CHAPTER VIII

OUTLINE OF A GENERALISED THEORY OF ARC PLASMA FROM EXPERIMENTAL RESULTS.

A vast literature has accumulated on the properties of glow discharge but the corresponding work on the properties of arc plasma has been reported to a much lesser extent. For example, no comprehensive theory has been worked out regarding the underlying physical processes responsible for the occurance of arc plasma, though two theories namely the thermionic emission theory and field omission theory have been advanced. With a view to understand the basic physical processes occuring in an arc plasma and to study the transition from glow discharge to arc plasma a programme of work has been undertaken in this laboratory and a number of papers has been published in this line (Reference of the end). The results obtained and the theoretical analysis provided will be reviewed and an attempt will be made to understand the basic physical processes that occur in the initiation and maintanance of an arc plasma.

A) Voltage current and power relation in an arc plasma in a transverse magnetic field.

The effect of a magnetic field on the positive column of a glow discharge has been analysed mathematically by Beckman (1948). The theory has further been extended by Sen and Gupta (1971) to explain the variation of current in the glow discharges in air, carbondioxide, neon and helium under a transverse magnetic field. To find the variation as the density of the plasma is increased when glow to arc transition takes place and whether the theory developed in case of a low current discharge as regards the variation of current and voltage in a transverse magnetic field can be extended to similar variation in arc discharge, work was undertaken by Sen and Das (1973) in which the voltage current and dissipated power were measured in case of a mercury arc (1.3, 1.5, 1.8 and 2 amp initial arc current) under a transverse magnetic field varying from zero to 2000 gauss. It has been observed that the arc current decreases and voltage ~~x~~ across the arc increases and the power consumed gradually increases with the increase of the magnetic field and attaining a maximum value for a particular magnetic field which is different for different initial currents gradually decreases.

In order to explain the variation of current, voltage and power in the arc plasma under the transverse magnetic field the following results obtained by by Sen and Gupta (1971), Sen and Gupta (1969), Blevin and Haydon (1958) have been utilized.

$$E_H = E\left[1 + C_1 \frac{H^2}{P^2}\right]^{1/2} \tag{8.1}$$

where E_H and E are the axial electricak field in presence and in absence of magnetic field, $C_1 = \left(\frac{e}{m}\frac{L}{v_r}\right)^2$ where L is the mean free path of the electron at a pressure of 1 torr and v_r is the random velocity of the electron.

$$n_H = n \exp(-aH) \quad \left[\text{Sen \& Gupta 1971}\right]$$

where n_H is the electron density at a distance 'r' from the axis, n is the axial electron density and

$$a = e E C_1^{1/2} r / 2K T_e P \tag{8.2}$$

Further it has been deduced that

$$\frac{T_{eH}}{T_e} = 1 + r \log\left[\frac{1}{\left\{1 + C_1 \frac{H^2}{P^2}\right\}^{1/2}}\right]$$

$$\left[\text{Sen and Gupta 1969}\right] \tag{8.3}$$

Where

$$r = \frac{2 T_e}{T_e + e v_i / K.}$$

where T_e is the electron temperature and V_i is the ionization potential of the gas and

$$\lambda_H = \frac{\lambda}{\left(1 + c_1 \frac{H^2}{p^2}\right)^{1/2}} \tag{8.4}$$

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

$$I = 5 \cdot 76 \times 10^{-10} \frac{n_e \lambda}{\sqrt{T_e}} E \tag{8.5}$$

when the magnetic field is applied n_e, λ, T_e and E are modified and putting the corresponding values from equations (8.1 to 8.4) in eqn. (8.5) it can be deduced that

$$\frac{I_H}{I} = \frac{\exp(-aH)}{\left[1 + r \log\left\{\frac{1}{(1 + c_1 H^2/p^2)^{1/2}}\right\}\right]^{1/2}} \tag{8.6}$$

or

$$\frac{1}{I}\frac{dI_H}{dH} = \frac{\exp(-aH)}{\left[1+r\log\left\{\frac{1}{(1+C_1 H^2/p^2)^{1/2}}\right\}\right]^{1/2}} \times \left[-a + \frac{r C_1 H/p^2}{\left\{1+C_1\frac{H^2}{p^2}\right\}.\left\{1+\log\frac{1}{(1+C_1\frac{H^2}{p^2})^{1/2}}\right\}}\right]$$

The value of the expression within the bracket has been calculated for H = 200 G to H = 2000 G and it has been found to be negative whereas the term outside the bracket is always positive. Hence the current will always decrease with the increase of the magnetic field. Physically this means that under the action of the magnetic field electrons are deflected from their direction of motion and the number of electrons contributing to the total current gradually decreases with the increase of the magnetic field which reduces the current.
The increase in the value of voltage drop across the arc can be explained from the analytically deduced expression

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

To calculate the magnetic field at which the power consumed becomes a maximum if W_H and W represent the power with and without magnetic field then

$$\frac{W_H}{W} = \exp(-aH) \frac{\left(1 + c_1 \frac{H^2}{p^2}\right)^{1/2}}{\left[1 + r \log\left\{\frac{1}{1 + c_1 \frac{H^2}{p^2}}\right\}\right]^{1/2}}$$

$$\frac{1}{W} \frac{dW_H}{dW} = 0 = -a\left[1 + c_1 \frac{H^2}{p^2}\right] + c_1 \frac{H}{p^2} + \frac{\frac{r}{2} c_1 \frac{H^2}{p^2}}{1 - r \log \left\{1 + c_1 \frac{H^2}{p^2}\right\}^{1/2}}$$

To simpl.fy calculation it is noted that even for a field of 2000 G the term $r \log \left\{1 + c_1 \frac{H^2}{p^2}\right\}^{1/2}$ can be neglected in comparison to unity. Hence

$$aH^2 - \left(1 + \frac{r}{2}\right)H + \frac{ap^2}{c_1} = 0$$

or

$$H_{max} = \frac{\left(1 + \frac{r}{2}\right) + \left[\left(1 + \frac{r}{2}\right)^2 - \frac{4a^2p^2}{c_1}\right]^{1/2}}{2a} \tag{8.7}$$

It has been shown by Sen & Das (1973) that the agreement between the theoretical value calculated from eqn. (8.7) and experimental results regarding the value of the magnetic field at which the power delivered becomes a maximum agrees quite well upto a magnetic field H = 1440G.

The work has further been extended for higher arc currents and transverse magnetic field varying upto 2000G by Sen and Gantait (1988).

(B) Conductivity and power relation in an arc plasma in a transverse magnetic field.

Voltage current and conductivity between the two probes for four different arc currents namely 2.25, 2.5, 3.0 and 4.0 amps. in a transverse magnetic field varying from zero to 1660 G were measured by high impedance meters.

The voltage for all values of arc current was found to increase and the current itself to decrease with the increase of the magnetic field. The output power becomes a maximum for a certain value of the magnetic field which increases with the increase of the arc current. The variation of log σ/σ_H as obtained from measurements against magnetic field where σ_H and σ are the conductivities with and without magnetic field it has been shown (Sen and Gantait, 1988) that the variation can be represented by

$$\sigma_H = \sigma e^{-aH} \tag{8.8}$$

where a is a constant. Comparing with Beckman's expression as modified by Sen and Gupta (1971)

$$a = \frac{e E Q^{1/2} r}{2 K T_e P} \tag{8.9}$$

where E is the voltage drop per unit length of the arc. Taking the corresponding values of the quantities it is possible to calculate C_1 for different discharge currents as the values of a can be obtained from the variation of log σ/σ_H against H. The results are consistent with the values obtained earlier by Sen and Das (1973).

Table 8.1

Values of a and C_1.

