and anode fall respectively. $R$ the series resistance (220 K$\Omega$), $l$ is the length of the positive column and $L$ is the mean free path of electron at 1 Torr. As under the condition of the experiment the positive column extends from cathode to anode, $l$ is taken to be the distance between the two electrodes.

$$j=\frac{ne^2L[V_0-\{V_A+V_c\}-IR]}{\sqrt{3mk}\,Pl\sqrt{T_e}}.$$

The total current

$$I=\frac{ne^2L[V_0-\{V_A+V_c\}-IR]}{\sqrt{3mk}\,Pl\sqrt{T_e}}2\pi\int_0^{R_w} nr\,\mathrm{d}r,$$

where $R_w$ is the radius of the discharge tube.

Hence

$$I=\frac{V_0-(V_c+V_A)}{R+C}, \tag{1}$$

where

$$\frac{1}{C}=\frac{e^2L}{\sqrt{3mk}\,Pl\sqrt{T_e}}2\pi\int_0^{R_w} nr\,\mathrm{d}r. \tag{2}$$

In the cathode region most of the electrons move with relatively high speed normal to the cathode surface. A longitudinal magnetic field therefore has little effect upon the properties of the dark space except to inhibit the radial motion of those electrons which are scattered by hitting gas molecules. Hence no significant effect on cathode fall has been noticed when a longitudinal magnetic field is applied. The theory of the anode fall proposed by Von Engel shows that a longitudinal magnetic field will have little effect on anode fall. Further it has been shown by Penning, Moubis and Jurriaanse[7)] that there is a slight variation in cathode and anode fall (of the order of 2.5 volts for a change of discharge current of 10 mA). The maximum change of discharge current here is of the order of .080 milliamperes and hence for this small change of discharge current variation of cathode and anode fall have not been taken into consideration. If it is assumed that the application of magnetic field changes the electron temperature and radial electron density the current in presence of longitudinal magnetic field is

$$I_H=\frac{V_0-(V_c+V_A)}{R+C_H}, \tag{3}$$

where

$$\frac{1}{C_H}=\frac{e^2L}{\sqrt{3mk}\,Pl\sqrt{T_{eH}}}2\pi\int_0^{R_w} n_H r\,dr, \quad (4)$$

where $n_H$ and $T_{eH}$ are the electron density and electron temperature in presence of the magnetic field. The values of $V_c$ and $V_A$ in case of air have been obtained from Brown[8]) and from the experimental values of $I$ and $I_H$ at different values of magnetic field it is possible to calculate the values of $C$ and $C_H$ from eqs. (1) and (3) and the results are entered in the second and third columns of Table I for a pressure of .685 Torr. Similar calculations have been performed for pressures of .807 and .925 Torr and the results are tabulated in Tables II and III respectively.

In order to evaluate theoretically the values of $C$ and $C_H$ and compare it with the experimental results it is necessary to assume

Table I. $P$=.685 Torr.

| Magnetic field in gauss | $C\times10^{-6}$ | $C_H\times10^{-6}$ | $C/C_H$ | $T_e/T_{eH}$ | $C/C_H$ from theory | $n_H/n$ from theory |
|---|---|---|---|---|---|---|
| 0 | .272 | | 1 | 1 | 1 | 1 |
| 50 | | .2576 | 1.056 | 1.006 | 1.049 | 1.029 |
| 100 | | .2485 | 1.094 | 1.013 | 1.087 | 1.045 |
| 150 | | .2388 | 1.139 | 1.019 | 1.131 | 1.092 |
| 200 | | .2305 | 1.180 | 1.025 | 1.162 | 1.148 |
| 250 | | .2240 | 1.213 | 1.029 | 1.199 | 1.176 |
| 300 | | .2187 | 1.242 | 1.034 | 1.226 | 1.196 |
| 350 | | .2169 | 1.256 | 1.036 | 1.242 | 1.233 |
| 400 | | .2146 | 1.268 | 1.038 | 1.250 | 1.262 |
| 500 | | .2108 | 1.290 | 1.040 | 1.275 | 1.268 |
| 600 | | .2092 | 1.301 | | | |

Table II. $P$=.807 Torr.

| Magnetic field in gauss | $C\times10^{-6}$ | $C_H\times10^{-6}$ | $C/C_H$ | $T_e/T_{eH}$ | $C/C_H$ from theory | $n_H/n$ from theory |
|---|---|---|---|---|---|---|
| 0 | .18 | | 1 | 1 | 1 | 1 |
| 50 | | .1737 | 1.039 | 1.015 | 1.029 | 1.017 |
| 100 | | .1698 | 1.060 | 1.026 | 1.052 | 1.028 |
| 150 | | .1661 | 1.083 | 1.034 | 1.078 | 1.056 |
| 200 | | .1623 | 1.109 | 1.047 | 1.093 | 1.087 |
| 250 | | .1595 | 1.128 | 1.052 | 1.110 | 1.125 |
| 300 | | .1573 | 1.145 | 1.058 | 1.132 | 1.151 |
| 350 | | .1549 | 1.162 | 1.061 | 1.152 | 1.162 |
| 400 | | .1531 | 1.176 | 1.064 | 1.162 | |
| 500 | | .1497 | 1.202 | 1.067 | 1.189 | |
| 600 | | .1483 | 1.213 | 1.069 | 1.192 | |

Table III. $P$=.925 Torr.

| Magnetic field in gauss | $C\times10^{-6}$ | $C_H\times10^{-6}$ | $C/C_H$ | $T_e/T_{eH}$ | $C/C_H$ from theory | $n_H/n$ from theory |
|---|---|---|---|---|---|---|
| 0 | .084 | | 1 | 1 | 1 | 1 |
| 50 | | .0835 | 1.006 | 1.007 | 1.002 | 1.008 |
| 100 | | .0826 | 1.017 | 1.016 | 1.010 | 1.024 |
| 150 | | .0807 | 1.041 | 1.023 | 1.032 | 1.042 |
| 200 | | .0789 | 1.064 | 1.027 | 1.059 | 1.069 |
| 250 | | .0778 | 1.080 | 1.030 | 1.071 | 1.066 |
| 300 | | .0761 | 1.104 | 1.034 | 1.092 | 1.122 |
| 350 | | .0749 | 1.121 | 1.037 | 1.113 | 1.131 |
| 400 | | .0732 | 1.148 | 1.041 | 1.129 | |
| 500 | | .0710 | 1.183 | 1.044 | 1.159 | |

some radial distribution function for the electron density for evaluation of the integral in eqs. (2) and (4).

