CHAPTER VII

HALL EFFECT IN AN ARC PLASMA.

Introduction

The hall effect is a standard diagonistic method for determining the charge particle density and mobility in semi-conductors and it has also been utilized for measurement of plasma parameters in a glow discharge. The effect of transverse magnetic field on the positive column of a glow discharge has been studied among others by Beckmann (1948) and the variation of current in a variable transverse magnetic field has been studied by Sen and Gupta (1971). With regard to the effect of a transverse magnetic field on an arc discharge, Allen (1951), observed in the case of a heavy current pulsed arc discharge in hydrogen that the voltage current characteristics showed a slight negative gradient over the range of 25 to 80 amperes with no magnetic field, ~~th~~ but became increasingly negative with increase of magnetic field. Forrest and Franklin (1966) have described a theoretical model for a low pressure arc discharge in a magnetic field in which predictions have been made for radial electron number density profile and radial light emission profile. Anderson (1964) investigated the Hall Effect in the positive column in the glow discharge in some rare gases and obtained the drift velocities of electrons for a range of (E/P) values. In his calculation he utilized the expression for the radial electron density distribution provided by Beckmann and the reported results for drift velocities in agreement with literature values. Axial electron density variation in a magnetically confined arc has been investigated by Mashic and Kwen (1977) who showed that the variation is more pronounced in the high pressure region ($p \sim 10$ torr) and is weakly dependent upon magnetic field. The voltage current characteristics and the power relation have been investigated in a mercury arc carrying current from 1.3 amp. to 2 amp. in presence of a transverse magnetic field upto 3000 G by Sen and Das (1973). The Hall effect in a toroidal discharge plasma has been investigated by Zhilinsky et al (1979) Goldferb (1973) had presented some diagnostic techniques for the arc plasma. In contrast to semiconductors or metals it is to be noted that when arc or a glow plasma is placed in an external magnetic field the radial electron density distribution and discharge current are significantly altered and this effect has to be taken into consideration in calculating the Hall coefficient in a plasma. In the present investigation results are reported on the measurementof Hall effect and calculation of axial density and drift velocity of electrons in a mercury arc plasma is presented.

Theoretical Treatment

The Hall voltage Ey per unit length when the conductor carrying a current i is placed in a transverse magnetic field H is given by

$$Ey = \frac{iH}{ne} \tag{7.1}$$

where i is the current per unit area and n the electron density. It has however been shown that in the case of an arc, current gradually decreases in a transverse magnetic field. Sen and Das (1973) have shown following an analysis by Beckmann (1948) that the electron density decreases and the electron temperature increases in an arc plasma in a transverse magnetic field.

The electron density n_H in presence of a magnetic field H has been shown to be given by

$$n_H = n_0 \exp(-aH) \tag{7.2}$$

The effect of a transverse magnetic field on the positive column of a glow discharge has been investigated by Beckman (1948). It has been shown by him that the axial voltage increases in the presence of a magnetic field from E to E $\left[\alpha + (\beta^2/\alpha) \right]^{1/2}$

where

$$\alpha = 1 - h^2 + h^4 \exp \int_h^{\infty} \frac{\exp(-h)}{h} dh.$$

$$\beta = \frac{h}{2}\sqrt{\pi}\left[1 - 2h^2 + 4h^2 \exp h^2 \int_h^{\infty} \exp(-h^2)\, dh\right]$$

$$h = \frac{eH\lambda}{m\omega}$$

and H is the magnetic field, λ is the electronic mean free path and ω is the most probable electronic speed and is given by

$$\omega^2 = (2KTe)/m.$$

The above expression can be reduced to a simplified form as shown

As

$$h = \frac{eH\lambda}{m\omega} \quad \text{and} \quad v_r = \sqrt{\frac{8KTe}{m\pi}}$$

where v_r is the random velocity

$$\lambda = \frac{2eHL}{m\,p\,v_r\sqrt{\pi}}$$

where L is the mean free path of the electron in the gas at a pressure of 1 mm of mercury. As λ is small for the values of magnetic field, used in the experiment.