Arc current	$a \times 10^3$	$C_1 \times 10^6$
2.25	5.117	3.767
2.5	3.733	2.004
3.0	2.033	0.5946
4.0	1.659	0.3961

Utilizing the eqn. (8.7) and taking the values of a and C_1 from table (8.1) the values of H_{max} was calculated and the results are reported in table (8.2). The results therefore, indicate that the agreement between theory and experiment is quite satisfactory for smaller values of magnetic field but discrepancy exists for higher magnetic field values. Similar conclusions were also arrived at earlier (Sen & Das, 1973). The disagreement

Table 8.2

Arc current	r	a x 10^3	C_1 x 10^6	H_{max} (G) (Calc)	(Expt)
2.25	0.1887	5.117	3.767	196.5	146
2.5	0.1887	3.733	2.004	283.1	275
3.0	0.1887	2.033	.5946	5202	760
4.0	0.1887	1.659	.3961	637.5	1310

observed for higher values of arc current and magnetic field may be attributed to the fact that the effect of magnetic field on the motion of the electron is linear for smaller values of magnetic field but involves squares and higher powers of magnetic field when it is high. Since equation (8.7) has been deduced on the assumption that the magnetic field is small terms involving higher powers of magnetic field are not considered. If eqn.(8.7) is modified to include higher power terms better agreement between theory and experiment can be expected.

(C) Voltage current and power relation in an arc plasma in a variable axial magnetic field.

In our earlier work we have investigated the effect of a transverse magnetic field on the voltage current characteristics and power relation in arc plasma. It is whorthwhile to investigate whether the same model is valid in the case of an arc plasma when subjected to an axial magnetic field. The object is also to findout whether the properties as well as plasma parameters of an arc plasma are dependent upon the alignment of the magnetic field with respect to direction of the flow of arc current.

Sen and Gantait (1987) studied the variation of voltage across the arc current and power developed for magnetic field varying from zero to 1.5 KG. When the magnetic field is applied the voltage across the arc increases linearly with magnetic field. The rate of increase is highest for the lowest initial current and decreases with the increase of the current. The arc current decreases with the increase of the magnetic field. The linear variation of arc voltage with magnetic field can be represented by an equation of the form

$$E_H = E_0 + m_0 H = E_0\left(1 + \frac{m_0}{E} H\right) = E(1 + mH) \qquad (8.10)$$

we further note that as reported by Sen and Das (1973) almost similar results have been obtained in transverse magnetic field as is now found in longitudinal magnetic field ~~in~~ but quantitatively there is a difference. In the case of the transverse magnetic field the maximum change of current is in the ratio 1.58 whereas in case of an axial magnetic field the ratio is much smaller (1.062) for a magnetic field of the order of 1.35 KG.

As a result the ratio of voltage change in the transverse magnetic field is 1.86 whereas in the case of axial magnetic field it is 1.37. We can thus conclude that in both the cases the effects are similar but the transverse magnetic field will have a more dominant effect on the properties of arc plasma than that of an axial magnetic field.

From the experimental results it is possible, to calculate the average conductivity of the arc plasma for the range of magnetic field investigated, and the values of σ_H the conductivity for values of magnetic field (upto 1.37) are provided by Sen and Gantait (1987). Let us assume that variation of σ_H with H can be represented by an eqn. of the form $\sigma_H = \sigma \exp(-\alpha H)$ where 'α' is a constant. The value of 'α' has been calculated statistically, for a current of 3 amp.

$$\alpha = 0.2859.$$

Calculating the value of σ_H with the value of α obtained and comparing with experimental values of σ_H extremely good agreement is obtained for the values of magnetic field investigated. Thus the variation can be represented as

$$\sigma_H = \sigma_0 \exp(-\alpha H). \tag{8.11}$$

From Beckman's expression (1948)

$$n_H = n_0 \exp(-aH)$$

with $a = eE\, C_1^{1/2}\, r / 2KT_e\, p$

Hence as conductivity is proportional to electron density

$$a = \alpha = eE\, C_1^{1/2}\, r / 2KT_e\, p \tag{8.12}$$

Taking the values of the terms from experimental data, a = 0.2375 which is in very good agreement with the value of α obtained in-dependently. Further we note that the output power of the arc

$$P_H = I_H E_H = \sigma_H E_H^2 = \sigma \exp(-\alpha H) E^2 (1 + mH)^2$$

$$\frac{dP_H}{dH} = \sigma E^2 \Big[-\alpha - \exp(-\alpha H) + m^2 2H \exp(-\alpha H) - m^2 H^2 \alpha \exp(-\alpha H) + 2m \exp(-\alpha H) - 2mH\alpha \exp(-\alpha H) \Big]$$

Maximising we get

$$H_{max} = (2/\alpha) - (1/m). \tag{8.13}$$

Putting α = 0.2859 and m = 0.2773

$$H_{max} = 3606 \text{ G}.$$

Since the maximum magnetic field used in the experiment is 1350 G the magnetic field for maximum power dissipation will be beyond this range and cannot be observed in the present experiment. Further the conductivity in an arc plasma with axial magnetic field can be represented by the expression

$$\sigma_H = \sigma_0 \exp(-\alpha H)$$

To compare the results with the transverse magnetic field we find that in both cases voltage increases and current decreases when the magnetic field is increased but the effect is much more pronounced in a transverse magnetic field. The power output becomes a maximum for a certain value of the magnetic field when the field is transverse whereas the power output shows almost a linear increase when the magnetic field is axial. The theory predicts that a maximum in power dissipation is expected at a very high value of the magnetic field.

From the above experimental investigation and theoretical analysis we can conclude that both glow discharge and arc plasma react similarly under an external magnetic field. The mathematical analysis deduced for glow discharge is also valid in the case of arc plasma in presence of a magnetic field. The mechanism of formation of a glow discharge and an arc plasma though different shows similar behaviour (once the plasma is formed) towards the external magnetic field.

(D) Azimuthal charge carrier distribution in an arc plasma.

The important point to study in the case of an arc plasma is the gradual transition from a glow discharge to an arc plasma. In this section we propose to investigate the process starting from glow discharge and analyse the steps which lead to glow to arc transition and finally to the development of fully stabilized arc. The important point in the problem is to find the charge carrier density distribution along the radial direction in an arc plasma and to find how it differs from the distribution in a glow discharge. In order to find the density distribution it is essential that the azimuthal conductivity of the arc plasma should be measured accurately and a method has been developed for this measurement, Ghosal, Nandi and Sen (1976).

When a conductor is placed inside a coil carrying a radiofrequency current a portion of the radiofrequency power is lost due to (a) the stray capacitance bypass of r.f. current, (b) the eddy current heating of the plasma. The latter effect is very small in the radio - frequency range in the case of glow discharge plasma. In the case of arc plasma where the percentage of ionization and hence the conductivity is much higher power, loss is essentially due to eddy current heating of the plasma.

Based on these two assumptions of loss a generalised theory is presented here showing the quantitative variation of loss factor from a plasma with small conductivity such as a glow discharge to a plasma with high conductivity as in an arc discharge. The theory developed in conjunction with the experimental observation enables us to obtain the azimuthal radiofrequency conductivity of the arc plasma.

Theoretical consideration:

As mentioned earlier, the loss of r.f. power of the resonant circuit due to the presence of the plasma column within the coil is affected by two factors.

(I) Eddy current loss -

A plasma can be assumed to be a cylindrical conductor. The alternating magnetic field associated with the r.f. current induces an r.f. electric current within the plasma, the magnitude of which is proportional to the azimuthal conductivity of the plasma. The plasma column itself can be considered to act like a secondary coil. The reflected resistance can easily be expressed in terms of eddy loss and hence in terms of azimuthal conductivity if it is assumed that the plasma almost forms a short circuited secondary of turn number unity.