In the region of pressure $10^{-1}$ to 10 mm of mercury where the diffusion theory holds it has been shown by Schottky[9] that the loss of ions and electrons is entirely due to diffusion; if volume recombination is neglected we have,

$$\frac{d^2n}{dr^2}+\frac{1}{r}\cdot\frac{dn}{dr}+\frac{\nu_i}{D_a}n=0,$$

where $\nu_i$ is the frequency of ionization that is the number of electrons produced per electron per unit time and $D_a$ is the ambipolar diffusion coefficient. The solution is the zero order Bessel function

$$n=n_0J_0\left(r\sqrt{\frac{\nu_i}{D_a}}\right).$$

In the balance of production rate $\nu_i$ and diffusion $D_a$ Brown[8] has shown that

$$\frac{\nu_i}{D_a}=\frac{1}{\Lambda^2},$$

where $\Lambda$ is the diffusion length.

So that $n=n_0J_0(r/\Lambda)$ Putting the value of $n$ in eq. (2)

$$\frac{1}{C}=\frac{n_0e^2L}{\sqrt{3mk}\,Pl\sqrt{T_e}}2\pi\Lambda R_wJ_1(R_w/\Lambda). \tag{5}$$

In presence of magnetic field assuming that $\nu_{iH}$ is the frequency of ionization per unit electron and $D_{aH}$ the ambipolar diffusion coefficient,

$$\frac{d^2n_H}{dr^2}+\frac{1}{r}\cdot\frac{dn_H}{dr}+\frac{\nu_{iH}}{D_{aH}}n_H=0,$$

and the solution of the equation is given by

$$n_H=n_0J_0\left(r\sqrt{\frac{\nu_{iH}}{D_{aH}}}\right),$$

now

$$D_a=\frac{D_e\mu_++D_+\mu_e}{\mu_++\mu_e},$$

where $D_e$ and $D_+$ are the diffusion coefficients of the electron and positive ion respectively and $\mu_e$ and $\mu_+$ are the respective mobilities; expressing $\mu/D=e/kT$ and neglecting the mobility of positive ion in comparison to that of electron we get

$$D_a=D_+\frac{T_e}{T_+}.$$

Since the independent diffusion of positive ions and the temperature of the positive ions are negligibly effected by the magnetic field the variation of $D_a$ in a longitudinal magnetic field will be the same as that due to variation of electron temperature in the magnetic field.

Hence we get

$$D_{aH}=D_+\frac{T_{eH}}{T_+}$$

and

$$\frac{\nu_{iH}}{D_{aH}}=\frac{1}{\Lambda_H^2},$$

where $\Lambda_H$ is the effective diffusion length in presence of the magnetic field. We have then

$$\frac{1}{\Lambda^2}=\frac{\nu_i}{D_A}=\frac{\nu_i}{D_+}\frac{T_+}{T_e},$$

and

$$\frac{1}{\Lambda_H^2}=\frac{\nu_{iH}}{D_{aH}}=\frac{\nu_{iH}}{D_+}\frac{T_+}{T_{eH}},$$

then

$$\frac{1}{\Lambda_H^2}=\frac{1}{\Lambda^2}\frac{\nu_{iH}}{\nu_i}\frac{T_e}{T_{eH}}.$$

It has been shown by Bickerton and Von Engel[6] who measured the axial electric field and the electron temperature at various values of the longitudinal magnetic field that

$$\frac{E_H}{E}=\frac{T_{eH}}{T_e}\sqrt{\frac{\kappa_H}{\kappa}},$$

where $\kappa_H$ and $\kappa$ are the fractions of energy lost by the electron due to elastic collision in presence of magnetic field and in its absence respectively. They further showed that as $\kappa_H=\kappa$ no new process results from the application of the magnetic field. As the values of $E_H$ have been measured directly in our experiment, it is possible to calculate the ratio $T_{eH}/T_e$ and the results are entered in the fifth column of Table I. As it has been shown by Bickerton and Von Engel that $T_e/T_{eH}=E/E_H$

$$\frac{1}{\Lambda_H^2}=\frac{1}{\Lambda^2}\frac{\nu_{iH}}{\nu_i}\frac{E}{E_H},$$

and hence

$$n_H=n_0J_0(r/\Lambda_H).$$

Putting the value of $n$ in eq. (4) and integrating we get

$$\frac{1}{C_H}=\frac{n_0e^2L}{\sqrt{3mk\,Pl}\sqrt{T_{eH}}}2\pi\Lambda_H R_w J_1(R_w/\Lambda_H). \quad (6)$$

Hence from eqs. (5) and (6) we get

$$\frac{C}{C_H}=\sqrt{\frac{E}{E_H}}\frac{\Lambda_H}{\Lambda}\frac{J_1(R_w/\Lambda_H)}{J_1(R_w/\Lambda)}$$
$$=\left\{\frac{\nu_i}{\nu_{iH}}\right\}^{1/2}\frac{J_1(R_w/\Lambda_H)}{J_1(R_w/\Lambda)}. \quad (7)$$

