CHAPTER IV

BREAKDOWN POTENTIALS IN
LONGITUDINAL MAGNETIC FIELDS.

4.1. INTRODUCTION

From long back, reports on the breakdown potentials ($V_s$), in air are available in the literature (Townsend 1915, Llewellyn Jones and Williams 1953, Boulind 1934, Raja Rao and Govindaraju 1971). Data on the Townsend's ionisation coefficients are also available. For the past two decades, great interest was shown on the study of $V_s$, in the presence of crossed electric and magnetic fields. (Dargan and Heylen 1968, Sen and Ghosh 1962, Sen and Bhattacharjee 1969, Gurumurthy and Govindaraju 1975, Sengupta et al 1978). But it is believed that no report is available in the literature on the effect of longitudinal magnetic fields ($B_{11}$), on the breakdown potentials.

The purpose of the present investigation is to study the effect of $B_{11}$ on $V_s$. $V_s$ was investigated for $0.04 \leq P_d \leq 5.56$ cm.torr. The intensity of the magnetic field ranged from 0 to 2050 Gauss.
For all the pressures studied, the introduction of the magnetic field lowered $V_g$. The results are explained qualitatively. The present data of $V_g$ in the absence of the magnetic field are compared with the results available, in the literature. Townsend's ionisation coefficients are calculated and the results are discussed.

4.2. EXPERIMENTAL DETAILS

The breakdown potential investigations were made with the discharge tube type 1 (DT1, shown in Figure 3.1). The discharge tube was cleaned as described in Section 3.2.3. The circuit diagram for the study is shown in the Figure 4.1.

The discharge tube was kept in between the pole faces of the electromagnet, such that the axis of the discharge tube coincided with the axis of the pole faces. The position of the discharge tube was such that the volume between the electrodes was completely immersed in the uniform longitudinal magnetic field. The volume between the electrodes was 1.51 $\text{cm}^3$ whereas the homogeneous field volume was 2.36 $\text{cm}^3$.

Dry air was filled in the discharge tube as described in Section 3.3. The rotary pump was
worked and the voltage adjusted for a discharge current of a few hundred microamperes. The discharge current was allowed for 15 minutes, in each direction to condition the electrodes, after which the circuit was cut off. The needle valve was used to adjust for the required pressure. When the pressure was steady, the voltage was applied across the tube, increased in steps and $V_s$ determined. In a similar way $V_g$ was determined in longitudinal magnetic fields of various intensities. The breakdown potential was measured a number of times, in the absence of $B_{11}$, to condition the electrodes (Govindaraju and Rajapandian 1976). For each magnetic field, the work was repeated a number of times, until reproducible results could be obtained within 1%. Pressure variation technique was applied to find $V_g$ at different $P_d$ values.

4.3. BREAKDOWN POTENTIAL MEASUREMENTS

Dargan and Heylen (1968) noted that there were several ways in which the spark and the corresponding voltage manifests itself:

(a) by an abrupt change in voltage
(b) by an abrupt change in current
(c) by an increase in light emission
In the present investigation, an abrupt increase in current, together with the onset of a faint diffused glow in the electrode space was taken as an indication of breakdown. The breakdown currents were of the order of $10^{-7}$ A. The same technique was followed by Llewellyn Jones and Davies (1951), to identify the occurrence of breakdown. The $V_g$ measured while decreasing $B_{11}$ did not differ by more than $3\text{V}$, which is less than $1\%$ for the minimum $V_g$ observed. Because of the limitation in the accuracy of VTVM used in the investigation (maximum error $3\%$) the overall error in the measurement of $V_g$ could be $<4\%$. But because of the consistency and reproducibility of results within $1\%$, it is believed that the maximum error in $V_g$ could be $<1\%$. However according to Loeb (1955) often the accuracy in breakdown measurements is not better than 3 to 5%.

4.4. RESULTS AND DISCUSSION

The results of the investigation are shown in Figures 4.2, 4.3, and 4.4.

Figure 4.2 is a plot of $V_g$ versus log P and $V_{SB}$ (Breakdown potential in the presence of longitudinal magnetic field) versus log P at
constant $B_{11} (= 1775 \text{ G})$.

Figure $\{4.3\}$ is a plot of $(V_S - V_{SB})$ versus log $P$, at $B_{11} = 1775 \text{ G}$.

Figure $\{4.4\}$ is a plot of $V_{SB}$ versus $B_{11}$ at fixed $P$ values.

