CHAPTER V

GLOW DISCHARGE CURRENT IN PRESENCE OF LONGITUDINAL MAGNETIC FIELD.

INTRODUCTION

Townsend (1912) worked out the motion of a random swarm of electrons moving in electric and magnetic fields in absence of space charge effects. Detailed calculations regarding the motion of electrons in presence of both electric and magnetic fields have been carried out by Allis and Allen (1937), Tonks and Allis (1937), and Huxley (1937). Later work by Townsend (1938) obtained the coefficient of diffusion and mobilities of electrons in a gas in presence of electric and magnetic fields. In presence of a magnetic field of intensity 'H', the electrons move in spirals about axes parallel to the direction of magnetic field with angular frequency also called gyro-frequency ω_b given by

$$\omega_b = \frac{eH}{m}$$

'e' & 'm' are the charge and mass of the electrons. The coefficient of diffusion of electrons D_H perpendicular to the magnetic field is given by

$$D_H = \frac{D}{1+\omega_b^2\tau^2}$$

where 'D' is the normal diffusion coefficient and τ is the mean free time of flight of an electron between collisions. In parallel electric and magnetic fields the drift velocity is independent of the magnetic force. But when the magnetic fields be in a direction perpendicular to the electric force the drift velocity and hence the mobility in the field direction is reduced and is given by

$$\mu_H = \frac{\mu}{1+\omega_b^2\tau^2}$$

where μ is the mobility in absence of magnetic field.

When a magnetic field acts upon a glow discharge, various changes such as increase of equivalent pressure, decrease in the length of the cathode dark space, a change in radial ion density in the positive column and marked changes in current voltage characteristics of the discharge take place. In presence of longitudinal magnetic field on a positive column of low pressure discharge, the charged particles, having velocity components in all directions spiral about the magnetic field lines. Because of small masses, only the electrons are appreciably affected by the magnetic field. The spiralling parallel to the axis of the tube between collisions reduce the diffusion of electrons to the surface of the tube. Since their radial velocities are the same, the radial flow of both charges will decrease. Hence the rate of ionization required to balance the loss due to diffusion is diminished so also the electric field in the column. Also a smaller radial electric field is required to maintain the equality between the number of ions and electrons arriving at the non-conducting tube wall and thus the electron temperature is reduced. The effect is most noticeable in gases at low pressures and may be observed either in the positive columns of direct current discharges, or in oscillatory discharges.

The outward flow of ions is made to balance that of electrons by a readjustment of radial electric field. Nearly all workers have found results consistant with the general picture, but there is disagreement on one point, namely whether or not the magnetic field changes the radial distribution of ions and electrons from the normal Bessel function. Cumming and Tonks (1941) in a detailed theory of positive column in a longitudinal magnetic field, concluded that no change in radial distribution is to be expected. The radial potential distribution should also be unaltered in shape but reduced in scale, although they concluded that in large magnetic fields the radial electric field may become zero or even reverse i.e. the axis may become negative with respect to the walls. According to Tonks (1941) the apparent axial concentration of a discharge when placed in a uniform magnetic field is due entirely to a concentration being propagated from the cathode end. In the absence of a magnetic field this would have dispersed within a short distance. Tonks (1941) has calculated approximately the dispersal effect along a cylindrical column. The solution for the radial electron and ion distribution is the sum of a series of zero order Bessel functions. They tested their theory by experiments on the positive column of a mercury arc, at a pressure of 5 x 10^{-3} mm.Hg., and at a current of 4.0 amperes.

Rokhlin (1939) observed the spectral intensity of a mercury vapour discharge having pressure $\sim 10^{-3}$ mm.Hg. and carrying current between 1.5 to 4.0 amperes in a uniform longitudinal magnetic field. The relative intensity of several lines at the centre of the discharge attains a maximum and then decrease with increasing magnetic field. The maximum is due to two opposing effects, the increased concentration of electrons at the centre and the decrease in their energy.

A detailed experimental measurements of electron temperature, radial electron density and the axial field by the probe method in cases of glow discharges in Helium in presence of longitudinal magnetic field varying from 0 to 600 gauss has been carried out by Bickerton and von Engel (1956). The experimental results, in general, are in agreement with the theoretical prediction of lowering of electron temperature, axial electric field and increase of radial concentration of electrons.