$$\beta = \frac{\lambda}{2}\sqrt{\pi} = \frac{eL}{m\,v_r}\,\frac{H}{p} \quad \text{and } \alpha \simeq 1$$

then

$$E_H = E\left[1+\beta^2\right]^{1/2}$$

$$E_H = E\left[1 + C_1\,\frac{H^2}{p^2}\right]^{1/2} \qquad (7.3)$$

where C_1 is a constant for a particular gas and is given by

$$C_1 = \left(\frac{e}{m}\,\frac{L}{v_r}\right)^2$$

From eqn. (7.3)

$$\frac{E_H{}^2 - E^2}{E^2} = C_1\,\frac{H^2}{p^2}$$

Langmuir (1925) while studying the scattering of electrons in a mercury arc discharge deduced an expression for current given by

$$I = 5{\cdot}76 \times 10^{-10} \frac{n_e \lambda}{\sqrt{T_e}} E \tag{7.4}$$

where n_e is the electron density, λ the mean free path of the electron, T_e is the electron temperature and E is the axial electric field per centimeter. Further it has been shown by Beckmann (1948) that due to a transverse magnetic field the electron density at a distance μ from the axis is given by

$$n_H = n_0 \exp\left(\frac{-c\mu \cos\phi}{2D_a}\right) J_0\left(2{\cdot}405 \frac{\mu}{R}\right) \tag{7.5}$$

where n_0 is the electron density at the axis, R is the radius of the tube,

$$c = b_i E(\beta/\alpha).$$

where b_i mobility, D_a is the ambipolar diffusion coefficient and J_0 is the Bessel function of zero order and of first kind. In the absence of the magnetic field the electron distribution in the positive column is given by Schottky's formula

$$n_e = n_0 J_0 \left(2{\cdot}405 \frac{\mu}{R} \right)$$

(7.6)

Then

$$\frac{n_H}{n_e} = \exp\left(\frac{- c \mu \cos \phi}{2 D_a} \right)$$

(7.7)

As $C = b_i E (\beta / \alpha)$ where $\beta = C_1^{1/2} (H / P)$

and $\alpha \simeq 1$ and assuming $\phi = 0$

$$\frac{n_H}{n_e} = \exp(- a H)$$

where

$$a = \frac{b_i E C_1^{1/2} \mu}{2 D_a P} = \frac{e E C_1^{1/2} \mu}{2 K T_e P}$$

It is well known that when a magnetic field acts upon an ionised gas, the equivalent pressure concept as developed by Blevin and Haydon (1958) provided that the electronic mean free path changes from λ to λ_H where

$$\lambda_H = \frac{\lambda}{\left[1 + C_1 \frac{H^2}{P^2} \right]^{1/2}}$$

where $C_1 = \left(\frac{e}{m} \cdot \frac{L}{v_r} \right)^2$

Further from the theory of positive column and assuming the Maxwell Boltzmann distribution Law, von Engel (1963) deduced that

$$\frac{\exp(x)}{x^{1/2}} = 1\cdot 2 \times 10^7 \left(c' P R \right)^2 \tag{7.8}$$

where $x = (e V_i)/(k T_e)$, V_i being the ionization potential of the gas

$$c' = \left(\frac{a' \, V_i^{1/2}}{K^+ \, P} \right)^{1/2}$$

R is the radius of the tube and P the pressure. K^+ is the mobility of the positive ions and a' the efficiency of ionization.

Hence from eqn. (7.8) when the magnetic field is applied and remembering that the mobility K^+ of positive ions is practically unaffected by the magnetic field, due to their large mass.

$$\frac{\exp\left[(e v_i)/(K T_{eH})\right]}{\left(\dfrac{e v_i}{K T_{eH}}\right)^{1/2}} = \frac{1\cdot 2\times 10^{7} a' v_i^{1/2}}{K+} R^2 P_H \quad (7.9)$$

where T_{eH} is the electron temperature in the presence of the magnetic field and p_H is the equivalent pressure. From the eqn. (7.8) and (7.9)

$$\left(\frac{T_{eH}}{T_e}\right) \exp\left(\frac{e v_i}{K} \cdot \frac{T_{eH} - T_e}{T_e \cdot T_{eH}}\right) = \frac{P}{P_H}$$