The values of $V_S$ and $V_{SB}$ versus $B_{11}$ for different $P$ values are reported in Table 4.1.

It is seen in Figure $\{4.2\}$ that the application of the $B_{11}$, decreases $V_S$ over the entire Paschen curve. In the Paschen minimum region and to the right side of it, the curve in the presence of $B_{11}$ runs almost parallel to the one in the absence of $B_{11}$. The average reduction in $V_S$ in these regions is $17.68 \text{ V}$ which is $4.64\%$ of $V_S$ at the Paschen minimum and $2.31\%$ of $V_S$ at $P = 11.64 \text{ torr}$. At the left side of the Paschen minimum, the reduction in $V_S$ increases with decrease in $P$, and the curve is divergent to the one in the absence of $B_{11}$. The divergence starts at $P = 0.4 \text{ torr}$ and at the minimum pressure studied, i.e. $0.08 \text{ torr}$, the reduction in $V_S$ was $23\%$.

4.4.1. Paschen curve in the absence of $B_{11}$

Many investigators (Thompson 1903, Schumann...
1923, Engel and Steenbeck 1934, Paschen 1889) have established the general form of $V_S$ versus $pd$ curve. This well known curve has a minimum potential at $pd$ between 0.5 and 4 torr.Cm (Ehrenkranz 1939). The $V_S$ versus $p$ (at fixed $d$) in the absence of $B_{11}$ shown in Figure 4.2 is of similar form and has a minimum at 0.76 torr.Cm. The $V_S$ minimum obtained in the present investigation is 381.15 V. Raja Rao (1971) with 6 mm electrode separation got a minimum of 368 V.

4.4.2. Paschen curve in the presence of $B_{11}$

Figure 4.2 shows that the application of the longitudinal magnetic field decreases the breakdown potentials at all the pressures studied.

According to Howatson (1965), the effect of a magnetic field on $V_S$ is determined by its influence on the drift motion of charged particles and particularly electrons. Elementary theory shows that an electron moving freely through a magnetic field, gyrates about the field lines with a frequency

$$f_c = \frac{eB}{2\pi m} \quad (4.1)$$

where
$f_c$ is the frequency in Hertz,
$e$ the electronic charge in Coulomb,
$m$ the electronic mass in kg, and
$B$ the magnetic flux in Weber/m$^2$.

Force experienced by a moving charge in a magnetic field is given by

$$\vec{F} = q(\vec{V} \times \vec{B}) \quad (4.2)$$

where

$\vec{F}$ is the force experienced by the charge, in Newtons/m$^2$,
$q$ the value of the charge in coulomb and
$\vec{V}$ the velocity of the electron in m/sec.

Equation (4.2) shows that the velocity of the charge parallel to $\vec{B}$ is not at all affected by $\vec{B}$. But the velocity perpendicular to $\vec{B}$ produces rotation. Free electrons are therefore, effectively anchored to the flux lines. Hence the electron flow is severely restricted across the longitudinal magnetic field.

According to Townsend (1915), the diffusion coefficient and mobility in the presence of $B_{11}$ are reduced by a factor of $1/1 + \omega_c^2 \tau^2$. 
where

$$\omega_c$$ is the angular cyclotron frequency of the electron about the flux lines, and

$$\tau$$ is the mean free time. The gyration of electrons about the flux lines in a longitudinal magnetic field causes an increased path length in spanning a given distance and hence a greater number of collisions. Hence the reduced diffusion and mobility losses tend to decrease the breakdown potential.

Blevin (1964) points out that the equation of motion of an electron in electric and magnetic fields is given by

$$m\ddot{\mathbf{V}} = e(\mathbf{E} + \dot{\mathbf{V}} \times \mathbf{B})$$ \hspace{1cm} (4.3)

Consequently a magnetic field which is applied parallel to the electric field has no influence on particle motion in the direction of the electric field, and there is no change in such parameters as electron and ion drift velocities, energy gain, free path and electron mean energy. It follows that for a system with infinite plane electrodes, the breakdown potential is unchanged by the application of a longitudinal magnetic field. However the lateral diffusion of electrons and ions is reduced
by the magnetic field, and this can have an effect on the value of $V_S$ in some instances. For example, in a system with electrodes of limited extent, such that the electrode separation $d$ is greater than the electrode dimensions, charge loss by diffusion to the walls results in a higher value of $V_S$, than would occur for an infinite electrode system. The presence of $B_{11}$ will reduce the loss of charged particles and consequently the value of $V_S$ also.