(II) Capacitative by pass -

From the composite equivalent circuit adopted considering the above two factors the effective resistive impedance of the coil can be written as (Ghosal, Nandi & Sen, 1976).

$$R' = R_0 + \frac{R_2 C^2}{(C_0 + C)^2 + \omega^2 R_2^2 C^2 C_0^2} + \frac{\omega^2 M^2}{R_1^2 + \omega^2 L_1^2} R_1$$

(8.14)

where the symbols have their usual significance, it has been shown that for the lower values of conductivity in the case of glow discharge the third term is very small in comparison to second term and ($R' - R_0$) i.e. the change in the band width increases with the increase in conductivity attaining a maximum value when $R_2 = \frac{C_0 + C}{\omega C C_0}$ with further increase in conductivity when

$$(C_0 + C)^2 > \omega^2 R_2^2 C^2 C_0^2 (R' - R_0)$$

Conductivity decreases. For some higher values of the conductivity that is for glow to arc ~~xx~~ transition both the second and third terms of eqn. (8.14) are significant and ($R' - R_0$) reaches a minimum. Finally in the arc region the reflected resistance term only becomes predominent and the band width rises linearly until R_1^2 and $\omega^2 L_1^2$ are comparable. When $R_1^2 = \omega^2 L_1^2$ the curve shows another maxima. In the present experiment $\omega^2 L_1^2 << R_1^2$ and eqn. (8.14) can be written in the arc region as

$$R' = R_0 + \frac{\omega^2 M^2}{R_1} \tag{8.15}$$

Thus the above equation brings out the gradual changes from glow to arc transition. If i_0 and i_1 be the tuned radio frequency currents through the coil before and during the discharge respectively the azimuthal conductance is given by

$$\sigma_1 = \frac{R_0(\alpha - 1)}{\omega^2 M^2} \quad \text{where } \alpha = i_0/i_1$$

To determine the azimuthal conductivity σ_S is given by

$$\sigma_S = \frac{\pi(\alpha - 1)}{l\,\omega^2 M^2} R_0 \tag{8.16}$$

Thus knowing (α - 1), σ_S can be calculated for different discharge currents. Detailed methods of measurement and experimental result have been given in the paper by Ghosal, Nandi and Sen (1976).

Derivation of the distribution function

In this section we shall derive the radial distribution function of the charged particles in an arc plasma. It is well known that a plasma within a tube cannot be regarded as uniform with regard to radial electron density distribution and in case of glow discharge the radial distribution of charge density is cylindrically symmetric and can be represented by the Bessel function which is known as a Schottkey model. The Schottkey model as applied to glow discharge can also be assumed to be valid in the case of a glow pressure arc. At a very low pressure of the order of 10^{-5} torr. the Schottkey model is no longer valid and the free fall model was developed by Tonks and Langmuir (1968) in which it was assumed that ions are lost to the wall due to free fall in radial electric field. The validity or other wise of these assumed models has been put to some experimental tests in the case of glow discharge by the probe method but no elaborate experimental investigation in this regard has been carried out in case of arc plasma. In the previous Section we have provided a method of measuring the azimuthal radio frequency conductivity of an arc plasma and it has been assumed that the plasma is of uniform conductivity. Experimental evidence has already indicated however that an arc plasma cannot be regarded as a medium of uniform charge density or conductivity and previous attempts such as those of Schottkey or of Tonks and Langmuir are based on some assumed theoretical models. In the present investigation it is our aim to start with some generalised radial conductivity distribution and to measure experimentally a quantity which is a function of this assumed conductivity distribution. The next step will be to find the nearly exact distribution function which gives the closest approach to the experimental results (Ghosal, Nandi and Sen, 1978).

Let us consider an annular cylinder defined by the radii r and r + dr and length l where l is the length of the coil. The reflected impedance of this annular cylindrical plasma under certain approximations (Ghosal et al. 1976) is given by $\omega^2 M^2(r) / R(r)$ where R (r) is the azimuthal resistance of the annular cylinder and M (r) is the mutual inductance between the coil and the annular cylinder of the plasma and ω is the angular frequency of the applied radio frequency field. In terms of conductivity the reflected impedance of the annular cylinder of the plasma is

$$\frac{\omega^2 l M^2(r) \ \sigma(r)\, dr}{2\pi r}.$$

where $\sigma(r)$ is the azimuthal conductivity of the plasma at a distance 'r' from the axis. The total reflected impedance will be the sum of the contributions of all the elementary annular cylinders imagined within the plasma column. Consequently if R_0 is the radio frequency resistance of the primary coil the total effective impedance of the coil will be

$$R' = R_0 + \frac{\omega^2 l}{2\pi} \int_0^R \frac{M^2(r)\,\sigma(r)\,dr}{r}. \tag{8.17}$$

where R is the radius of the arc tube. M (r) can be written as $M(r) = Kr^2$ where K is a constant depending upon the number of turns of the primary coil. If α denotes the ratio of the radio frequency current without and with plasma we get from eqn. (8.17)

$$\alpha - 1 = \frac{\omega^2 K^2 l}{2\pi R_0} \int_0^R r^3\,\sigma(r)\,dr. \tag{8.18}$$

If $\sigma(r) = \sigma_0$,

then

$$\sigma_0 = \frac{8\pi(\alpha - 1)}{l\omega^2 M^2(r)} R_0$$

This formula differs by a numerical factor from the expression used in the previous paper (Ghosal et al. 1976) due to the fact that previously an average value of mutual inductance and current path was taken whereas M(r) has been assumed here to be a function of r in the form $M(r) = K r^2$. In obtaining the above equations, it has however been assumed that the skin depth is much greater than the arc radius because it has been calculated in the paper (Ghosal et al 1976) that for a frequency of 5.1 MHz as used in the present experiment the skin depth is 2 cm.

If 'I' denotes the arc current and E the axial voltage drop per unit length

$$\int_0^R \sigma(r)\, r\, dr = I / 2\pi E \tag{8.19}$$

Then from eqn. (8.14) and (8.15)

$$\frac{\int_0^R r^3 \sigma(r)\, dr}{\int_0^R r\, (\sigma)(r)\, dr} = \frac{(\alpha - 1)}{f^2 K^2 \ell} \frac{E}{I} R_0 \tag{8.20}$$

where $f = \omega / 2\pi$ is the frequency of the radio frequency current. Since all the terms on the right handside of equation (8.20) can be obtained experimentally eqn. (8.20) contains the information regarding the radial distribution of conductivity, but it is evident that from the experimental measurement of the expression on the right hand side of equation (8.20) it is not possible to determine uni-qualy the nature of the radial variation of $\sigma(r)$

However, the utility of the equation lies in the fact that the factor on the right hand side can be determined experimentally and any proposed form of $\sigma(r)$ will become invalid unless the expression on the left hand side calculated on the basis of the proposed form, is equal to the right hand side obtained from experimental measurement.

Regarding the form of $\sigma(r)$ let us make the following assumptions -

a) $\sigma(r)$ is cylindrically symmetric
b) It is a monotonically decreasing function
c) $\sigma(r) = 0$ at r = R.

Thus the general form of $\sigma(r)$ can be written as a polynomial expansion around r = R. It is however advantageous to assume $\sigma(r)$ of the approximate form

$$\sigma(r) = \sigma_0 \left[1 - \left(\frac{r}{R}\right)^2 \right]^n \tag{8.21}$$

where σ_0 and n are to be determined. If we denote by "a" the experimentally determined expression on the right hand side of eqn. (8.20) we get from eqn.(8.20) and (8.21)

$$n = \left[\frac{R^2}{a} - 2 \right] \tag{8.22}$$

Hence inserting the value of 'a' in eqn. (8.22) n can be determined and we can obtain an expression for the radial distribution function for $\sigma(r)$ from eqn.(8.21).

<u>Results and Discussion:</u>

The values of "a" determined from the expression

$$a = \frac{(\alpha - 1)}{f^2 K^2 l} \frac{E}{I} R_0$$

are entered in table (8.3) for different value of I/E.

Table (8.3)

I/E amp.cm/volt	a cm^2
3.36	0.131
6.56	0.096
9.41	0.094
10.59	0.091

It can be shown that if $\sigma(r)$ is assumed uniform

$$a = \frac{\int_0^R r^3 \sigma(r)\, dr}{\int r\sigma(r)\, dr} = \frac{R^2}{2}$$

if parabolic distribution is assumed then $a = \frac{R^2}{3} = 0.187 \text{ cm}^2$

Next, we turn our attention to eqn.(8.22) and obtain the values of n for different values of 'a' corresponding to the different values of the parameter (I/E) as entered in table (8.4) and the values of n thus obtained are entered in table (8.4) for corresponding values of (I/E).