Toader (1969) studied the behaviour of the positive column in neon and helium for discharge current 200 mA in presence of longitudinal magnetic field of maximum intensity 3.6 K. Gauss and pressure varying from 0.5 torr. to 4.0 torr. The results showed that the axial electric field decrease with increase of magnetic field upto a certain critical value and beyond that magnetic field, the longitudinal electric fields indicated a much higher diffusion rates across the magnetic field. The effect becomes prominent with the lowering of gas pressure.

The discharge current is a function of electron energy, electron concentration and the axial electric field. These parameters are affected in presence of longitudinal magnetic field and their combined effects are expected to cause a change in the total current. So, it is proposed to study the variation of discharge current of glow discharge column in longitudinal magnetic field and to investigate the effect of variation of these parameters controlling the total discharge current in presence of longitudinal magnetic field. Attempts have been made to explain the results by considering the known variations of the different parameters that are affecting the total discharge current in presence of longitudinal magnetic field.

EXPERIMENTAL ARRANGEMENT

The discharge vessel is a cylindrical glass tube of radius 1.5 cm. and height 2.2 cm. fitted with internal electrodes. The magnetic field is produced by a solenoid of 30 cm. long. The discharge tube is placed at the central part of the solenoid so that the magnetic field lines are parallel to the axis of the discharge tube.

Before starting the experiment, the discharge tube is evacuated and baked and then it is flushed a number of times by the experimental gas to ensure the atmosphere of the gas within the discharge tube. The pressure of the gas is adjusted by using a needle valve and the pressure of the gas is measured by a calibrated pirani gauge. The high voltage power supply is connected across the discharge tube in series with a 100 K Ω resistance. The voltage is gradually increased to cause breakdown of the gas and to form a glow discharge within the vessel.

For zero magnetic field, the current through the glow discharge column is adjusted and measured by a d.c. milliammeter and the corresponding applied voltage by a d.c. voltmeter. The magnetic field is gradually increased and the corresponding discharge current noted for the same applied voltage. The measurement is repeated a number of times to test the reproducibility of the results. The measurement is repeated for different values of I_o , the current in absence of magnetic field and for different molecular gases viz. hydrogen, oxygen, air and nitrogen.

RESULTS AND DISCUSSION.

The variation of total discharge current in presence of longitudinal magnetic field for different intial discharge currents I_o in absence magnetic field are plotted in Fig. 5.1. The curves I, II and III are the variations of discharge current for hydrogen at a pressure of 0.2 torr. curves IV & V for oxygen at 0.5 torr. curves VI ~~&&~~ and VII for air at 0.6 torr. and curves VIII, IX & X for nitrogen at 0.5 torr. respectively. It is found that the discharge current 'I' rises at first with increase of magnetic field 'H' and then slowly decreases with the increase of 'H' values showing a maximum value of 'I' for each I_o . The value of 'H' at which 'I' becomes maximum are found to be same for different I_o values investigated in the present experiment for all gases except nitrogen where a small increase of 'H' values at maximum 'I' values are observed.

The number density of electrons and positive ions are nearly same in the active discharge region while the