The variation of $\nu_{iH}$ with magnetic field has been studied by Bickerton and Von Engel in case of helium where it is shown that $\nu_{iH}$ decreases with the increase of the magnetic field. The effect is considerable at low pressure (Bickerton and Von Engel,[6] $P=.048$ Torr); to calculate the change at the pressure at which the present experiments have been carried out it is noted from the expression given by Brown[8] that

$$\frac{\nu_{iH}}{\nu_i}=\frac{\exp(-eV_i/kT_{eH})}{\exp(-eV_i/kT_e)}\frac{[1+eV_i/kT_{eH}]}{[1+eV_i/kT_e]},$$

as $eV_i/KT_e$ is $\gg 1$

$$\frac{\nu_{iH}}{\nu_i}=\exp\left[-\frac{eV_i}{k}\frac{T_e-T_{eH}}{T_eT_{eH}}\right]\frac{T_e}{T_{eH}}$$
$$=\exp\left[-\frac{eV_i}{k}\frac{E-E_H}{\alpha EE_H}\right]\frac{E}{E_H}$$
$$=\frac{E}{E_H}-\frac{eV_i}{k}\frac{E-E_H}{\alpha E_H^2},$$

where $\alpha$ is the proportionality between the electron temperature and the electric field, for constant pressure. It is thus possible to calculate $\nu_{iH}/\nu_i$ for different values of the magnetic field and pressure. In case of a cylindrical tube

$$\frac{1}{\Lambda}=\left[\left\{\frac{\pi}{h}\right\}^2+\left\{\frac{2\cdot405}{R_w}\right\}^2\right]^{1/2},$$

where $h$ is the distance between the electrodes and $R_w$ is the radius of the discharge tube. Putting the value of $h$ and $R$ $1/\Lambda=2.078\,\text{cm}^{-1}$.

It is thus possible to calculate theoretically the ratio $C/C_H$ from eq. (7) and the results are entered in the sixth columns of Tables I, II and III for the three pressures and for various values of the magnetic field. It is thus evident that the theoretical results though not exactly equal to experimental values are very close specially for low values of magnetic field used. This can be taken as a justification of our assumption that the electron density profile is given by

$$n=n_0J_0(r/\Lambda),$$

in absence of the field and by

$$n_H=n_0J_0\left(\frac{r}{\Lambda}\left\{\frac{\nu_{iH}}{\nu_i}\frac{E}{E_H}\right\}^{1/2}\right),$$

when the the longitudinal magnetic field is present. The last column in all the three tables gives the ratio $n_H/n$ as calculated from the above relations. The results further show that magnetic field does not change the radial distribution of ions and electrons from the normal Bessel function. Cummings and Tonks[10] also came to the same conclusion from a detailed theoretical analysis.

We can thus bring out the difference in the behaviour of a swarm of electrons and their associated properties in transverse and longitudinal magnetic fields. In case of a transverse field and following the theory of Beckman[4] we note that the axial field and electron temperature increase whereas the radial electron density decreases and as reported in our previous paper (Sen and Gupta[5]) the discharge current shows a maximum at a certain value of the magnetic field which is dependent upon the pressure. In case of a longitudinal magnetic field the axial electric field and electron temperature decrease whereas the radial electron density increases and the discharge current gradually increases and finally assumes a constant value. In both the cases however, the radial distribution of electrons is governed by the normal Bessel function.

It is further noted that though the measurements reported here have been made for a magnetic field upto 1600 gauss, the observed change in current and voltage is significant upto a field of 800 gauss and beyond that both assume a constant value. The case of anomalous diffusion will depend not only upon the magnetic field $H$, but on the ratio of $H/P$ where $P$ is the pressure. In our present investigation for the values of $H/P$ used no evidence of anomalous diffusion has been observed.

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# Validity of diffusion theory in radio frequency breakdown in molecular gases in longitudinal magnetic field

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# Validity of diffusion theory in radio frequency breakdown in molecular gases in longitudinal magnetic field

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**Abstract.** The breakdown of a gas excited by a radio frequency voltage of frequency 5·6 MHz has been studied in a cylindrical discharge tube 7·2 cm long and 2·9 cm in dia and fitted with two internal electrodes at a distance of 2·5 cm in hydrogen, oxygen and air within the pressure range of a few microns to 2 torr in the presence of a longitudinal magnetic field varying from zero to 800 G. Experimental results indicate that the breakdown is diffusion controlled and the values of $(\alpha/P)$ at different $E/P$ values calculations obtained by Brown as well as by Kihara's theory have been compared with $(\alpha/P)$ values obtained in the literature. It is concluded that the diffusion theory is also valid when the frequency of the exciting voltage is scaled down to radio frequency provided the collision frequency is much higher than the exciting frequency. The change of diffusion length in the presence of longitudinal magnetic field has been obtained from measured $E/P$ values and comparison with theoretical values indicates that there is quantitative agreement for small $(H/P)$ values where $H$ is the magnetic field. The calculated values of pressure at which the breakdown voltage shows a minimum in the presence of magnetic field is in very good agreement with experimental values. It is concluded that in the presence of magnetic field also the loss of electrons takes place predominantly by the process of diffusion.

**Keywords.** Breakdown of gas; diffusion; radiofrequency.

## 1. Introduction

The study of the breakdown of a gas excited by high frequency electromagnetic field has shown that the breakdown voltage depends upon the pressure of the gas, the dimension of the discharge tube and the frequency of excitation. The dominant factors responsible for the loss of electrons are diffusion and mobility and if the gas is electron attaching, the loss also takes place by electron attachment. It has been observed that when the pressure of the gas is of the order of a few millitorr and the length of the discharge tube is large as compared with the mean free path of the electrons in the gas, both the mobility and diffusion are the dominant factors by which electrons are removed. On the other hand, when the gas pressure is high and the exciting frequency of the applied voltage lies in the microwave region, the electrons are lost mainly by diffusion. The theoretical method of calculating the breakdown voltage of a gas excited by high frequency voltages at high pressure has been developed by Herlin and Brown (1948) where the dominant factor for electron removal process has been assumed to be diffusion. Starting from a molecular model, Kihara (1952) developed a theoretical method to calculate the breakdown voltage of a gas under high frequency excitation taking into consideration the loss due to mobility and diffusion. In a series of papers from this laboratory (Sen and Ghosh 1963; Sen and Bhattacharjee 1965, 1966, 1967) the experimental results have indicated that when the pressure is of the order of a few millitorr and the frequency of excitation of the order of a few MHz, the major electron removal processes are diffusion and mobility.