The above arguments indicate that a reduction in $V_S$ must be expected in the presence of a longitudinal magnetic field. The following physical picture may be given to explain the influence of $B_{11}$ on $V_S$.

Under normal conditions any sample of a gas can be expected to contain a number of ions and electrons. At ground level, the atmosphere contains an average in the order of 1000 positive and negative ions per cm$^3$ due to ultraviolet and cosmic radiation and radioactivity (Howatson 1965). In the absence of an electric field, the electrons, in between the electrodes in the discharge tubes, will have random velocities. But when an electric field is applied, the free electrons will drift along the field direction and will have ambipolar diffusion
towards the walls.

If the electron acquires sufficient energy to ionize the gas molecules, cumulative ionisation will take place and the gas will breakdown.

Let us concentrate on a particular electron which diffuses across the flux lines. This electron with an energy, say, $k_s$, traverses a distance $l_s$, inside the sphere of influence of a molecule, in the absence of $B_{11}$. Let the time of collision be $t_s$. (Figure 4.5,a)

In the presence of $B_{11}$, the electron with an energy, $k_{SB}$, is made to spiral as shown in Figure 4.5,b. Hence, the electron moves for a longer distance $l_{SB}$, inside the sphere of influence of the molecule. Let the corresponding time of collision be $t_{SB}$. Obviously

$$l_{SB} > l_s \text{ and hence}$$

$$t_{SB} > t_s .$$

All other physical conditions remaining the same, the probability of ionisation should be proportional to the electron energy and the time of collision, i.e. if $P_s$ is the probability for
an ionizing collision, then

\[ P_s = L \ k_s \ t_s \]  \hspace{1cm} (4.4)

Similarly in the presence of \( B_{11} \)

\[ P_{SB} = L \ k_{SB} t_{SB} \]  \hspace{1cm} (4.5)

where \( L \) is the proportionality constant.

For breakdown

\[ P_s = P_{SB} \]

Since \( t_{SB} > t_s \), \( k_{SB} \) should be less than \( k_s \), i.e., in the presence of \( B_{11} \), a smaller energy for the electron, than that in the absence of \( B_{11} \), is sufficient for breakdown to take place. So it is enough if it derives a smaller energy from the external electric field. Hence the breakdown potential in the presence of \( B_{11} \) should be smaller than that in the absence of \( B_{11} \). Hence the experimental findings are in agreement with the theoretical considerations.

In Figure 4.2 it is observed, that the Paschen curve in the presence of the longitudinal magnetic field (\( B_{11} = 1775 \text{ G} \)) runs almost parallel to the one in the absence of the field, in the Paschen minimum region and on the right side of it.
The average reduction of $V_s$ due to $B_{11} = 1775$ G, in this region is 17.68 Volts.

According to Cobine (1958), very slow moving electrons, will not produce ionisation. Electrons of moderate speeds, but having energy less than the ionisation potential may excite an atom, and then the excited atom may be struck by another slow moving electron to gain enough energy to complete the ionisation. This process requires a very dense beam of electrons, since the mean life of a normal excited state is of the order of $10^{-8}$ Sec. Obviously in a perfect gas, this is not possible.

Hence it is reasonable to assume that, in the present breakdown studies, before an ionising collision, electron should possess an energy at least equal to the ionisation potential of the gas. For an electron moving across the flux lines, the radius of gyration about the flux lines is given by (Tanenbaum 1967)

$$a = \frac{mv}{eB} \quad (4.6)$$

where

- $a$ is the radius of gyration in metres
- $m$ is the mass of the electron in Kg.
- $e$ is the electronic charge in Coulomb
the magnetic flux in Weber m$^{-2}$ and $v$ the velocity of the electron, in a direction perpendicular to the flux lines.