Table 8.4

$\frac{I}{E}$ $\frac{\text{Amp.cm}}{\text{Volt}}$	n
3.36	2.293
6.563	3.859
9.408	3.984
10.59	4.181

To obtain the nature of the distribution function $\sigma(r)$ from eqn. (8.21) the value of σ_0 has been calculated for different (I/E) values from equation (8.19)

$$\int_0^R \sigma_0 \left[1 - \left(\frac{r}{R}\right)^2\right]^n r.\, dr = \frac{1}{2\pi E}$$

and after integration we get

$$\sigma_0 = \frac{I/E}{2\pi} \quad \frac{2(n+1)}{R^2}$$

The distribution function represented by eqn. (8.21) has been shown for different I/E values, Ghosal, Nandi and Sen (1978).

From the nature of the curves it is evident that not only the conductivity at the axis shows a rapid increase with the increase of the arc current but at the same time the nature of the distribution of the azimuthal conductivity undergoes a remarkable change which is evident from the nature of the curves indicating that the discharge becomes more and more constricted with the increase of the arc current. The variation of half width with I/E shows a rapid fall as the arc current is changed from 2.3 amp. to 3.1 amp. and then the change is slower and the curve shows a tendency to saturation towards higher currents.

It has been noted that in a mercury vapour tube the arc completely fills the tube for low currents but as the current is increased the arc column contracts and the light becomes more intense at the axis of the tube which is also corroborated by the present investigation.

The distribution curves obtained here closely resemble the curves obtained by Hoyank (1968) for a low pressure arc where the magnetic self constriction is predominent but the constriction observed in the present investigation cannot be due to magnetic self constriction as the order of the current is much smaller.

The increase of the constriction of the plasma column at higher currents is probably due to the fact that the increase energy input causes an increase in the gas temperature at the axis thereby lowering the gas density.Consequently the increased mean free path facilities the ionization probability causing a higher charge density at the axis. If however, the gas density becomes too low an opposing effect may occur. Due to reduction of gas density the total ionization collision of neutral particles with electrons will be lowered thereby decreasing the ionixation probability. The saturation observed in the present case may be partly due to this effect.

In the first portion of this article we have utilized Beckman's theoretical deduction regarding the increase of the axial electric field and also the decrease of radial electron density distribution in presence of magnetic field to explain the observed results regarding the increase of the axial electric field, decrease of arc current and the occurance of maxima in the power relation. The theoretical deduction of Beckman is strictly valid for a glow discharge where the radial distribution is given by a Bessel function. In the later part of the paper it has been established that the radial distribution in case of an arc plasma is not governed by Bessel function but a new distribution formula has been presented. To this extent the results of the first part are less accurate. However, the radial distribution function derived here reduces approximately to Bessel distribution function under very limited approximations.

(E) Measurement of plasma parameters in an arc plasma by a single probe method.

The object of investigation that will be reported in thisssection is the measurement of plasma parameters in an arc plasma. It is proposed to find whether the standard diagonistic tool, the Langmuir probe method can be used for the measurement of plasma parameters in an arc plasma. It is further known that the loss of charged particles in a plasma is due to ambipolar diffusion process. By measuring the diffusion voltage it has been shown by Sen, Ghosh and Ghosh (1983) that in a glow discharge, electron temperature and its variation with a transverse magnetic field can be studied. The process of diffusion is basically interrelated with the radial distribution function of charged particles and since a radial distribution function has been provided in the earlier section (Ghosal, Nandi and Sen, 1978) the experimental results can be analysed in the light of the above theories. Experimental details and results obtained have been described in detail in the paper by Sen, Gantait and Acharyya (1988). Analysing the experimental probe data electron temperature T_e and electron density n_e have been obtained for values of arc current varying from 2 to 4.5 amps. for three background air pressures of .075, .1 and .13 torr.

Langmuir has deduced that in case of an arc, the arc current I is given by

$$I = \frac{5.76 \times 10^{-10} n_e \lambda E}{\sqrt{T_e}} \tag{8.23}$$

where λ is the mean free path of the electron in the gas and E is the voltage drop per unit length. Hence for a particular pressure $\frac{I\sqrt{T_e}}{n_e E}$ should be a constant for different arc currents. The numerical value of this quantity has been computed from the experimental data Sen, Acharyya and Gantait (1988) and entered in table (8.5). It is evident that the value agrees with a fair degree of consistency justifying the validity of equation (8.23) proposed by Langmuir . From equation (8.23) it is possible to calculate λ taking the mean value of $\frac{I\ T_e^{1/2}}{n_e E}$ for different background air pressures. The values thus calculated have been entered in table (8. 6) column 3 and results show that P λ is almost a constant and L = P λ where L is the mean free path of the electron in the gas at a pressure of 1 torr can be obtained. This compares favourably with the classical expression of L, though the mean free path of the electron is a function of the energy of the electron (Townsend Ramsauer effect).

The variation of diffusion voltage with an arc current shows that the diffusion voltage becomes a minimum for a certain value of arc current at a particular pressure and this decreases with the increase of pressure. It has been shown by Ghosal, Nandi and Sen (1978) that

$$\sigma(r) = \sigma_0 \left[1 - \left(\frac{r}{R} \right)^2 \right]^n$$

$$\text{and} \quad n = \left[\frac{R^2}{a} - 2 \right] \tag{8.23(a)}$$

where a is an experimentally determined quantity which varies with arc current. Further it has been shown by Sen, Ghosh and Ghosh (1983) that V_R the diffusion voltage is given by

$$V_R = - \int \frac{d n_e}{n_e} \frac{K_1 T_e}{e}$$

as σ is proportional to n we can write

$$n_e = n_0 \left[1 - \left(\frac{r}{R} \right)^2 \right]^n$$

$$V_R = - \frac{n K T_e}{e} \int \frac{-(2r/R^2)}{(1 - r^2/R^2)} dr$$

$$= \frac{2 n K T_e}{e} \log \frac{R}{\sqrt{R^2 - r^2}}$$

The values of T_e can be obtained from the first part of the paper. The value of 'n' has beenexperimentally determined for different arc currents and the calculated values of V_R have been entered in table (8.8). Though the quantitative agreement is not very satisfactory yet it is observed that the minimum voltage occurs at the same value of current in both the cases. The value of the current at which the diffusion voltage becomes a minimum also decreases with the increase of pressure as is observed experimentally. We can thus x conclude that the distribution formula for azimuthal conductivity proposed by Ghosal, Nandi and Sen (1978) gives results in quantitative agreement with experimental results and further that Langmuir probe can also be used for measurement of electron density and electron temperature in an arc plasma as in case of glow discharge.

Table 8.5

Variation of electron temperature and electron density at different arc currents for different pressures.

Beckground air pressure in torr	Arc current in Amp.	Mercury vapour pressure in torr	Electron temp. in ^{o}K	Electron density x 10^{-12} cm^{-3}	Arc drop in volts	$\frac{I T_e^{1/2}}{n E} \times 10^{10}$	Average $\frac{I T_e^{1/2}}{n E} \times 10^{10}$
	2.0	.2343	11487.3	0.6967	42	0.5159	
	2.5	.2752	10131.0	0.7803	41	.5534	
0.075	3.0	.3032	9572.8	0.9812	39	.5406	.5352
	4.0	.3342	9041.6	1.2964	38	.5448	
	4.5	0.3658	8521.9	1.5608	36	.5213	
	2.0	.2348	8195.6	0.7856	44	.3694	
	2.5	.2752	7593.5	0.8580	43	.4159	
0.1	3.0	.3032	6066.9	1.0092	42	.389	.3875
	4.0	.3342	5839.4	1.3208	41	.398	
	4.5	.3658	5532.1	1.5766	39	.3653	
	2.0	.2343	7785.8	0.8473	47	.3124	
	2.5	.2752	7079.2	0.9335	46	.3453	
0.13	3.0	.3032	5696.9	1.0948	44	.3313	.3321
	4.0	.3342	4800	1.3704	42	.3395	

Table 8.6

Calculation of electronic mean free path at different pressure.

Beckground Pressure in torr	$\frac{I T_e}{nE}^{1/2} \times 10^{10}$	λ	$P\lambda = L$
0.075	0.5352	9.294×10^{-2}	6.971×10^{-3}
0.1	0.4875	6.728×10^{-2}	6.728×10^{-3}
0.13	0.3321	5.765×10^{-2}	7.494×10^{-3}

Table 8.7

Experimental values of arc current at which diffusion voltage is minimum for different pressures.