To test the limitations of the diffusion theory, it is proposed here to undertake some experiments on the breakdown voltages of gases where the frequency of the exciting voltage is of the order of a few MHz and the pressure of the gas is of the order of a few torr. To study the effect of attachment, breakdown measurements have been made in some electron attaching gases such as air and oxygen. The object of the present investigation is to find out whether the loss mechanism remains the same when the frequency of the exciting voltage is scaled down from microwave to radio frequencies keeping the pressure in the range of a few torr.

The breakdown of a gas excited by a radio frequency field in presence of a magnetic field has been studied previously by Lax *et al* (1950) who performed experiments on the breakdown voltage of helium containing a small admixture of mercury vapour and obtained breakdown curves for different values of the pressure. Ferritti and Veronesi (1955) performed experiments for frequencies ranging from 10 to 30 MHz in air, the magnetic field varying from 0–600 G and observed a lowering of breakdown voltage in the presence of magnetic field. Sen and Bhattacherjee (1969) performed experiments in the case of air, hydrogen, oxygen and carbon dioxide in the presence of a magnetic field from 300–1800 G.

Brown (1956) has explained the change of breakdown voltage observed in presence of magnetic field by assuming that the diffusion length in the presence of a magnetic field is altered according to the equation.

$$\Lambda_H^2 = \Lambda^2 \left[1 + \frac{\omega_B^2}{\nu_C^2}\right]$$

where $\Lambda$ and $\Lambda_H$ are respectively the diffusion lengths in the absence and in the presence of magnetic field. $\omega_B$ is the electron cyclotron frequency and $\nu_C$ is the collision frequency. To make a further test of diffusion theory in the presence of a magnetic field, it is also proposed to verify the above equation of Brown from the experimental results obtained in the present set of experiments. The results are expected to prove the validity of the diffusion theory in the presence and absence of the applied magnetic field.

## 2. Experimental arrangement

The method of measurement of breakdown voltage was the same as was used earlier (Sen and Ghosh 1963). The discharge tube of 7·2 cm long, cylindrical, and fitted with two internal electrodes with a separation distance of 2·5 cm and discharge tube was 2·9 cm in dia. The radio frequency voltage was supplied from a tuned grid tuned plate oscillator, the frequency of the oscillator being variable from 3·5–11 MHz and the output of the oscillator could be continuously varied from 0–550 volts. The r.m.s. output voltage was measured with a vacuum tube voltmeter.

The pressure of the gas was measured with a calibrated Mcleod gauge. The magnetic field was provided by an electromagnet, the lines of force were parallel to the length of the discharge tube which was placed entirely within the polepieces of the electromagnet. The magnetic field was measured with a calibrated fluxmeter. Keeping the magnetic field at a constant value, the pressure was varied and the breakdown voltage measured for various values of gas pressure. The experiments were repeated and the results were found to be reproducible within $\pm 1\%$.

Pure and dry air was passed through phosphorus pentoxide to remove traces of water vapour. Hydrogen was prepared by electrolysing warm concentrated solution of barium hydroxide in a hard glass U-tube fitted with nickel electrodes in which hydrogen gas was liberated at the cathode. The gas was dried by passing it over broken pieces of potassium hydroxide and then over purified phosphorus pentoxide. Pure oxygen was evolved at the anode in the electrolysis of barium hydroxide solution and was passed through pure concentrated sulphuric acid before collection in the discharge tube.

## 3. Results and discussion

The breakdown voltages for hydrogen, oxygen and air have been plotted for different values of pressure (0·1 to 2·4 torr) with and without magnetic field (110 g to 795 g) in figures 1, 2 and 3 respectively. It is observed that the breakdown voltage is always smaller in the presence of the magnetic field than in its absence for all values of pressure and the pressure at which the breakdown voltage becomes