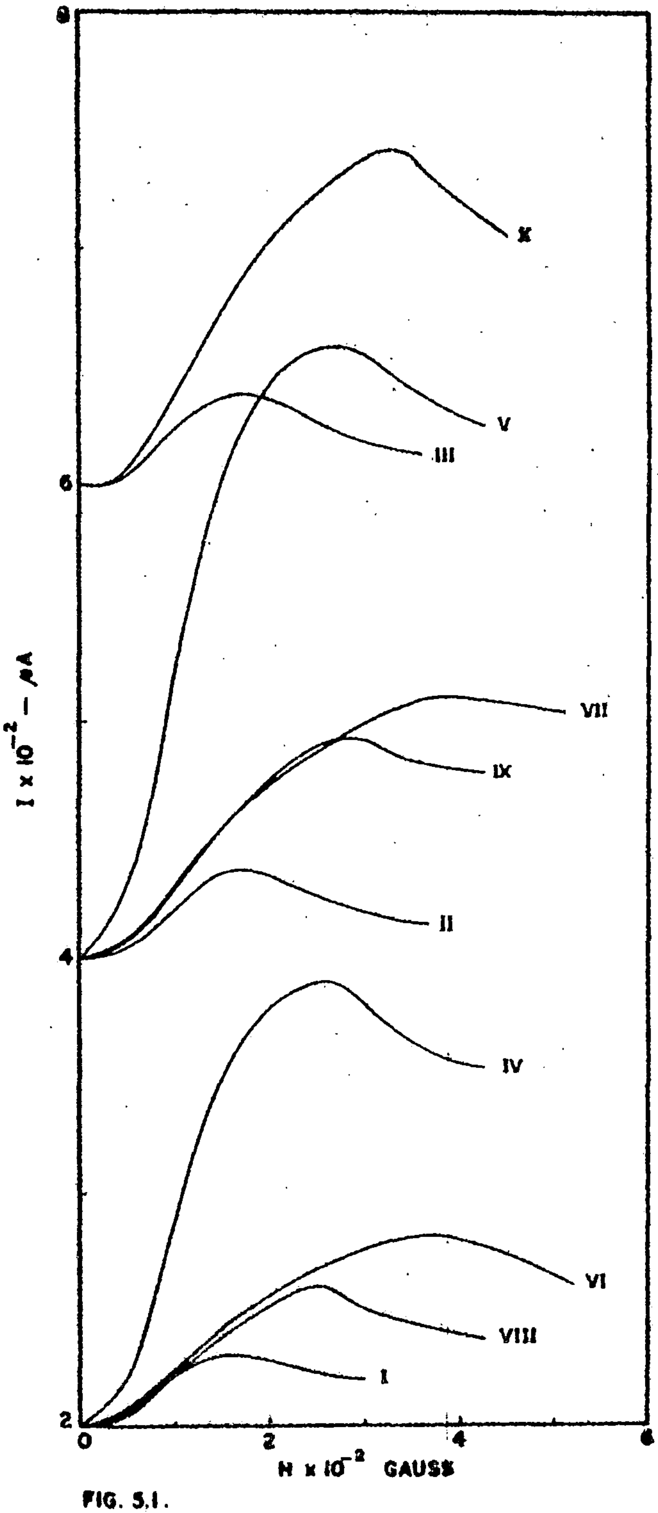

FIG. 5.1.

ratio of drift velocity of positive ions to that of electrons is $\sim 10^{-2}$ because of the large masses of positive ions. Hence the current in the active discharge is mainly carried by the electrons and the current density is given by

$$j = nev \qquad \ldots (5.1)$$

where e = electronic charge

n = number density of electrons

v = drift velcity of electrons

The drift velocity of electrons in an effective field E is given by

$$\vartheta = \frac{eE}{m\nu_c}$$

where m = electronic mass

ν_c = collision frequency of electrons with the neutrals.

$= \eta p$

η being a constant and 'p' be the pressure of the gas. Hence

$$j = \frac{ne^2E}{m\nu_c} \qquad \ldots (5.2)$$

The density of electrons 'n' in a column at a distance 'r' from the axis of the column is a function of 'r'. This radial distribution of charge concentration is obtained by equating the ionization rate to the diffusion loss and is given by

$$n = n_0 J_0\left(r\sqrt{\frac{\nu_i}{D_a}}\right) \qquad \ldots (5.3)$$

where n_0 = electron density on the axis of the column

J_0 = zero order Bessel function

ν_i = frequency of ionization of electrons

D_a = ambipolar diffusion coefficient.

For a small discharge current when the space charge effect is not appreciable, the ratio of ionization frequency and ambipolar diffusion coefficient may be written as

$$\frac{\nu_i}{D_a} = \frac{1}{\Lambda^2} \qquad \text{... (5.4)}$$

where Λ is the characteristic diffusion length of the discharge vessel. For a cylindrical vessel of height 'h' and radius 'R' the characteristic diffusion length is given by

$$\frac{1}{\Lambda^2} = \left(\frac{\pi}{h}\right)^2 + \left(\frac{2.405}{R}\right)^2$$

Hence

$$n = n_0 J_0 (r/\Lambda) \qquad \text{... (5.5)}$$

Putting this value of 'n' in eqn. (5.2) the current density is obtained as

$$j = \frac{n_0 e^2 E}{m \nu_c} \cdot J_0 \left(\frac{r}{\Lambda}\right) \qquad \text{... (5.6)}$$

The total discharge current 'I' is given by

$$I = \int_0^R 2\pi r j \, dr \qquad \ldots (5.7)$$

which gives on integration after substitution of value of 'j' from eqn. (5.6)

$$I = \frac{2\pi n_0 e^2 R \Lambda E}{m \cdot \nu_c} \cdot J_1\left(\frac{R}{\Lambda}\right) \qquad \ldots (5.8)$$

where J_1 is the first order Bessel function.