$$= \frac{1}{\sqrt{\left(1 + C_1 \dfrac{H^2}{p^2}\right)}}$$

From experimental results it is known that $T_{eH}/T_e < 1$ and for values of T_{eH} not much different from T_e

$$T_{eH} = T_e + \frac{2 T_e^2 \log\left[\dfrac{1}{\sqrt{[(1+C_1(H^2/p^2)]}}\right]}{T_e + \dfrac{2 e v_i}{K}}$$

or

$$\frac{T_{eH}}{T_e} = 1 + \gamma \log \left[\frac{1}{\sqrt{\left(1 + C_1 \frac{H^2}{p^2}\right)}} \right]$$

where $\gamma = \dfrac{2\,T_e}{T_e + \dfrac{2 e V_i}{K}}$ (7.10)

Hence from eqn. (7.4) when the magnetic field is applied

$$I_H = 5.76 \times 10^{-10} \frac{n_H \lambda_H}{\sqrt{T_{eH}}} \cdot E_H \qquad (7.11)$$

Putting the values of n_H, λ_H, E_H and T_{eH} as deduced above, we get

$$\frac{I_H}{I} = \frac{\exp(-aH)}{\left[1 + \gamma \log\left(\frac{1}{\sqrt{[1 + C_1 (H^2/p^2)]}}\right)\right]^{1/2}}$$

In this

$$a = \frac{e\,E\,C_1^{1/2}\,\mu}{2\,K\,T_e\,P} \qquad (7.12)$$

where, E is the axial electric field, μ the electron mobility, K the Boltzmann constant, T_e the electron temperature, P the pressure, and

$$C_1 = \left(\frac{e}{m} \; \frac{L}{v_r} \right)^2$$

where L is the mean free path of the electron in the gas at a pressure of 1 torr, v_r, is the random velocity of the electron and $\gamma = \frac{2\,T_e}{T_e + 2\,eV_i/K}$

where V_i is the ionization ~~x~~ potential of the gas.

As both current and radial electron density change when the arc is placed in a magnetic field we get then from eqn. (7.1), (7.2) and (7.12)

$$E_y = \frac{iH}{n_0\, e \left[1 + \gamma \log \left\{ \frac{1}{(1 + C_1 H^2/p^2)^{1/2}} \right\} \right]^{1/2}} \tag{7.13}$$

Hence by measuring the Hall voltage for a range of values of the magnetic field the electron density in an arc plasma can be obtained. Further as i the current density $= n_0\, e\, v_d$ where v_d is the drift velocity of the electron, it is possible to calculate the drift velocity as well.

Experimental arrangement:- (MENTIONED in Chapter II)

Results and Discussion

Experimental results are given here for a mercury arc plasma carrying a current of 3 amp and the transverse magnetic field varying from 64 G to 526 G. The results are entered in Table 7.1.

Table 7.1

Magnetic field in Gauss	Hall voltage volts/cm	Value of n from the relation $E_y = \frac{iH}{ne}$	$1 + \delta \log \frac{1}{(1+C_1)(H^2/P^2)^{1/2}}$	Value of n_o from eqn.(7.13)
64	0.34	3.599×10^{12}	0.9910	3.631×10^{12}
112	0.71	3.533×10^{12}	0.9763	3.620×10^{12}
166	1.15	3.501×10^{12}	0.9576	3.656×10^{12}
216	1.76	3.483×10^{12}	0.9515	3.662×10^{12}
256	2.17	3.423×10^{12}	0.9374	3.652×10^{12}
306	2.62	3.356×10^{12}	0.9123	3.678×10^{12}
356	3.07	3.253×10^{12}	0.8993	3.617×10^{12}
406	5.57	3.180×10^{12}	0.8772	3.624×10^{12}
450	3.92	3.165×10^{12}	0.8756	3.606×10^{12}
476	4.40	3.108×10^{12}	0.8712	3.569×10^{12}
526	4.62	3.068×10^{12}	0.8610	3.563×10^{12}