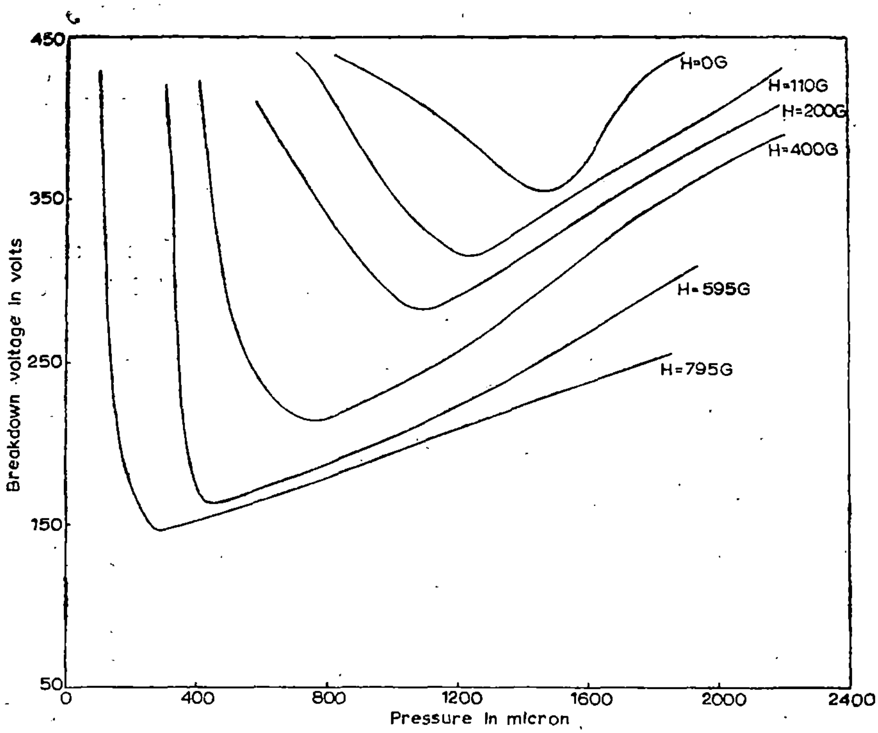


**Figure 1.** Variation of breakdown voltage with pressure: hydrogen.

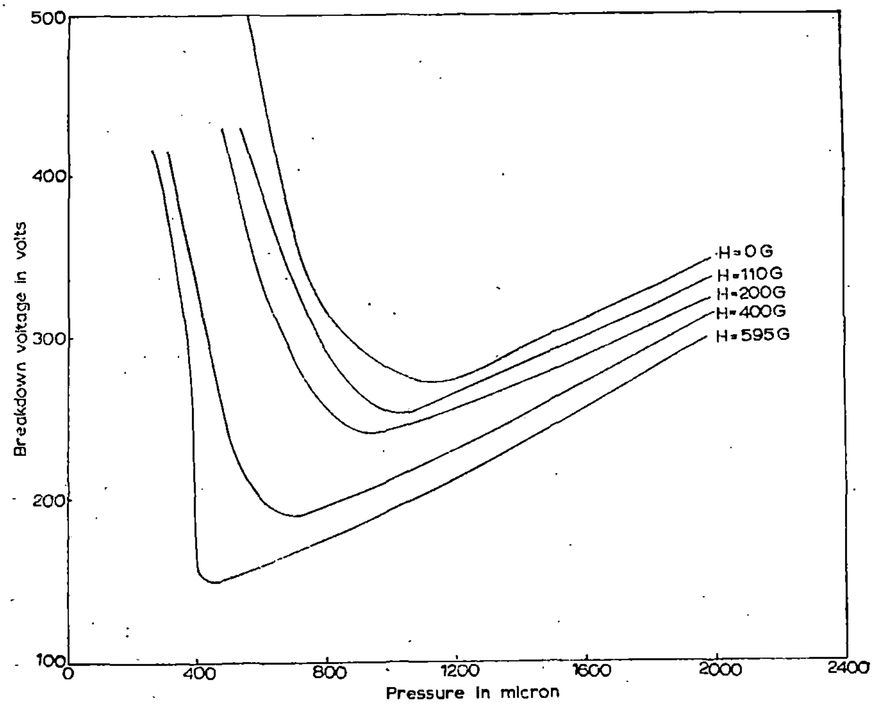


Figure 2. Variation of breakdown voltage with pressure: oxygen.

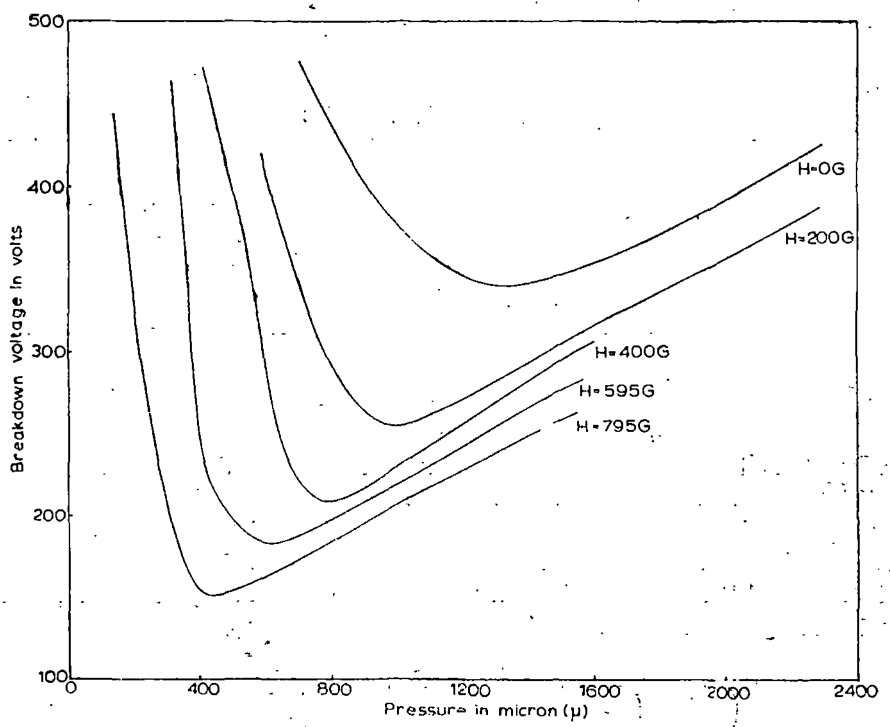


Figure 3. Variation of breakdown voltage with pressure: Air.

minimum always shifts to lower pressure with the increase of the magnetic field. To provide a meaningful interpretation, it is proposed to examine the results in the light of the prevalent theories (Brown 1959; Kihara 1952). In order to deter mine which process is predominant in electron removal under the present experimental set up the following points have been considered:

(i) According to Brown for the diffusion theory to be valid the dimensions of the discharge tube must be small compared to wavelength of the exciting power. As the wavelength is of the order of 51·2 cm and the length of the discharge tube is 7·2 cm and 2·6 cm dia. this condition is satisfied.