Neglecting the kinetic energy carried by the charged particles to the walls of the tube and balancing the energy the electrons gain from the electric field and the energy they loss by collision Bickerton & von Engel (1956) obtained a relation between the reduced longitudinal electric field E/p and the electron temperature as

$$\frac{E}{p} = 3\,(3\chi)^{1/2}\, T_e / 2\lambda_1 \qquad \ldots (5.9)$$

where T_e is electron temperature in volts and χ is the mean fraction of its random energy that is lost by an electron in a collision with a neutral molecule and λ_1 is the mean free path of an electron at a pressure of 1 torr.

It has been mentioned by von Engel (1965) that E/p does not depend on the current in molecular gases provided due correction is made for density change where 'p' designates the pressure which is equivalent to the gas density. But in rare gases and metal vapours E/p decrease with increasing 'I'. So, when 'p' is constant, E/p is independent of current of the discharge column in molecular gases and hence T_e is not a function of the discharge current. Using eqn. (5.9) the total discharge current,

$$I = \frac{\pi n_0 e^2 R \Lambda p T_e 3 (3\chi)^{1/2}}{m \nu_c \lambda_1} \cdot J_1\left(\frac{R}{\Lambda}\right) \qquad \ldots (5.10)$$

Bickerton and von Engel (1956) measured the variation of χ with E/p and have observed that χ increases with E/p for values of E/p higher than a few volts cm^{-1} $torr^{-1}$. Since T_e varies with E/p so comparing eqn. (5.9) with the experimentally observed variation of T_e with E/p in low current swarm experiments of ~~Ex~~ Deas and Emeleus (1949), the variation of χ with T_e is plotted in Fig. 5.2 for air, hydrogen and nitrogen for E/p values upto 240 volts cm^{-1} $torr^{-1}$, 120 volts cm^{-1} $torr^{-1}$ and 130 volts cm^{-1} $torr^{-1}$ respectively. No result is available for oxygen. It can be seen that the variation of χ with T_e is almost linear in this range of E/p values and may be represented by

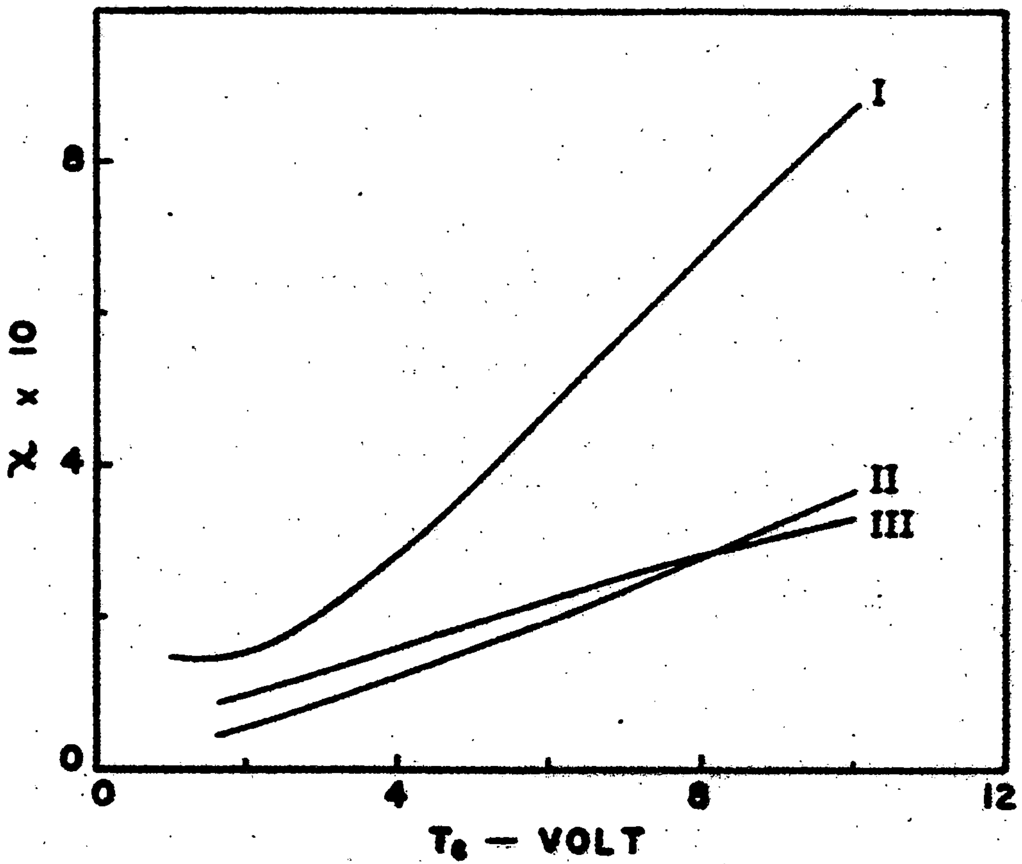

FIG. 5.2.