Values of 'n', the electron density in the third column of Table 7.1 have been calculated from the relation $E_y = \frac{iH}{ne}$ (eqn. 7.1) which assumes that the current and radial distribution of charged particles are the same as in the absence of magnetic field. The results consequently show that the electron density in absence of magnetic field shows a decrease with the increase of the magnetic field which however should be constant for all values of magnetic field as the magnetic field used for producing the Hall effect has been used here as a probe only. To take into account the effect of the radial distribution of charged particles in presence of the transverse magnetic field and also the change of current we have used in eqn. (7.13) for the 'Hall voltage and have taken T_e for the electron temperature to be 25000°K after Karelina and confirmed by Sadhya in our laboratory by a spectroscopic method, the value of r has been calculated to be 0.1887 as in the previous paper by Sen and Das (1973). C_1 is the square of the mobility of the electron in mercury vapour at a pressure of 1 torr and has been taken as 2×10^{-6} by Mc Daniee. Using these values of r and C_1 the numerical values of the term in eqn. (7.13) have been calculated for values of magnetic field varying from 64 gauss to 526 gauss and the results are entered in the fourth column of table 7.1. Now utilizing eqn. (7.13) the value of n_o the axial electron density in absence of the magnetic field has been calculated and the results are entered in the fifth column of table 7.1.

The Hall effect is used here as a diagnostic tool and the axial electron density in absence of magnetic field should be independent of magnetic field used for measuring Hall effect. The results show that the axial electron density in absence of magnetic field is almost constant for values of magnetic field varying from 64 gauss to 526 gauss and for higher values of magnetic field there is a fall in the values of 'n_o'.

This result is also consistent with the earlier observation by Sen and Das (1973) that eqn. (7.3) as deduced from the expressions of Beckmann is valid for values of magnetic field upto 1000 gauss and as in the present investigation of the maximum magnetic field is 526 gauss, eqn.(7.3) will hold in this region of magnetic field as well.

The average value of electron density is 3.638×10^{12}.

From this value of n_o, the drift velocity of electrons can be calculated $i = n_0 e v_d$

$$\frac{3}{3.14 \times (1.32)^2} = 3.638 \times 10^{12} \times 1.6 \times 10^{-19} v_d$$

So that $v_d = 0.94 \times 10^6$ cm/sec which is in agreement with the result reported by Brown.

It is thus concluded that the Hall effect can be utilized as useful diagnostic technique for measurement of electron density and drift velocity of electrons in an arc plasma. The radial particle density distribution and the change of arc current due to magnetic field have to be taken into account in calculating the parameters of the plasma.

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HALL EFFECT IN AN ARC PLASMA

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The Hall voltage in a mercury arc plasma carrying a current of 3 amperes with a background air pressure of .2 torr has been measured for a range of magnetic field varying from 64 gauss to 526 gauss. Taking into consideration the variation of arc current and radial electron density in a transverse magnetic field as deduced by Sen and Das[1] from the theoretical formulation of Beckman[2], the expression for Hall voltage in an arc plasma has been deduced. The value of electron density and drift velocity have thus been calculated which are in agreement with literature values. The utility of the method as a plasma diagonostic tool has been discussed.

Keywords : Hall Effect; Arc Plasma; Magnetic Field; and Electron Density

Introduction

The Hall effect is a standard diagnostic method for determining the charged particle density and mobility in semi-conductors and it has also been utilized for measurement of plasma parameters in a glow discharge. The effect of a transverse magnetic field on the positive column of a glow discharge has been studied among others by Beckman[2] and the variation of current in a variable transverse magnetic field has been studied by Sen and Gupta[3]. With regard to the effect of a transverse magnetic field on an arc discharge, Allen[4] observed in the case of a heavy current pulsed arc discharge in hydrogen that the voltage current characteristic showed a slight negative gradient over the range of 25 to 80 amperes with no magnetic field, but became increasingly negative with increase of magnetic field. Forrest and Franklin[5] have described a theoretical model for a low pressure arc discharge in a magnetic field in which predictions have been made for radial electron number density profile and radial light emission profile. Anderson[6] investigated the Hall effect in the positive column in the glow discharge in some rare gases and obtained the drift velocities of electrons for a range of (E/P) values. In his calculation he utilised the expressions for the radial electron density distribution provided by Beckman[2] and reported results for drift velocities in agreement with literature values. Axial electron density variation in a magnetically confined arc has been investigated by Mashic and Kwen[7], who showed that the variation is more pronounced in the high pressure region ($p \sim 10$ torr) and is weakly dependent upon magnetic field. The voltage current characteristics and the power relation have been investigated in a mercury arc carrying current from 1.3 amp. to 2 amp. in presence of a transverse magnetic field upto 3000G by Sen and Das[1]. The Hall effect in a toroidal discharge plasma has been investigated by Zhilinsky *et al.*[8] and Goldferb[9] has presented some diagnostic techniques for the arc plasma. In contrast to semiconductors or metals it is to be noted that when an arc or a glow plasma is placed in an external magnetic field the radial electron density distribution and discharge current are significantly altered and this effect has to be taken into consideration in calculating the Hall coefficient in a plasma. In the present investigation results are reported on the measurement of Hall effect and calculation of axial density and drift velocity of electrons in a mercury arc plasma.