If the temperature of the electrons is $T$, then (Tanenbaum 1967)

$$v = \left( \frac{3kT}{m} \right)^{\frac{1}{2}} \quad (4.7)$$

As per the assumption, the energy of the electron is $V_1$ eV, where $V_1$ is the ionisation potential of the gas. For air,

$$V_1 = 16.3 \text{ V} \quad (\text{Knoll et al 1933})$$

But

$$1 \text{ eV} = 11600 \text{ eV} \quad (\text{Tanenbaum 1967})$$

$$\therefore \quad T = 16.3 \times 11600 \text{ eV} \quad (4.8)$$

Substituting relation (4.8) and (4.7) in equation (4.6)

$$a = 0.0939 \text{ mm} \quad (4.9)$$

$$2\pi a = 0.59 \text{ mm} \quad (4.9)$$

For a pressure $p$, the mean free path of an electron is approximately given by (Yarwood 1955).

$$\lambda_e = \frac{5}{p \text{ (microns)}} \cdot \frac{4}{\sqrt{2}} \text{ Cm} \quad (4.10)$$
Hence
\[ \lambda_e (p = 5 \text{ torr}) = 0.057 \text{ mm} \]
\[ \lambda_e (p = 10 \text{ torr}) = 0.03 \text{ mm} \]
\[ \lambda_e (p = 2 \text{ torr}) = 0.14 \text{ mm} \] (4.11)

From relations (4.9) and (4.11), it is seen that, for all the pressures on the right-hand side of the Paschen minimum, \( \lambda_e < 2\pi a \) (the gyrocircumference). In the Paschen minimum region also, \( \lambda_e < 2\pi a \).

Assuming a finite sphere of influence, no matter how strong \( B_{11} \) is, when \( \lambda_e \) is sufficiently small, the electrons are to be scattered by collisions and get themselves removed from the sphere of influence of the molecule. So the influence of \( B_{11} \) is only limited on \( V_S \) in the regions of Paschen curve considered. For the same reason, the reduction in \( V_S \) is also more or less the same, in the Paschen minimum region and on the right-hand side of it. Therefore, the Paschen curve, in the presence of \( B_{11} \) runs parallel to the one in the absence of \( B_{11} \).

On the contrary, on the left side of the Paschen minimum, \( \lambda_e \) is comparable to or greater than \( 2\pi a \). For example, at \( p = 0.4 \text{ torr} \), where
the Paschen curve in the presence of $B_{11}$ starts diverging from the one in the absence of $B_{11}$.

$$\lambda_e = 0.70 \text{ mm},$$

which is slightly greater than $2n\alpha (= 0.59 \text{ mm})$. Hence this permits the electron to spend more time in the sphere of influence because of the bending of the trajectory of the electron by the externally imposed $B_{11}$. So the magnetic field plays a more significant role and reduces the breakdown potentials. As $\lambda_e$ increases on the left side of Paschen minimum, $B_{11}$ plays more and more significant role and hence the curve in the presence of $B_{11}$ is divergent to the one in the absence of $B_{11}$. It appears, as $\lambda_e$ increases more and more, the electron trajectory is more and more controlled by $B_{11}$. One can as well say, that the Paschen minimum and its right side are collision dominated regions, while the left side of the Paschen minimum is magnetic field dominated.

The observed results may also be explained on the basis of ambipolar diffusion of electrons to the walls of the discharge tube and its reduction in the presence of $B_{11}$. According to Loeb (1955) as $E/p$ (ratio of longitudinal electric field
per Cm to pressure) increases, the electron energy increases. The diffusion loss also increases with increase in E/p. At high E/p values, the radial ambipolar diffusion of electrons to the walls causes a serious loss of carriers, thus affecting the discharge economy. In microwave breakdown studies, the principal loss of carriers at pressures lower than 1 torr consists of ambipolar diffusion to the walls. Such a loss then decides the breakdown thresholds in gases.

Hence at the high pressure side of the Paschen minimum, E/p is small and also the loss of carriers by ambipolar diffusion. Thus even though the application of $B_{11}$ reduces the loss of carriers as discussed earlier in this Section, its influence on $V_S$ is small. On the other hand, on the low pressure side of the Paschen minimum, since $p$ is small, E/p is high and hence the diffusion loss of electrons is also high. The application of $B_{11}$ reduces the diffusion loss and hence the reduction in $V_S$ is also large. This also explains the divergence of the Paschen curve in the presence of $B_{11}$ from the one in the absence of $B_{11}$.