$$\chi = A_0^2 T_e \qquad \ldots (5.11)$$

where A_0^2 is a constant. It is assumed that the variation of χ with T_e will follow eqn. (5.11) for all the four gases studied. Putting the value of χ from eqn. (5.11) in eqn. (5.10) the total discharge current becomes

$$I = \frac{\pi n_0 e^2 R \Lambda p A_0 3^{3/2} T_e^{3/2}}{m \nu_c \lambda_1} \cdot J_1\left(\frac{R}{\Lambda}\right) \qquad \ldots (5.12)$$

In presence of a steady longitudinal magnetic field, following Cummings and Tonks (1941) the radial distribution of electrons is assumed to remain, Bessel form, so that the total discharge current becomes

$$I_H = \frac{\pi n_0 e^2 R \Lambda_H p A_0 3^{3/2} T_{eH}^{3/2}}{m \nu_c \lambda_1} \cdot J_1\left(\frac{R}{\Lambda_H}\right) \qquad \ldots (5.13)$$

where T_{eH} and Λ_H are the electron temperature and characteristic diffusion length respectively in presence of a magnetic field. In the cathode region most of the electrons move with relatively high speed normal to the cathode surface. A longitudinal magnetic field has therefore 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. 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 (1946) 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 in this experiment is less than 1 mA. and hence for this small change of discharge current, variation of cathode and anode fall have not been taken into consideration.

When collision frequency ν_c is independent of energy, Sen and Das (1973) obtained an expression for T_{eH} as

$$\frac{T_{eH}}{T_e} = 1 + \gamma \log_e\left(\frac{\nu_c}{\sqrt{\nu_c^2 + \omega_b^2}}\right) \qquad \ldots (5.14)$$

where $$\gamma = \frac{2T_e}{T_e + \frac{2eV_i}{k}}$$

Here V_i is the ionization potential of gas atoms and 'k' is the Boltzmann constant. Eqn. (5.14) can be written as

$$T_{eH} = T_e\left[1 - \frac{\gamma}{2}\log_e\left(1 + \omega_b^2\nu_c^{-2}\right)\right] \qquad \ldots (5.15)$$

For ~~xx~~ a cylindrical vessel with magnetic field along the axis the diffusion length of the vessel is given by

$$\frac{1}{\Lambda_H^2} = \left(\frac{\pi}{h}\right)^2 + \frac{\nu_c^2}{\nu_c^2+\omega_b^2}\left(\frac{2.405}{R}\right)^2 \qquad \ldots (5.16)$$

With the value of T_{eH} and Λ_H from eqns. (5.15) and (5.16) respectively, Eqn. (5.13) reduces to

$$I_H = \frac{\pi n_0 e^2 R A_0 p 3\sqrt{3}\, T_e^{3/2}}{m \nu_c \lambda_1}\left[1-\frac{\gamma}{2}\log_e\left(1+\frac{\omega_b^2}{\nu_c^2}\right)\right]^{3/2}$$

$$\times\left[\left(\frac{\pi}{h}\right)^2 + \frac{\nu_c^2}{\nu_c^2+\omega_b^2}\cdot\left(\frac{2.405}{R}\right)^2\right]^{-1/2} \times J_1\left[R\sqrt{\left(\frac{\pi}{h}\right)^2 + \frac{\nu_c^2}{\nu_c^2+\omega_b^2}\cdot\left(\frac{2.405}{R}\right)^2}\right] \ldots (5.17)$$

which gives the variation of discharge current with the applied magnetic field. The discharge current becomes maximum when $\frac{dI_H}{dH} = 0$. ~~W~~ So, differentiating eqn. (5.17) w.r.t. 'H' and putting $\frac{dI_H}{dH} = 0$, we get the condition for maximum current as

$$\Lambda_H\left[2-\frac{R}{\Lambda_H}\cdot J_0\left(\frac{R}{\Lambda_H}\right)\Big/ J_1\left(\frac{R}{\Lambda_H}\right)\right]\times\left[\left(\frac{2.405}{R}\right)^2 \times \frac{\nu_c^2}{\nu_c^2+\omega_b^2}\right]$$