(ii) The maximum mean free path of the gases used here is 0·6 cm at a pressure of 0·1 torr (Townsend 1947) which is much smaller than either the length or radius of the tube.

(iii) The amplitude of electron oscillation when calculated from the equation

$$x = \frac{eE_0}{m\omega\,[\omega^2 + \nu^2]^{1/2}}$$

where $E_0$, the field intensity, is 0·02 cm at a pressure of 1 torr and will be smaller at higher pressures.

(iv) The collision frequency is $v_r/\lambda_e$ where $v_r$ is the random velocity and $\lambda_e$ is the mean free path and is of the order of $10^9$ collisions/sec and is much greater than the exciting frequency even at a pressure of 1 torr.

Under the above conditions, it is apparent that the electrons make many oscillations of small amplitude, because the motion is restricted by collisions and the cloud of electrons appear stationary (there being no drift motion), spreading outwards only by diffusion. Hence loss due to drift can be neglected. New charged particles are formed due to ionizing collisions and loss due to diffusion predominates. In case of electron attaching gases, the loss due to attachments should also be taken into consideration.

As stated above, under the present experimental set up and range of pressure investigated the electron suffers many collisions per oscillation of the field. Brown pointed out that as pressure increases, mean free path decreases and the energy gain per mean free path is proportional to mean free path at constant $E$. In order to cause breakdown, the field must increase in inverse proportion with the mean free path or in direct proportion with pressure. Thus at high pressure where the electrons make many collisions per oscillation their behaviour is much the same as in the case of d.c. field. The value of $(\alpha/P)$ where $\alpha$ is the ionization coefficient can then be calculated from the experimental values of $E/P$ from the Townsend's relation

$$\alpha/P = A_0 \exp\,[-B_0/(E/P)] \tag{1}$$

where $A_0$ and $B_0$ are the values of constants for a particular gas.

Kihara (1952) has treated the phenomenon of electrical discharge by adopting a proper molecular model for collision processes. Assuming a model for the cross section of the molecule for elastic, exciting and ionization collisions with a Maxwellian distribution of electron velocities which is nearly valid for the case of molecular gases studied here, he has deduced that

$$\frac{\alpha}{P} = \left(\frac{N}{P}\right)\frac{\sigma}{C_i}\left(\frac{3\lambda}{\rho}\right)^{1/2} \exp\left[\frac{-mC_i^2\left(\frac{N}{P}\right)(3\lambda\rho)^{1/2}}{2e\cdot(E/P)}\right] \tag{2}$$

where $\sigma$ is a molecular constant equivalent to collision cross section, $\lambda$ is another constant having the dimension of $cm^3\ S^{-1}$, $N$ is the number density of the gas atom, $K$ is the Boltzman constant, $\rho$ is another molecular constant having the dimension of cms. The values of these molecular constants have been provided by Kihara (1952).

The values of $(\alpha/P)$ have been calculated from eq. (1) using the experimental values of $(E/P)$ obtained in the present investigation for hydrogen. The values of $(\alpha/P)$ have also been calculated from eq. (2) for corresponding values of $(E/P)$ using the numerical values of the constants given by Kihara. The results for hydrogen have been plotted in figure 4 and for purposes of comparison, the published experimental values of $(\alpha/P)$ from literature are also plotted in the figure. In the case of electron attaching gases such as air and oxygen, the loss due to attachment is also taken into consideration and the ionization coefficient $(\alpha/P)$ have been calculated from the expression

$$\frac{\alpha}{P}=\frac{\alpha_a}{P}+A_0\exp\left(-\frac{B_0}{E/P}\right). \tag{3}$$

Similarly from Kihara's theory it can be shown that when attachment is taken into consideration

$$\nu-\nu_a=N\cdot\frac{3\sigma}{C_i}\frac{KT_e}{m}\exp\left[-\frac{mC_i^2}{2KT_e}\right]$$

and hence

$$\frac{\alpha}{P}=\frac{\alpha_a}{P}+\frac{N}{P}\cdot\left(\frac{\sigma}{C_i}\right)\left(\frac{3\lambda}{\rho}\right)^{1/2}\exp\left[\frac{-mC_i^2\left(\frac{N}{P}\right)(3\lambda\rho)^{1/2}}{2e\cdot E/P}\right]. \tag{4}$$

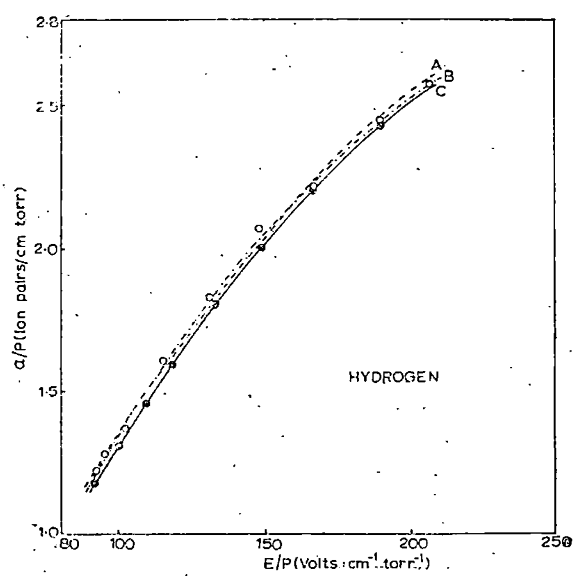


**Figure 4.** Variation of $(\alpha/P)$ with $E/P$ for hydrogen A: Kihara; B: Brown; C: Literature values.

The values of $(\alpha_a/P)$ for air and oxygen for different $(E/P)$ values have been obtained from (Brown 1959) and $(\alpha/P)$ values have been calculated from eq. (3) using experimental values of $(E/P)$ obtained and also from eq. (4) and then plotted in figures 5 and 6 for oxygen and air respectively together with values obtained from literature.