The plot of $V_S - V_{SB}$ against log p in the left side of Paschen minimum region in
Figure 4.3 is nearly a straight line. It appears that in this region at constant $B_{11}$,

$$V_S - V_{SB} = K \ln p \quad (4.12)$$

The breakdown potentials in the presence of $B_{11}$ of different intensities are reported in Table 4.1. Some of the results are also plotted in Figure 4.4. One can observe in the tables as well as in the figure, that the decrease in $V_S$ is sharp for small magnetic fields and appears to attain saturation with large $B_{11}$. The saturation is prominent for higher pressures rather than for lower pressures. For example, at

$$p = 0.5 \text{ torr}$$

$$V_S - V_{SB}(B_{11} = 300 \text{ G}) = 419.4 - 414.0$$

$$= 5.4 \text{ V}$$

$$= 1.29\% \text{ of } V_S$$

$$V_S - V_{SB}(B_{11} = 1500 \text{ G}) = 419.4 - 408.6$$

$$= 10.8 \text{ V}$$

$$= 2.58\% \text{ of } V_S$$

$$V_S - V_{SB}(B_{11} = 1775 \text{ G}) = 419.4 - 406.8$$

$$= 12.6$$

$$= 3.0\% \text{ of } V_S$$
At $p = 0.08$ torr

$V_S - V_{SB} (B_{11} = 300 \text{ G}) = 660.00 - 507.65 = 152.35 \text{ V}$

$= 23.08\% \text{ of } V_S$

$V_S - V_{SB} (B_{11} = 1175 \text{ G}) = 660.00 - 492.10 = 167.90 \text{ V}$

$= 25.44\% \text{ of } V_S$

$V_S - V_{SB} (B_{11} = 1775 \text{ G}) = 660.00 - 481.50 = 178.50 \text{ V}$

$= 27.05\% \text{ of } V_S$

4.5. TOWNSEND IONISATION COEFFICIENTS

4.5.1. Evaluation of Townsend Ionisation Coefficients

The Townsend's second ionisation coefficient $\gamma$ was evaluated using the relation

$$V_S = \frac{Bpd}{A pd \ln \left( \frac{1 + \frac{A}{B} \gamma}{\gamma} \right)} \tag{4.13}$$

where,

$A$ and $B$ are constants, which Lewis (1958) and
Heylen (1958) have shown to be characteristic of the gas and also depend on \( E/p \). Equation (4.13) may be derived from the breakdown criterion (Townsend 1915)

\[
\gamma (\exp \alpha d - 1) = 1 \quad (4.14)
\]

where \( \alpha \) is the Townsend's first ionisation coefficient,

and the Townsend's relation,

\[
\frac{\alpha}{p} = A \exp \left( \frac{-BE}{E} \right) \quad (4.15)
\]

For an electron attaching gas, the breakdown criterion is given by (Prasad 1959)

\[
\frac{\gamma \alpha}{\alpha - \eta} \int \exp (-\alpha \eta) d - 1 = 1 \quad (4.16)
\]

where \( \eta \) is the attachment coefficient. But \( \eta \) ceases to be important for air and oxygen for \( E/p > 65 \) (Loeb 1955). Raja Rao (1971) observed that \( \eta \) was not significant for \( 49.17 \leq E/p \leq 965.46 \text{ V cm}^{-1}\text{torr}^{-1} \). In the present investigation, \( \alpha \) and \( \gamma \) were evaluated in the range of \( E/p \) from 134.64 to 676.20 \text{ V cm}^{-1}\text{torr}^{-1} \). Hence the attachment coefficient was not taken care of in the analysis. If \( \eta = 0 \), (in Eqn 4.16) the breakdown criterion for electron attaching gases
also will be given by equation (4.14).

The values of $A$ and $B$, in relation (4.13) were taken from Rajapandian (1973). The $V$ obtained from equation (4.13) was substituted in - equation (4.14) to determine $\alpha$.

The values of $\alpha$ and $\alpha/p$ are reported against $E/p$ in the presence as well as in the absence of $B_{11}$, in Table 4.2.

The $V$ values are reported in Table 4.3 against $E/p$, in the presence as well as in the absence of $B_{11}$.

The overall error in the measurement of $V_s$ was <1%. This leads to an error (Equation 4.13) <16% in $V$ at 11.58 torr and <4% in the Paschen minimum region. The above error in $V$ leads to (Equation 4.14) a maximum error in $\alpha$ <3% at 11.58 torr and <1% in the Paschen minimum region.