Pressure in torr	Arc current in amp. at which the diffusion voltage is minimum.
0.075	3.5
0.1	3.25
0.13	3.0

Table 8.8

Experimental and calculated values of diffusion voltage at different arc currents for three different pressures.

Pressure	Arc current in amps.	Diffusion voltage in volts	
		Experimental	Theoretical
	2.0	0.498	0.575
	2.5	0.470	0.527
0.075 torr	3.0	0.438	0.506
	3.5	0.412	0.495*
	4.0	0.518	0.539
	4.5	0.670	0.544
	5.0	0.78	0.589*
	2.0	0.458	0.410
	2.5	0.438	0.374
0.10 torr	3.0	0.435	0.348
	3.25	-	0.334
	3.5	0.447	0.336
	4.0	0.556	0.348
	4.5	0.700	0.353
	5.0	0.796	0.369*
	2.0	0.446	0.390
	2.5	0.425	0.348
	3.0	0.410	0.307
0.13 torr	3.5	0.450	0.297*
	4.0	0.570	0.304
	4.5	0.719	0.313*
	5.0	0.823	0.334*

* from extrapolated value.

F. Evaluation of electron temperature is transverse and axial magnetic field in an arc plasma.

In order to understand the physical processes occuring in an arc plasma due to interaction of an external magnetic field it is proposed to measure the variation of electron temperature in both the transverse and axial magnetic field in an arc plasma. The results are reported in the paper by Sen, Gantait, Acharyya and Bhattacharjee (1989). The experiment consists in measuring the diffusion voltage in the arc plasma for three arc currents (2.5 A, 3.0A and 3.5 A) in both transverse and axial magnetic field for magnetic field variation (zero to 1 KG). From the nature of the variation of diffusion voltage with transverse magnetic field it can be shown that the results are best reported by the expression

$$V_{RH} = V_R\left(1 + m' H^2\right) \tag{8.23(b)}$$

and the value of "m' ", has been calculated statistically to be m' = 3.6526 for 2.5 A, m' = 3.4302 for 3A and m' = 3.4106 for 3.5 A arc current. We have already deduced the following results

$$\sigma(r) = \sigma_0\left[1-\left(\frac{r}{R}\right)^2\right]^n$$

$$n = \left[\frac{R^2}{a'} - 2\right]$$

Ghosal, Nandi and Sen (1976)

$$V_R = -\int \frac{dn_e}{n_e} \frac{k\,T_e}{e}$$ Sen, Ghosh & Ghosh(1983)

$$n_{eH} = n_e \exp(-aH)$$ Sen & Gupta (1971)

From these equations it can be deduced that

$$\frac{T_{eH}}{T_e} = (1 + m' H^2) \Bigg/ \left(1 + \frac{aH}{2n \log \frac{R}{\sqrt{R^2 - r^2}}}\right)$$

From the calculated values of m', n_1, a, the values of T_{eH}/T_e can be calculated and if T_{eH}/T_e is plotted against H for three arc currents then each curve shows a minimum around (200 - 300) gauss of magnetic field.

In case of axial magnetic field it can similarly be shown that

$$\frac{T_{eH}}{T_e} = \frac{V_{RH}}{V_R} \frac{2n \log \frac{R}{\sqrt{R^2 - r^2}}}{\left(2n \log \frac{R}{\sqrt{R^2 - r^2}} + \alpha H\right)}$$

where α is expressed by the equation $\sigma_H = \sigma \exp(-\alpha H)$ (Sen and Gantait, 1988). Taking the values of α and n from the paper (Sen & Gantait, 1988) and experimental results for V_{RH} and V_R, $\frac{T_{eH}}{T_e}$.

can be calculated. A plot of $\frac{T_{eH}}{T_e}$ against H shows a maximum at approximately the same region as in the case of transverse magnetic field.

In a two fluid model of the plasma we may assume that two distinct temperatures T_e (for electron) and T_g (for gas) exist. From the energy balance equation it can be shown that (Hirsh and Oskam, 1978)

$$\frac{T_e - T_g}{T_e} = \frac{\pi m_g}{24 m_e} \frac{\lambda^2 E^2 e^2}{K^2 T_e^2} \tag{8.24}$$

In presence of magnetic field, (8.24) becomes

$$\frac{T_{eH} - T_g}{T_{eH}} = \frac{\pi m_g}{24 m_e} \frac{\lambda_H^2 E_H^2 e^2}{K^2 T_{eH}^2} \tag{8.25}$$

Further $\lambda_H = \dfrac{\lambda}{\left(1 + C_1 \frac{H^2}{P^2}\right)}$ [Blevin and Haydon (1958)]

& $E_H = E(1 + mH)$ (8.26)

[Sen & Gantait 1988] [Sen and Ghosh (1963)]

so that from eqns. (8.25) (8.26) & with an approximation $T_{eH} + T_e \approx 2T_e$

$$\frac{T_{eH}}{T_e} = 1 + \beta \left[\frac{m^2 H^2 + 2mH - C_1 H^2/P^2}{1 + C_1 H^2/P^2} \right] \tag{8.27}$$

where $$\beta = \frac{E \lambda^2 \bar{\lambda} m_g e^2}{T_e^2 \left[2 - \frac{T_g}{T_e}\right] 24 m_e K^2}$$

Differentiating T_{eH} / T_e with H and equalizing to zero we get

$$H = m / C_1 / P^2$$

In order to find whether the value of H corresponds to maximum or minimum we note that

$$\frac{d^2 T_{eH}}{dH^2} = 2\beta \left[m^2 - \frac{C_1}{P^2} + \frac{m^4 p^2}{c_1} + \frac{m^6 p^4}{C_1^2} + \cdots \right]$$

Putting $m = .295 \times 10^{-3}$ and $C_1 = .125 \times 10^{-6}$ (Sadhya and Sen, 1980) $d^2 T_{eH} / dH^2$ is a negative quantity and putting $m = 5.55 \times 10^{-3}$ & $C_1 = 2.8 \times 10^{-6}$, Sen and Das (1973) $d^2 T_{eH} / dH^2$ is +ve quantity.

Thus we find from the above analysis that in case of an axial magnetic field a maximum in the value of T_{eH} and in case of transverse magnetic field a minimum in the value of T_{eH} is expected. The experimental results thus support the theoretical deductions. Further the values of H_{max} or H_{min} have been calculated from the measured values of m, c_1 and P^2 and the results are entered in table (8. 9) and (8.10).

Table (8.9)

Axial Magnetic Field.

Arc current in Amps.	H_{max} K.G. theory.	H_{max} K.G. Expt.
3	.31	.3285
4	.2	.2818
5	.142	.201

Table (8.10)

Transverse magnetic field.

Arc current in Amps.	H_{max} KG Theory	H_{max} K.G. Expt.
2.5	.288	.2735
3	.201	.181
3.5	.188	.132

The slight small disagreement between the theoretical and experimental values for the magnetic field as shown in the above tables may be attributed to the uncertainty in the value of C_1 however agreement is observed at least in the right order of magnitude. Thus we can conclude that (a) the two fluid model of the plasma is ~~the~~ correct approach in evaluating the properties of arc plasma in the right direction, (b) measurement of diffusion voltage can be an alternative tool for measurement of electron temperature in an arc plasma as in the case of glow discharge and (c) the radial charge distribution formula as proposed by Ghosal, Nandi and Sen is valid in case of arc plasma.

(G) Measurement of electron atom collision frequency in an arc plasma by Radiofrequency coil probe in conjunction with a longitudinal magnetic field.

Sen et al (1989) has explored the tensorial behaviour of plasma conductivity in an arc plasma in presence of magnetic field and hence from the measured impedance parameters both in presence and in absence of magnetic field, the electron - atom collision frequency has been determined. The relevant theory has been developed taking theeffect of radial distribution of conductivity into account.

Theoretical Consideration:

If a plasma is embadded in a static magnetic field and it is assumed that the electric field is purely azimuthal then the azimuthal component of current density $J_\phi = \sigma_\phi E_\phi$ which is different from axial conductivity σ_z in presence of magnetic field

$$J_z = \sigma_z E_z$$

and

$$\sigma_\phi = \frac{\sigma_z}{1 + \omega_{eB}^2 / \nu_{ce}^2}$$

where ω_{eB} is the electron cyclotron frequency and ν_{ce} the collision frequency.