Theoretical Treatment

The Hall voltage E_y per unit length when the conductor carrying a current i is placed in a transverse magnetic field H is given by

$$E_y = \frac{iH}{ne} \qquad \ldots(1)$$

where i is the current per unit area and n the electron density. It has, however, been shown that in the case of an arc current gradually decreases in a transverse magnetic field. Sen and Das[1] have shown following an analysis by Beckman[2] that the electron density decreases and the electron temperature increases in an arc plasma in a transverse magnetic field. The electron density n_H in presence of a magnetic field H has been shown to be given by

$$n_H = n_0 \exp(-aH) \qquad \ldots(2)$$

where a is defined below. Taking these two effects into consideration, Sen and Das[1] deduced the expression for the arc current i_H in a transverse magnetic field as

$$\frac{i_H}{i} = \frac{\exp(-aH)}{\left[1 + r \log\left\{\frac{1}{(1 + C_1 H^2/P^2)^{1/2}}\right\}\right]^{1/2}} \qquad \ldots(3)$$

In this $a = \dfrac{eEC_1^{1/2}\mu}{2KT_eP}$ where E is the axial electric field, μ the electron mobility, K the Boltzman constant, T_e the electron temperature, P the pressure and $C_1 = \left(\dfrac{e}{m}\dfrac{L}{v_r}\right)^2$ where L is the mean free path of the electron in the gas at a pressure of 1 torr, v_r is the random velocity of the electron and $r = \dfrac{2Te}{T_e + 2eV_{i/k}}$ where V_i is the ionization potential of the gas.

As both current and radial election density change when the arc is placed in a magnetic field we get then from equation (1), (2) and (3)

$$E_y = \frac{iH}{n_0e\left[1 + r \log\left\{\frac{1}{(1 + C_1 H^2/P^2)^{1/2}}\right\}\right]^{1/2}} \qquad \ldots(4)$$

Hence by measuring the Hall voltage for a range of values of the magnetic field the electron density in an arc plasma can be obtained. Further as i the current density

$= n_0 e v_d$ where v_d is the drift velocity of the electron it is possible to calculate the drift velocity as well.

Experimental Set up

The Hall voltage measurement has been carried out in a mercury arc plasma which has been produced within a cylindrical glass tube of radius 1.32 cm. and a distance between the two mercury pool electrodes of 26.4 cms. The arc is run on d.c. voltage (220 volts) with regulating rheostats in series : arc current has been varied from 2 amp. to 3 amps. The background air pressure within the arc is maintained ata .2 torr. Two horizontal metallic plates (2.5 cm. $\times$ 1 cm.) at a distance of .8 cm. are introduced within the arc tube for measuring the Hall voltage. The magnetic field which is at right angles to both to the direction of the flow of current and measuring electrodes has been provided by an electromagnet. The power to run the electromagnet has been supplied by a stabilised power supply. The magnetic field which has been varied from zero to 550 gauss has been measured by an accurately calibrated gauss meter. The gauss meter operates on the principle of the Hall effect. The Hall probe is made of a highly pure indium arsenide crystal and is encapsulated in a nonmagnetic sheath of approximately 50 mm. $\times$ 5 mm. $\times$ 2 mm. and is connected to a three feet cable. A transparent cap is provided for the protection of the probe. The accuracy of the reading is $\pm$ 2.5 per cent upto 10 kilogauss. The Hall voltage developed in the arc plasma has been measured by a V.T.V.M. (Simpson Model No. 321–1). The valve tube voltmeter is a Versatile instrument designed for accurate measurement of voltage (both a.c. and d.c.). The d.c. voltages upto 1500 volts can be measured in seven stages, input impedance is 35 megaohms in all the ranges and the accuracy of reading is $\pm$ 3 per cent.