$$= 1.5\,\gamma\left[1-\frac{\gamma}{2}\log_e\left(1+\frac{\omega_b^2}{\nu_c^2}\right)\right]^{-1} \qquad \ldots (5.18)$$

which gives

$$\gamma = \frac{A}{1.5+AC} \qquad \ldots (5.19)$$

where

$$A = \Lambda_H^2 \left[2 - \frac{R}{\Lambda_H} \cdot J_0\left(\frac{R}{\Lambda_H}\right) / J_1\left(\frac{R}{\Lambda_H}\right)\right] \times \left[\left(\frac{2.405}{R}\right)^2 \times \frac{\nu_c^2}{\nu_c^2 + \omega_b^2}\right].$$

and

$$C = \frac{1}{2} \log_e \left(1 + \frac{\omega_b^2}{\nu_c^2}\right)$$

The constant $\eta \left(= \nu_c / p\right)$ for hydrogen, oxygen and air have been obtained from Brown (1956) and values are shown in Table-5.1. Taking the values of 'H' at which I_H is maximum T_e is calculated from eqn. (5.19) for hydrogen, oxygen and air and tabulated in Table-5.2. Since V_i for air is not available in standard literature, an approximate value of V_i = 15 volts is taken (Bhattacharjee and Das, 1982). No calculation can be made for nitrogen as ν_c is not independent of energy of electrons (Brown, 1959).

TABLE-5.1

Gas	V_i volts.	$\eta \times 10^{-9}$, collisions per Torr.	$a \times 10^2$, ion ~~pair~~ pairs/cm per primary electron	$K^+ \times 10^{-3}$ cm/sec. per volt/cm.
Hydrogen	15.4	5.9	21	10.0
Oxygen	12.1	3.5	24	1.0
Air	15.0	4.3	26	1.4
Nitrogen	15.5	-	26	2.0

From the theory of positive column and assuming the Maxwell-Boltzmann distribution law, the Schottky theory for medium pressure (10^{-1} torr. to 10 torr.) has been extended by Francis (1956) to obtain an universal expression for T_e in terms of similarity formula which was later formulated in another way by von Engel (1965) as

$$x^{-1/2} \exp(x) = \frac{(e/m)^{1/2}}{(2.4)^2} \cdot (cpR)^2 \qquad \ldots (5.20)$$

where $x = \frac{eV_i}{kT_e}$ and $c = \left(\frac{aV_i}{K^+ p}\right)^{1/2}$

K^+ is the mobility of positive ions in their own gas and 'a' is the slope of the efficiency of ionization by electrons. The basic assumptions for obtaining this expression lead to results which are independent of the current (Francis, 1956) and the variation of 'E', T_e and 'n' with discharge current can be discussed only in qualitative term. The values of 'a' and K^+ for hydrogen, oxygen, nitrogen and air are taken from ~~x~~ von Engel (1965) and are tabulated in Table-5.1. The values of T_e calculated from eqn. (5.20) for all the gases studied are tabulated in Table-5.2 and have been compared with the values obtained from eqn. (5.19).

TABLE-5.2.

Gas	p Torr.	H_m Gauss.	T_e from eqn. (5.19) V. *	T_e from eqn. (5.20) V. *
Hydrogen	0.2	175	3.4	3.5
Oxygen	0.5	275	2.5	2.4
Air	0.6	375	3.3	2.2
Nitrogen	0.5	300	-	2.4

* 1 V = 7740°K ($3/2\ kT_e = eV$).

CONCLUSION.

The values of T_e calculated from eqn. (5.19) and also from eqn. (5.20) show good agreement in case of hydrogen and oxygen, but there is some discrepancy in case of air. This is may be due to uncertainty in the values of V_i taken for air.

The increase of H_m with increase of I_o in case of nitrogen may be due to large change of ν_c for a small change in electron energy in presence of magnetic field. Since ν_c has been taken as constant, independent of electron energy, so this shift of H_m can not be explained by using equation (5.19). However, it may be noted that if a constant value of ν_c , of similar magnitude as other three gases studied, be taken then eqn. (5.19) will yield a value of T_e comparable in order of magnitude with T_e obtained from eqn.(5.20).

So it may be concluded that the general expression of total discharge current when modified by taking into consideration of the changes in electron temperature, radial electron density distribution and diffusion rate of electrons in presence of longitudinal magnetic field can successfully explain the present experimental results.

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