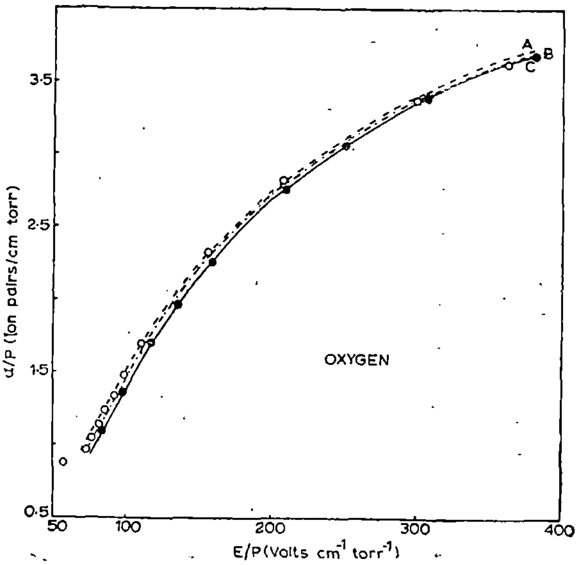


**Figure 5**: Variation of $(\alpha/P)$ with $(E/P)$ for oxygen: A: Kihara; B: Brown; C: Literature values.

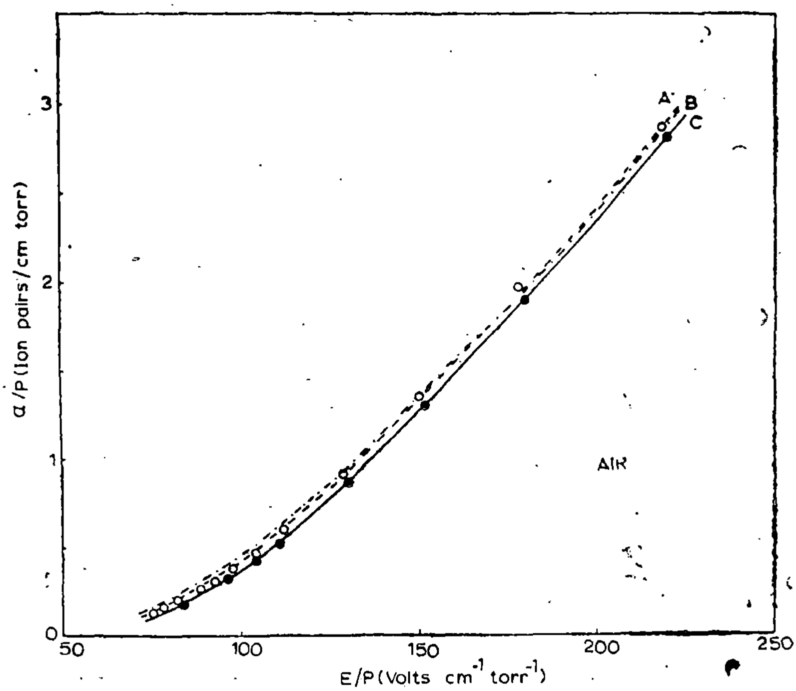


**Figure 6**. Variation of $(\alpha/P)$ with $(E/P)$ for air; A: Kihara; B: Brown; C: Literature values.

It is thus evident that in the case of all the gases studied here the values of $(\alpha/P)$ calculated from breakdown voltage are in fairly good agreement with the values of $(\alpha/P)$ obtained from literature for $(E/P)$ values studied here. Further the results calculated from Brown's expression are in better agreement than those alculated from Kihara's theory. This may be due to uncertainties in the values of molecular constants introduced by Kihara. We can further conclude that under the present experimental conditions and where the electrons make a large number of collision per oscillation, diffusion is the dominating factor for the loss of electrons and the breakdown process is identical with the d.c. breakdown mechanism.

## 4. Effect of magnetic field

In the above discussion we have concluded that under the present experimental set up and for the values of pressure and the frequency of the applied radio frequency field used, diffusion is the main electron removal process. However, the effect of an external magnetic field is to modify the breakdown mechanism to the same extent as the process of diffusion. As the diffusion perpendicular to the magnetic field is reduced, the breakdown field will show a reduction in value. The mean square displacement travelled by an electron is proportional to diffusion constant and Brown has shown that the effective diffusion length $\Lambda_H$ appropriate to infinite parallel plate is given by

$$\Lambda_H = \Lambda \left[1 + \frac{\omega_B{}^2}{\nu_C{}^2}\right]^{1/2} \tag{5}$$

where $\omega_B$ is the cyclotron frequency $= (eH)/m$ and $\nu_C$ is the collision frequency at the pressure considered. In a recent communication (Sen and Jana 1976) we have measured the collision frequency of the electrons in hydrogen, oxygen and air by the radio frequency conductivity method and the value at a pressure of 1 torr for hydrogen is $1 \cdot 74 \times 10^9$, for oxygen $3 \cdot 58 \times 10^9$ and for air $3 \cdot 222 \times 10^9$. In order to verify whether Brown's expression for the modified diffusion length is valid the values of $\Lambda_H/\Lambda$ have been calculated for each gas separately for different values of $H/P$ from 50–500 G torr$^{-1}$. To see whether these are consistent with the experimental values, $\Lambda_H/\Lambda$ has also been calculated from values of $E$ and $E_H$ obtained experimentally. It has been shown that the discharge is diffusion controlled and the breakdown criteria is given by

$\nu/D = 1/\Lambda^2$ or $(\alpha\mu E)/D = 1/\Lambda^2$ where $\mu$ is the mobility as $\mu/D = e/(KT_e)$, where $T_e$ is the electron temperature

$$\left(\frac{\alpha}{P}\right)\frac{eEP}{KT_e} = \frac{1}{\Lambda^2}.$$

From Townsend's equation $\alpha/P = A_0 \exp\left(-B_0/(E/P)\right)$ and

$$\frac{KT_e}{e} = \frac{L}{\sqrt{R}} \cdot \frac{E}{P} = r \cdot \left(\frac{E}{P}\right) \text{ Von Engel (1955)}$$

where $r = L/\sqrt{R}$ and $L$ is the mean free path of the electron in the gas at a pressure of 1 torr and $R = 2m/M$ where $m$ is the mass of the electron and $M$ is the mass of the ion.