4.5.2. Townsend's first ionisation coefficient $\alpha$

The $\alpha/p$ values of the present investigation in the absence of any magnetic field are compared with some of the other results (Townsend 1947, Masch 1932, Emeleus et al 1936, Bhiday et al 1970), available in the literature, in Figure 4.67. It is seen, that upto $E/p = 300 \text{ V Cm}^{-1}\text{torr}^{-1}$, the
present results of $\alpha/p$ are in very good agreement with all the other results. For $E/p > 300 \, V \, \text{cm}^{-1} \, \text{torr}^{-1}$ the present values are higher than the other results. For example, at $E/p = 500 \, V \, \text{cm}^{-1} \, \text{torr}^{-1}$ the present results are higher than that of Bhiday et al. (1970) by 14.5% and of Masch (1932) by 7.14%.

The higher values of $\alpha/p$ at high $E/p$ in the present investigation are possibly because of two reasons: (i) Mercury vapour trap was not used in the present investigation, and since mercury pressure gauzes were used there may be a small contamination of mercury in air, which will result in high $\alpha/p$ values (Loeb 1955). (ii) Because of the small electrode separation, the electrons are not in equilibrium with the field and since $\alpha/p$ is a strong function of the collision number, higher $\alpha/p$ values can be obtained (Chanin and Rork 1963).

Plotting $\log(\alpha/E)$ against $\log(E/p)$, it is seen that nonequilibrium sets in at $E/p = 398 \, V \, \text{cm}^{-1} \, \text{torr}^{-1}$ (Loeb 1955). (Curve not shown).

It is seen in Table 4.2 and Figure 4.7 that as the magnetic field increases, $\alpha$ decreases, at all the pressures studied. For a magnetic field of 1775 G the reduction in $\alpha$ is of the same order, i.e., about 5% for the range $137.64 \leq E/p \leq 676.20$.
The reduction is gradual, when the magnetic field is increased. Typically, for 

\( p = 10.64 \text{ torr} \), the reduction in \( \alpha \) is 2.24\% for 

\( B_{\perp} = 600 \text{ G} \) and 3.68\% for \( B_{\perp} = 1175 \text{ G} \) and 

5.20\% for \( B_{\perp} = 1775 \text{ G} \).

A magnetic induction \( B \), applied to a discharge plasma, effectively reduces the freepaths of the charges in directions perpendicular to \( B \), to less than the radius of curvature \( \rho = v/w \), where \( v \), being the velocity and \( w \) the angular frequency of the particle (Chanin and Rork 1963). Bickerton (1956) on the basis of Schottky's (1924) radial distribution of electrons, derived a relation, for the rate of ionisation by the electron per second \( (\lambda) \), which is given by

\[
\frac{4 D_a}{R V_+} = \frac{1}{x} \frac{J_0(x)}{J_1(x)}
\]  \hspace{1cm} (4.17)

In relation (4.17),

- \( R \) is the radius of the discharge tube,
- \( V_+ \) the velocity of the positive ions
- \( x = (\sqrt{\gamma D_a} R)^{1/2} \),
- \( D_a \) the ambipolar diffusion coefficient and 
- \( J_0(x) \) and \( J_1(x) \) are Bessel functions of order
zero and one. Using the relation (4.17) it was shown (Bickerton 1956) theoretically that $\lambda$ decreased with decrease in $D_a$. But $D_a$ decreases with increase in $B_{11}$. Hence $\lambda$ should decrease with increase in $B_{11}$. It was also shown experimentally that $\lambda$ decreased with increase in $B_{11}$.

Since $\alpha$ is the number of ion pairs produced by one electron per cm length in the direction of the electric field, and $\lambda$ the number of ion pairs produced by one electron per second,

$$\lambda = \alpha \nu,$$ where

$\nu$ is the velocity of the electron in the direction of the electric field. $\nu$ is unaltered by $B_{11}$. Hence if $\lambda$ decreased with $B_{11}$, $\alpha$ also should decrease with $B_{11}$. Thus the results of the present investigation are in agreement with theory and earlier results.