Results and Discussion

Experimental results are reported here for a mercury arc plasma carrying a current of 3 amp. and the transverse megnetic field varying from 64 G to 526 G. The results are entered in Table I.

Values of n, the electron density in the third column of Table I have been calculated from the relation $E_y = \dfrac{iH}{ne}$ (eq. 1) which assumes that the current and radial distribution of charged particles are the same as in the absence of magnetic field. The results consequently show that the electron density in absence of magnetic field shows a decrease with the increase of the magnetic field which however should be constant for all values of magnetic field as the magnetic field used for producing the Hall effect has been used here as a probe only. To take into effect the radial distribution of charged particles in presence of the transverse magnetic field and also the change of current we have used equation (4) for the Hall voltage, and have taken T_e, the electron temperature to be 25000 K after Karelina[10] and confirmed by Sadhya[11] in this laboratory by a spectroscopic method, the value of r has been calculated to be 0.1887 as in the previous paper by Sen and Das[1]. C_1 is the square

TABLE I

Magnetic field in Gauss	Hall voltage volts/cm.	Value of n from the relation by $E_y = \frac{iH}{ne}$	$\left[1 + r \log \frac{1}{(1 + C_1)\,(H^2/P^2)^{1/2}}\right]^{1/2}$	Value of n_0 from eqn. (4)
64	.34	3.599×10^{12}	.9910	3.631×10^{12}
112	.71	3.533×10^{12}	.9763	3.620×10^{12}
166	1.15	3.501×10^{12}	.9576	3.656×10^{12}
216	1.76	3.483×10^{12}	.9515	3.662×10^{12}
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476	4.40	3.108×10^{12}	.8712	3.569×10^{12}
526	4.62	3.068×10^{12}	.8610	3.563×10^{12}

of the mobility of the electron in mercury vapour at a pressure of 1 torr and has been taken as 2×10^{-6} by Mc Daniee[12]. Using these values of r and C_1 the numerical values of the term in equation (4) have been calculated for values of magnetic field varying from 64 gauss to 526 gauss, and the results are entered in the fouth column of Table I. Now utilizing equation (4) the value of n_0 the axial electron density in absence of the magnetic field has been calculated and the results are entered in the fifth column of Table I. The Hall effect is used here as a diagnostic tool and the axial electron density in absence of magnetic field should be independent of magnetic field used for measuring the Hall effect. The results show that the axial electron density in absence of magnetic field is almost a constant for values of magnetic field varying from 64 gauss to 526 gauss and for higher values of magnetic field there is a fall in the value of n_0. This result is also consistent with the earlier observation by Sen and Das[1] that equation (3) as deduced from the expressions of Beckman[2] is valid for values of magnetic field upto 1000 gauss and as in the present investigation the maximum magnetic field is 526 gauss equation (3) will hold in this region of magnetic field as well. The average value of electron density is 3.638×10^{12}. From this value of n_0, the drift velocity of electrons can be calculated.

$$i = n_0 e v_d$$

$$\frac{3}{3.14 \times (1.32)^2} = 3.638 \times 10^{12} \times 1.6 \times 10^{-19}\, v_d$$

So that $v_d = .94 \times 10^6$ cm/sec. which is in agreement with the result reported by Brown[13].

It is thus concluded that the Hall effect can be utilised as a useful diagnostic technique for measurement of electron density and drift velocity of electrons in an arc plasma. The radial particle density distribution and the change of arc current due to magnetic field have to be taken into account in calculating the parameters of the plasma. Work is in progress with other arc sources and results will be reported.

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