Working formulae:

The two expressions as given by Ghosal, Nandi and Sen (1978) are reproduced here:

$$\alpha - 1 = \frac{\omega^2 K^2 \ell}{2\pi R_0} \int_0^R r^2 \sigma(r)\, dr \tag{8.27}$$

and

$$\sigma(r) = \sigma_0 \left[1 - \left(\frac{r}{R}\right)^2 \right]^n \tag{8.28}$$

where α denotes the ratio of the radio frequency current without and with the plasma, R_0 radiofrequency resistance of the coil and K is the constant depending upon the number of the turn of the primary coil.

They introduced a term 'a' defined to be the constriction parameter and is given by

$$a = \frac{\int_0^R r^3 \sigma(r)\, dr}{\int_0^R r\, \sigma(r)\, dr} = \frac{E}{I}(\alpha - 1)\frac{R_0}{f^2 K^2 \ell}$$

$$= \frac{\int_0^R r^3 f(r)\, dr}{\int_0^R r\, f(r)\, dr} \tag{8.29}$$

where I denotes the arc current, E the axial voltage drop per unit length, l the length of the coil and f measures the frequency of the r.f. field.

But in presence of magnetic field in the Z-direction the identity (Eqn. 8.29) is not valid. This is evident because,

$$\frac{\int_0^R r^3 \sigma_\phi(r)\, dr}{\int_0^R r\, \sigma_z(r)\, dr} = \frac{\int_0^R r^3 \sigma_{0\phi} f_B(r)\, dr}{\int_0^R r\, \sigma_{0z} f_B(r)\, dr} = \frac{\sigma_{0\phi} \int_0^R r^3 f_B(r)\, dr}{\sigma_{0z} \int_0^R r\, f_B(r)\, dr} \qquad (8.30)$$

where $\sigma_{0\phi}$ and σ_{0z} are the on-axis azimuthal and axial conductivities respectively, $f_B(r)$ represents the relevant distribution function in presence of magnetic field

It we write
$$\frac{\int_0^R r^3 f_B(r)\, dr}{\int_0^R r\, f_B(r)\, dr} = a_B \qquad (8.31)$$

a_B may still be said to be the constriction parameters in presence of magnetic field since a_B is only dependent on the form of the conductivity distribution function $f_B(r)$. Thus in analogy with equation (8.28) we get

$$\frac{\sigma_{0\phi}}{\sigma_{0z}} a_B = \frac{E_B}{I_B} (\alpha_B - 1) \frac{R_0}{f^2 K^2 \ell} \tag{8.32}$$

where the suffix B indicates the corresponding quantities in presence of magnetic field.

Writing

$$\frac{E_B}{I_B} (\alpha_B - 1) = a_B' \tag{8.33}$$

and

$$\frac{E}{I} (\alpha - 1) = a' \tag{8.34}$$

we get from eqn. (8.32) and (8.33)

$$\frac{\sigma_{0\phi}}{\sigma_{0z}} a_B = a_B' \frac{R_0}{f^2 K^2 \ell}. \tag{8.35}$$

and from eqn. (8.29) and (8.33)

$$a = a' \frac{R_0}{f^2 K^2 \ell}. \tag{8.36}$$

So from eqns. (8.35) and (8.36)

$$\frac{\sigma_{0\phi}}{\sigma_{0z}} \cdot \frac{a_B}{a} = \frac{a_B'}{a'} \tag{8.37}$$

If it is now assumed that for small magnetic fields which will be used here the confining effect is negligible that is the radial distribution function remains the same in presence and in absence of magnetic field i.e. $a_B = a$

we get

$$\frac{\sigma_{0\phi}}{\sigma_{0z}} = \frac{a_B'}{a'} \qquad (8.38)$$

The quantities a_B' and a' may be experimentally determined and their ratio if found different from unity will indicate the tensorial behaviour of conductivity in the magnetic field.

We get from equation,

$$\sigma_\phi = \frac{\sigma_z}{\left(1+\frac{\omega_{eB}}{\nu_{ce}}\right)^2}$$

$$\nu_{ce} = \frac{\omega_{eB}}{\left[\frac{a'}{a_B'}-1\right]^{1/2}} = \frac{1.76\times10^7 B}{\left[\frac{a'}{a_B'}-1\right]^{1/2}} \qquad (8.39)$$

where B is expressed in gauss.

The experimental arrangement has been given in detail in the paper (Ghosal, et al, 1976). A mercury arc has been utilised, the arc tube of which is cylindrical (length 10.8 cm and dia. 1.83 cm) and is energised by a stabilised d.c. source with a rheostat to control the current which is measured by an ammeter. The mercury arc is placed between the pole pieces of an electromagnet energized by a stabilised d.c. source. The lines of force are parallel to the direction of the flow of arc current (frequency = 3.69 Mc/Sec.) The tuned r.f. current was measured with a radiofrequency milliammeter and a magnetic field was then superimposed. The probe to probe voltage with and without magnetic field was measured by a high impedance voltmeter at different magnetic fields (100G, 150G, 230 G, 280G, 345 G). Each set of observation was taken at three different pressures namely .052 torr, .075 torr, and 0.17 torr. The values of (α - 1) where $\alpha = i_0/i$ thus obtained have been plotted against arc current for three different pressures. The probe to probe voltage for three different arc currents for three different pressures have been measured and the values of E and $a = \frac{E}{I}(\alpha-1)$ for zero magnetic field have been entered in table (8. 10). The corresponding quantities, E_B and α_B in presence of different magnetic fields (100G, 150G, 230G, 280G and 345 G in case of arc current 2A and 100G, 150G, 230G, 280G, 345 G and 430G in case of arc currents 2.5A and 3A) have been measured and detailed entreis have been made in table (8.10) in columns 2, 3, 7, 8, 12 and 13, for three different pressures. The corresponding values of $a_B' = \frac{E_B}{I_B}(\alpha_B - 1)$ have been entered in table (8. 10) colums 4, 9 and 14. The values of $\sqrt{\frac{a'}{a_B'} - 1}$ have been entered in the table (column 5, 10, and 15). The values of [$(\alpha_B - 1)$] have been plotted against the corresponding values of magnetic field for the three arc currents. The values of $\sqrt{\frac{a'}{a_B'} - 1}$ have been entered in columns 5, 10 and 15. The values of $\sqrt{\frac{a'}{a_B'} - 1}$ have been plotted against the corresponding values of magnetic field for three arc currents for pressure .052 torr, .075 torr and 0.17 torr. [Ref Ghosal, et al. 1976] As may be observed they are found to be straight lines passing through the origin. The proportionality between $\sqrt{\frac{a'}{a_B'} - 1}$ and B confirms the theoretical assumption made earlier. Thus assuming the validity of the equation

$$\nu_{ce} = \frac{1.76 \times 10^7 B}{\sqrt{\frac{a'}{a_B'} - 1}}$$

the values of momentum transfer electron atom collision frequency for three different discharge currents and three different pressures have been obtained and the results are entered in table (8. 10) columns, 5,6, and 16.

The results for momentum transfer electron atom collision frequencies are consistent with those obtained by microwave transmission method in this laboratory and also with literature values. From the results obtained it is evident that collision frequency increases with the increase of pressure for each value of current which is quite natural. The increase of collision frequency with the increase of arc current as may be observed from the table is evident since as the current increases the mercury gets more and more heated and the vapour pressure increases and consequently increase the collision frequency. It is to be noted however, that the current is not the only factor which determines the vapour pressure of mercury. Actual mercury temperature is dependent on many factors viz the voltage across the arc, voltage across the positive column ambient temperature and over and above the colling arrangements. For this reason we have not tried to correlate momentum transfer collision frequency ν_{ce} with arc current.

It is to be noted further that though the axial magnetic field has been increased upto 345 gauss the value of momentum transfer collision frequency is the same for values of different magnetic fields investigated for a particular arc current. This is as it should be.

as ... indicated in the theory put forward because here the magnetic field has been used as a probe. If higher magnetic fields are used the simple theory postulated will breakdown. Further the analysis of the results shows that the assumption that the radial conductivity distribution is not much changed specially for small values of magnetic field used here from the distribution without field is justified.
It can be concluded that though the procedure of measurement is rather elaborate it enables us to measure not only the electron atom collision frequency for momentum transfer accurately but its variation with arc current and mercury vapour pressure can also be investigated.