Hence

$$A_0 \exp\left(-\frac{B_0 P}{E}\right) \cdot \frac{P^2}{r} = \frac{1}{\Lambda^2}$$

or

$$E/P = \frac{B_0}{\log\left[A_0 P^2 \Lambda^2/r\right]}. \tag{6}$$

When magnetic field is present if $E_H$ is the breakdown field for the same value of $P$

$$E_H/P = \frac{B_0}{\log\left[A_0 P^2 \Lambda_H{}^2/r\right]} \tag{7}$$

Hence

$$\frac{\Lambda_H}{\Lambda} = \left[\exp \frac{B_0 P (E - E_H)}{E E_H}\right]^{1/2}. \tag{8}$$

From the experimental values of $E$ and $E_H$ values of $\Lambda_H/\Lambda$ for all the three gases have been obtained from eq. (8) and entered in table 1 for $H/P$ varying between 50 and 500 gauss torr$^{-1}$.

From a comparison of the theoretical and experimental values, it is evident that the values are more or less consistent with one another and lends additiona support to the assumption that the loss of electrons under the present experimental set up is governed mainly by diffusion.

We further note that maximising eq. (6) with respect to pressure, the pressure at which the breakdown voltage becomes a minimum, is given by

$$P_{\min} = \frac{2E_{\min}}{B_0} \tag{9}$$

and in the presence of magnetic field

$$\frac{2\,(E_H)_{\min}}{(P_H)_{\min}\left[1 + \dfrac{\omega_B{}^2}{C^2\,(P_H)^2_{\min}}\right]} = B_0 \tag{10}$$

where $(P_H)_{\min}$ is the pressure at which the breakdown voltage becomes $(E_H)_{\min}$ and $C$ is the collision frequency at a pressure of 1 torr, from eqs (9) and (10);

**Table 1.** Theoretical and experimental values of $\Lambda_H/\Lambda$ for different $(H/P)$ values

| Hydrogen | | | Oxygen | | | Air | | |
|---|---|---|---|---|---|---|---|---|
| $(H/P)$ Gauss torr$^{-1}$ | $\frac{\Lambda_H}{\Lambda}$ (Theory) | $\frac{\Lambda_H}{\Lambda}$ (Expt.) | $H/P$ Gausst torr$^{-1}$ | $\frac{\Lambda_H}{\Lambda}$ (Theory) | $\frac{\Lambda_H}{\Lambda}$ (Expt.) | $H/P$ Gauss torr$^{-1}$ | $\frac{\Lambda H}{\Lambda}$ (Theory) | $\frac{\Lambda H}{\Lambda}$ (Expt). |
| 78·57 | 1·008 | 1·038 | 61·1 | 1·002 | 1·031 | 90·90 | 1·116 | 1·260 |
| 89·80 | 1·010 | 1·140 | 111 | 1·006 | 1·053 | 111·1 | 1·169 | 1·167 |
| 181·8 | 1·042 | 1·212 | 160·6 | 1·008 | 1·060 | 200 | 1·481 | 1·382 |
| 250·0 | 1·077 | 1·293 | 222 | 1·014 | 1·108 | 250 | 1·682 | 1·793 |
| 350·0 | 1·186 | 1·301 | 285·7 | 1·024 | 1·079 | 333·3 | 2·077 | 1·892 |
| 533·3 | 1·317 | 1·342 | 333·3 | 1·034 | 1·134 | 371·8 | 2·263 | 1·982 |

Table 2. Theoretical and experimental values of $(P_H)_{min}$ from equation (11).

| Magnetic field (Gauss) | Hydrogen | | Oxygen | | Air | |
|---|---|---|---|---|---|---|
| | $(P_H)_{min}$ (calc) torr | $(P_H)_{min}$ Expt. torr | $(P_H)_{min}$ Calc. torr | $(P_H)_{min}$ Expt. torr | $(P_H)_{min}$ Calc. torr | $(P_H)_{min}$ Expt. torr |
| 110 | 1·268 | 1·25 | 1·062 | 1·05 | .. | .. |
| 200 | 1·0792 | 1·09 | 0·9899 | 0·95 | 0·9661 | 0·99 |
| 400 | Indeterminate | 0·75 | 0·6534 | 0·66 | 0·6972 | 0·73 |
| 595 | .. | .. | Indeterminate | 0·45 | Indeterminate | 0·60 |

$$(P_H)_{min} = \frac{P_{min}\dfrac{(E_H)_{min}}{E_{min}} \pm \left(P_{min}^2\dfrac{(E_H)_{min}^2}{E_{min}^2} - 4\omega_B{}^2/c^2\right)^{1/2}}{2}. \tag{11}$$

The values of $(P_H)_{min}$ thus calculated for the three gases for different values of the magnetic field are given in table 2.

## 5. Conclusions

It is thus concluded that when the frequency of excitation is much smaller than the collision frequency, the major factor responsible for electron removal is the process of diffusion and this is also the dominating factor when the magnetic field is applied. The mechanism of breakdown becomes almost identical with d.c. breakdown of gases and the experimental results are in agreement with theoretical values calculated on the basis of these assumptions. It is further noted that eq. (11) becomes invalid for values of magnetic field greater than 400 gauss which shows that deductions are valid for low values of magnetic field, and also corroborated by the values of $\Lambda_H/\Lambda$ as shown in table 1.

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