4.5.3. **Townsend's Second Ionisation Coefficient**

Figure 4.8 is a plot of $\nu$ vs $E/p$ in the absence of $B_{11}$. It is seen that $\nu$ decreases up to $E/p = 225 \text{ V cm}^{-1} \text{ torr}^{-1}$ and then increases. The general form of the curve is similar to the one obtained by Raja Rao and Govindaraju (1971).
Llewellyn Jones and Williams (1953) observed a general increase of $\gamma$ with $E/p$. $(E/N)_p$, $(E/N)$ at Paschen minimum, where $N$ is the number of molecules in one $\text{cm}^3$ in discharge tube, is greater or smaller than $(B/No)$, where $B$ is the constant appearing in equation (4.15) corresponding to the Paschen minimum and $No$, the number of molecules per $\text{cm}^3$ at $p = 1$ torr at $0^\circ\text{C}$, (which is $3.56 \times 10^{16}$ $\text{cm}^{-3}$ (Howatson 1965) according as $\gamma$ increases or decreases with $E/p$ (Blevin and Haydon 1958). In the present investigation $\gamma$ increases with $E/p$, and $(E/N)_p = 156.68 \times 10^{-16}$ $\text{V cm}^{-2}$ and $(B/No) = 111.29 \times 10^{-16}$, which is in accordance with the above criterion. The results of the present investigation are compared with the results of Raja Rao and Govindaraju (1971) in Table 4.4. The overall accuracy claimed was $\pm 25\%$. But they observed a large uncertainty in $\gamma$ at constant $E/N$ with different $N$ values. For example, at $E/N = 25.40 \times 10^{-16}$ V $\text{cm}^{-2}$, $(E/N) = 81.47$ V $\text{cm}^{-1}$ torr$^{-1}$) $\gamma$ values were $0.95 \times 10^{-3}$ and $2.70 \times 10^{-3}$ for values of $N = 28.2 \times 10^{16}$ $\text{cm}^{-3}$ and $N = 30.80 \times 10^{16}$ $\text{cm}^{-3}$ respectively, which is an uncertainty of 184% and at $E/N = 49.50 \times 10^{-16}$ V $\text{cm}^{-2}$ (E/P = 158.77 V $\text{cm}^{-1}$ torr$^{-1}$) $\gamma$ values were $1.38 \times 10^{-3}$ and $2.30 \times 10^{-3}$ for
values of \( N = 14.18 \times 10^{16} \text{ cm}^{-3} \) and \( 16.55 \times 10^{16} \text{ cm}^{-3} \) respectively, which is an uncertainty of 66.67%. In view of this, the agreement between the present results and that of Raja Rao and Govindaraju (1971) should be considered as reasonable.

The values of \( \psi \) in the presence of \( B_{11} \) are reported in Table 4.3. For a few selected pressures the \( \psi \) is plotted against \( B_{11} \) in Figure 4.9. It is seen that \( \psi \) increases steadily with \( B_{11} \). An increase in \( \psi \) with \( B_{11} \) must be expected because \( \psi \) is related to \( V_S \) by the relation (4.13). Since \( V_S \) decreases with increase in \( B_{11} \), that in turn must increase \( \psi \).

The increase in \( \psi \) ranges from 9.00% (at \( p = 1.18 \text{ torr} \)) to 21.89% (at \( p = 10.06 \text{ torr} \)) for \( B_{11} = 600 \text{ G} \). For 1775 G the increase in \( \psi \) ranges from 20.48% (at \( p = 1.18 \text{ torr} \)) to 60.97% (at \( p = 6.64 \text{ torr} \)). It appears that in the Paschen minimum region, the percentage increase in \( \psi \) is smaller than that in other regions.

4.6. CONCLUSIONS

The breakdown potentials, in dry air, across plane parallel electrodes, were investigated as a function of \( \text{pd} \), by the method of pressure
variation technique. The range of pd values studied were \( 0.04 \leq pd \leq 5.56 \text{ Cm. torr} \).

Over the same pd range, the breakdown potentials were investigated, under longitudinal magnetic fields of various intensities ranging from 0 to 2050 gauss. \( B_{11} \) was found to lower the breakdown potential over the whole Paschen curve, the influence being more significant on the low pressure side of the Paschen minimum. The effect is attributed to the reduction in transverse diffusion of charges, at the macroscopic level and to the alteration of electron trajectories at the microscopic level.

From the breakdown potential data, the Townsend coefficients \( \alpha \) and \( \gamma \) were evaluated, for the range, \( 134.64 \leq E/p \leq 676.20 \text{ V Cm}^{-1}\text{torr}^{-1} \).

The \( \alpha/p \) values obtained in the absence of \( B_{11} \), are in agreement with the previously published data up to \( E/p = 300 \text{ V Cm}^{-1}\text{torr}^{-1} \). For \( E/p \geq 300 \text{ V Cm}^{-1}\text{torr}^{-1} \), \( \alpha/p \) values obtained were higher than the previous data in the literature, possibly due to the small mercury contamination and inequilibrium of electrons with the electric field.