Table 8.10

Magnetic field in Gauss	P = 0.052 Torr					P = 0.075 Torr					P = 0.17 Torr				
	E_B Volts/cm	$(\alpha'_B - 1)$	a'_B	$\sqrt{\frac{a'}{a'_B} - 1}$	ν_{ce}	E_B Volts/cm	$(\alpha'_B - 1)$	a'_B	$\sqrt{\frac{a'}{a'_B} - 1}$	ν_{ce}	E_B Volts/cm	$(\alpha'_B - 1)$	a'_B	$\sqrt{\frac{a'}{a'_B} - 1}$	ν_{ce}
Arc current 2 amp.															
0	0.587	0.5385	0.1580			0.6097	0.3857	0.1174			0.620	0.350	0.1080		
100	0.565	0.500	0.1413	0.340		0.587	0.3466	0.1076	0.265		0.609	0.335	0.1020	0.235	
150	0.554	0.470	0.1303	0.445	5.969 x 10^9	0.576	0.340	0.0979	0.395	6.714 x 10^9	0.598	0.320	0.957	0.350	7.612 x10^9
230	0.511	0.425	0.1086	0.675		0.533	0.325	0.0865	0.600		0.565	0.300	0.0848	0.530	
280	0.489	0.385	0.0941	0.820		0.511	0.300	0.0766	0.730		0.544	0.285	0.0775	0.640	
345	0.457	0.345	0.0788	1.010		0.489	0.280	0.0685	0.905		0.522	0.260	0.0679	0.790	
Arc current 2.5 amp.															
0	0.5174	0.655	0.1356			0.522	0.5076	0.1060			0.543	0.400	0.087		
100	0.500	0.623	0.1246	0.2450		0.517	0.4848	0.1003	0.220		0.533	0.390	0.083	0.195	
150	0.489	0.5968	0.1168	0.3650	7.22 x 10^9	0.500	0.4706	0.0941	0.330	8.042 x 10^9	0.522	0.380	0.0793	0.285	9.36 x10^9
230	0.457	0.5429	0.0991	0.5600		0.467	0.4478	0.0837	0.505		0.496	0.370	0.0733	0.430	
280	0.435	0.5286	0.0919	0.6850		0.457	0.4242	0.0775	0.610		0.478	0.360	0.0689	0.520	
345	0.4015	0.5015	0.0807	0.8400		0.435	0.3944	0.0686	0.755		0.457	0.345	0.0630	0.640	
400	0.391	0.4692	0.0734	0.9700		0.413	0.3714	0.0614	0.870		0.435	0.333	0.6270	0.740	
Arc current 3 amp.															
0	0.348	0.7925	0.0919			0.446	0.590	0.0877			0.500	0.600	0.0833		
100	0.337	0.7857	0.0882	0.1950		0.439	0.5806	0.850	0.165		0.496	0.490	0.0810	0.150	
150	0.330	0.7650	0.0843	0.2850	9.308 x 10^9	0.430	0.5737	0.0823	0.240	10.98 x 10^9	0.489	0.480	0.0783	0.225	11.79 x10^9
230	0.304	0.7544	0.0765	0.435		0.413	0.5555	0.0765	0.350		0.478	0.468	0.0747	0.345	
280	0.293	0.7250	0.0709	0.525		0.402	0.5385	0.0722	0.450		0.467	0.460	0.0717	0.410	
345	0.283	0.6949	0.0655	0.645		0.380	0.5230	0.0682	0.560		0.457	0.440	0.0670	0.510	
400	0.272	0.6750	0.0612	0.745		0.380	0.5077	0.0644	0.640		0.435	0.438	0.0635	0.590	

H. Hall effect in an arc plasma.

The Hall effect is a standard diagonistic method for determining the charged particle density and mobility in semi conductors and it has also been utilised for measurement of plasma parameters in a glow discharge. The voltage current characteristics have been investigated in a mercury arc carrying current from 1.3 to 2.0 A in presence of a transverse magnetic field upto 3000 gauss by Sen and Das (1973). The Hall effect in a toroidal discharge plasma has been investigated by Zhilinsky et al (1979) and Goldferb (1973) has presented some diagonistic techniques for the arc plasma. In contrast to semiconductors or metals it is to be noted that when an arc of 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 Sen and Ghosh (1985) 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

$$E_y = \frac{iH}{ne} \qquad (8.39)$$

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

$$\frac{i_H}{i} = \frac{\exp(-aH)}{\left[1 + r\log\left\{\frac{1}{(1 + C_1 H^2/P^2)^{1/2}}\right\}\right]^{1/2}} \qquad (8.40)$$

where $a = eEC_1^{1/2} r/2KT_eP$ where E is the axial electric field, 'r' is the distance at which the electron density is n_H, T_e is the electron temperature, P is the pressure, $C_1 = \left(\frac{e}{m}\frac{L}{v_r}\right)^2$ where L is the mean free path of the electron at a pressure of 1 torr, v_r is the random velocity of the electron and $r = \frac{2T_e}{T_e + 2eV_iK}$ where V_i is the ionization potential of the gas and it has been shown by Sen and Gupta (1971)

$$n_H = n_0 \exp(-aH) \qquad (8.41)$$

Hence we get from equation (8.39) & (8.41)

$$E_y = \frac{iH}{n_0 e\left[1 + r \log\left\{\frac{1}{1+C_1 H^2/p^2)^{1/2}}\right\}\right]^{1/2}} \quad (8.42)$$

Hence by measuring the Hall voltage for a range of values of the magnetic field the electron density in an~~x~~ arc plasma can be obtained and from the relation

$$i = n_0 e v_d \quad (8.43)$$

the drift velocity can be obtained.

Hall voltage measurements have been carried out in a mercury arc plasma and the arc current has been varied from 2 to 3 amps. the background air pressure has been maintained at 2 torr. The magnetic field supplied by an electromagnet has been varied from 64 to 526 gauss. The Hall voltage developed has been measured by a V.T.V.M. Results are reported here for an arc current of 3 amps.

Values of n the electron density have been calculated from eqn. (8.43) which assumes that the current and radial electron density are the same as in the absence of magnetic field. The results show that electron density decreases with the increase of the magnetic field which however, should be a constant for all values of

Table(8.11)

Mag.field in Gauss	Hall voltage volts/cm	Value of η from $E_y = \frac{i_H}{ne}$ x 10^{-12}	Value of η from eqn. (8.43) x 10^{-12}
64	.34	3.599	3.631
112	.71	3.533	3.620
166	1.15	3.501	3.656
216	1.76	3.483	3.662
256	2.17	3.423	3.652
306	2.62	3.356	3.678
356	3.07	3.253	3.617
406	3.57	3.180	3.624
456	3.92	3.165	3.606
476	4.40	3.108	3.569
526	4.62	3.068	3.563

magnetic field as the magnetic field used for observing the Hall effect is used here as a probe only. Hence we have calculated the values of n from the modified equation, which takes into account the charge of radial electron density and also the arc current with magnetic field. The values of the constants have been taken from the earlier results mentioned in this chapter previously. The results are entered in the last column in table (8.11) The results show that the electron density in absence of magnetic field is found to be almost a constant for values of magnetic field varying from 64 gauss to 525 gauss. The average value is found to be 3.638×10^{12}. From this value of electron density and utilizing the relation $i = n_e e v_d$ $v_d = .94 \times 10^8$ cm/sec which is in agreement with this result reported by Brown (1959).

It is thus concluded that Hall effect can be utilized as a useful diagonistic tool provided the variation of radial electron density and that of arc current are taken into consideration in a tranverse magnetic field.

(I) Voltage current characteristics of low current arcs in air with metal electrodes.

This section deals with voltage current characteristics of metal arcs in atmospheric pressure and the object is to calculate some parameters of the plasma after a systematic analysis of the experimental results.