The \( \alpha \) values were found to decrease with increase in \( B_{11} \), which has been explained by the decrease in ambipolar diffusion coefficient in the
presence of $B_{11}$.

The form of $\gamma$ versus $E/p$ plot was similar to the one found in the earlier literature. In general, $\gamma$ was found to increase in accordance with the Blevin and Haydon criterion.

$\gamma$ was found to increase steadily with increase in $B_{11}$. This was expected because a reduction in $v_s$ (by the introduction of $B_{11}$) implies an increase in $\gamma$. [relation (4.13)]
### Table 4.1

Breakdown Potentials in Longitudinal Magnetic Fields.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>P</th>
<th>V&lt;sub&gt;S&lt;/sub&gt;-V&lt;sub&gt;SB&lt;/sub&gt;</th>
<th>V&lt;sub&gt;S&lt;/sub&gt;</th>
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<tbody>
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<td></td>
<td>torr</td>
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<td>B&lt;sub&gt;11&lt;/sub&gt; = 600</td>
<td>B&lt;sub&gt;11&lt;/sub&gt; = 1175</td>
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<td>373.20</td>
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### TABLE 4.1

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TABLE 4.2

Townsend's first ionisation coefficient $\alpha$ in $B_{11}$

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<th>$E_p(B_{11}=0)$</th>
<th>$\alpha$ ($Cm^{-1}$)</th>
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TABLE 4.3

Townsend's Second ionization coefficient $\gamma$ in $B_{11}$

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<th>S. No</th>
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<th>$E/F(B_{11}=0)$</th>
<th>$V$ (cm$^{-1}$)</th>
<th>$\gamma \times 10^3$</th>
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Comparison of $\gamma$: present results and that of Raja Rao and Govindaraju (1971)

<table>
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<th>$\frac{E}{N}$ V. cm$^2$</th>
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<th>Results of Raja Rao &amp; Govindaraju</th>
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</table>
Fig. [4.1] Circuit Diagram

1. Power Supply
2. Potential divider
3. Ballistic Galvanometer
4. Discharge tube
5. Inlet for dry air
6. Outlet to Vacuum pump and Vacuum gauzes.
Fig. [4.2] Paschen curves
Fig [4.4] Breakdown Potential against $B_n$

$V$ vs $B_n$ graph with various pressures indicated:

- 0.18 torr
- 0.08 torr
- 0.13 torr
- 0.14 torr
- 0.36 torr
- 0.4 torr
- 0.44 torr
- 0.5 torr

Pressure values are marked with different symbols on the graph.
Fig. [4.5] Path of electron inside the sphere of influence of a molecule.

(a) In the absence of $B_{\parallel}$
(b) In the presence of $B_{\parallel}$

1. Sphere of influence of the molecule.
Fig. [4-6]

- Present investigation
- Townsend
- Masch
- Emeleus
- Bhiday

\[ \frac{\lambda}{p \text{ cm} \text{ torr}} \]

\[ E/P \text{ Volt cm}^{-1} \text{ torr}^{-1} \]
$P = 6.64 \text{ torr}$

$\left[ \frac{E}{P} \right]_{(B_n = 0)} = 204.69 \text{ V cm}^{-1} \text{ torr}^{-1}$

$P = 10.06 \text{ torr}$

$\left[ \frac{E}{P} \right]_{(B_n = 0)} = 154.04 \text{ V cm}^{-1} \text{ torr}^{-1}$

$P = 10.64 \text{ torr}$

$\left[ \frac{E}{P} \right]_{(B_n = 0)} = 146.69 \text{ V cm}^{-1} \text{ torr}^{-1}$

$P = 11.58 \text{ torr}$

$\left[ \frac{E}{P} \right]_{(B_n = 0)} = 137.64 \text{ V cm}^{-1} \text{ torr}^{-1}$

Fig. [4.7]
Fig. [4.8]
$P = 10.64 \text{ torr}$

$\left[ \frac{E}{P} \right]_{(B_n=0)} = 146.69 \text{ V cm}^{-1} \text{ torr}^{-1}$
$P = 158 \text{ torr}$

$
\left[ \frac{E}{P} \right]_{(B_u=0)} = 502.57 \text{ Vcm}^{-1} \text{ torr}^{-1}
$

FIG. 4.9 (b)
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