The results are reported here for silver-silver, copper-copper, iron-iron, and silver-copper electrodes for arc currents 2, 3, 3.5, 4.5 and 5 A. It has been observed that for small electrode separation the curve rises rapidly and then there is linear increase of arc voltage with electrode separation. The total voltage V_A can be represented as

$$V_A = V_C + V_P + V_a$$

V_C = cathode fall

V_P = fall of voltage at the positive column

V_c = annode fall.

The linear portion of the curve has been extrapolated to $x = 0$ and the intercept along the Y axis gives the sum of cathode and anode fall. The non-linear part of the curve extrapolated to $x = 0$ gives the value of cathode fall. The results are entered in table (8.12).

Table (8.12)

Electrode	V_c volts	V_a volts
Ag-Ag	9 - 9.5	9.5 - 10
Cu-Cu	10.0 - 10.5	17.5 - 18
Fe-Fe	9 - 11	10.0 - 10.5
Ag-Cu	12 - 12.5	11 - 11.5

The results are consistent with those reported by von Engel (1965).

Calculation of contact potential difference at the electrode.

As the arc voltage and arc currents for different electrode separations have been measured it is possible to calculate the power developed across the arc. The variation of power developed arcross the arc with separation of electrodes has been plotted for Ag-Ag. The extrapolation of the curve to x = 0 will give the value of the power loss at the electrodes when they are in contact. From these results it is possible to calculate R_r the external series resistance as well as V the contact potential difference at the electrodes.

Table 8.13

Arc current A	P_1 w	P_o w	$P_R=(P_o-P_1)$ w	R_r Ω	$V_{constant}$ V
			Ag-Ag		
5	50	500	450	18	10
4	42	400	358	22.37	10.2
3	34	300	266	29.55	11.3
2	21	200	279	44.75	10.5
			Cu-Cu		
5	63	500	437	17.48	12.6
4.5	58	450	392	19.36	12.8
4	48	400	352	22.00	12.2
3	38	300	262	29.8	12.66
2	24	200	176	44	12.00
			Fe-Fe		
5	52	500	448	17.93	10.4
4.5	47	450	403	19.90	10.44
4	42	400	358	22.38	10.5
3	30	300	270	30.09	10.0
2	20	320	180	45	10.5
			Ag-Cu		
5	45	500	455	18.2	9
4	34	400	364	22.68	9.5
3	28	300	272	30.22	9.3
2	18	200	182	45.5	9.0

P_1 is the power loss when the electrodes are in contact

P_o Power drawn from the source .

P_R Power loss at the external resistance

R_r Calculated value of external resistance

V_{con} Contact potential difference

It is thus apparent that for different values of arc current the contact potential difference is almost a constant though it varies with the nature of the electrodes which is to be expected.

From the nature of variation of P_A (power generated at the arc) with electrode separation (refer Sen, Gantait and Jana), it is evident the curves show a tendency of saturation at a certain electrode separation depending upon the nature of electrode and the arc current.

We have $P_A = V_A \cdot I_A = V_A^2 / R_a$.

$$V_A = V_S - I_A R_r = V_S / (1 + R_r / R_a)$$

where V_S is the source voltage and R_a is the arc resistance.

$$P_A = \frac{V_S^2}{\left(1 + \frac{R_r}{R_a}\right)^2 R_a} = \frac{V_S^2 \, P \frac{x}{S}}{\left(P \frac{x}{S} + R_r\right)^2}$$

where P is the specific resistance, x is the electrode separation and S is the area of cross section

$$x_{max} = R_r \, S \, \sigma$$

where σ is the conductivity of the arc plasma and x_{max} is the electrode gap at which the power consumed at the arc shows a tendency of saturation. The value of 'S' is obtained by measuring with a travelling microscope as well as by taking photographs the value (of R_a / x)

of R_a/x has been calculated from the linear portion of the curve and σ has been calculated. The calculated values of x_{max} are entered in table (8.14)

TABLE - 8.14

Ag - Ag		Cu - Cu	
Current A	X_{max}	Current	X_{max}
2	.1592	2	.1201
3	.2359	3	.1694
4	.3437	4	.2162
5	.4879	5	.2708

By studying and analysing the results of variation of arc voltage with arc current for different electrode systems an empirical relation has been established which can be represented by

$$V_A = C_g \, l_a^{\,m}$$

where C_g is a function of the electrode gap, for Ag-Ag, value of m = 0.343 for Cu-Cu, m = - 0.3780 for, Fe-Fe, m =-.3536. The value of m is nearly a constant and independent of gap separation. The equation is of the same form as proposed by Nottingham (1936). Thus from the analysis of the results it is possible to calculate the cathode and anode fall and the contact potential the contact potential arises probably due to passage of the current there is erosion of the electrodes and micro irregularities occur due to improper machining and unequal matching of the electrode surfaces. This causes a finite gap and a voltage developes even when the electrodes are in contact.

(J) Spectroscopic Investigation of Plasma:-

(I) Mercucy arc plasma in axial magnetic field -

Introduction

In a previous investigation (Sen and Das, 1973), it has been established that in case of a mercury arc plasma (current 1 amp. to 2.5 amps.) electron temperature increases in a transverse magnetic field and the results are in quantitative agreement with Beckman's theory (1948, modified by Sen and Gupta, 1971). In the present investigation variation of current and voltage across a mercury arc plasma as well as the electron temperature is proposed to be studied in a longitudinal magnetic field. Most of the results reported in case of mercury arc plasma are with argon as background gas; in the present investigation air is the background gas which will enable us to study how the excitation, ionization and de-ionization processes are influenced by the presence of air. In case of molecular gases the ionization is mainly due to electron impact of the ground state atom whereas in case of mercury arc, ionization will be mainly through inelastic electron impact with excited states like 6^3P_2 and with ground states, and the phenomena of associative ionization may also be present. Hence the physical processes occuring in a mercury arc plasma and how these processes are influenced by the magnetic field have to be taken into consideration in deducing the electron temperature and its variation in magnetic field.

(2) Experimental Measurements and Results.

Experiments were performed on a d.c. Hg. arc at low pressure burning in air. The experimental results as obtained by Sadhya and Sen (1980) are reproduced in table (8.15). From a detailed mathematical analysis it has been shown by Sadhya and Sen (1980) that

$$\frac{i}{i_B} = \frac{D_e}{D_{eB}} \left(\frac{T_{eB}}{T_e} \right)^{1/2}$$

as $$D_{eB} = \frac{D_e}{1 + C_1 B^2/p^2}$$

$$1 + C_1 \frac{B^2}{p^2} = \frac{i}{i_B} \left(\frac{T_e}{T_{eB}} \right)^{1/2}$$

A plot of $\frac{i}{i_B} \left(\frac{T_e}{T_{eB}} \right)^{1/2}$ against B^2/p^2 will be a straight line and the gradient determines the value of C_1.

Table 8.15

i = 2.5 amp., P_{Hg} = 0.3731 torr   Pair = .08 torr

Magnetic field in gauss	$\frac{(I_{5790})_B}{I_{5790}} = A$	$\frac{(I_{5770})_B}{I_{5770}} = B$	$\ln \frac{A}{B}$	Te in ev.
0	1	1	0	0.412
255	1.02586	1.01852	7.1806×10^{-3}	0.313
550	1.08621	1.07407	1.1239×10^{-2}	0.282
833	1.14655	1.12963	1.48867×10^{-2}	0.256
1050	1.17241	1.15278	1.6887×10^{-2}	0.243

Table 8.16

i = 2.25 amp P_{Hg} = 0.3022 torr P_{air} = .08 torr

Magnetic field in gauss	$\frac{(I_{5790})_B}{(I_{5790})} = A$	$\frac{(I_{5770})_B}{(I_{5770})} = B$	$\ln \frac{A}{B}$	Te in ev.
0	1	1	0	.412
255	1.02913	1.02	8.9072×10^{-3}	0.301
550	1.07282	1.06	1.2017×10^{-2}	0.276
835	1.13592	1.12	1.4116×10^{-2}	0.261
1050	1.19417	1.175	1.6187×10^{-2}	0.247

CONCLUSION

Considering the physical processes involved in a mercury arc discharge where the buffer gas is air and the pressure is low Sadhya and Sen (1980) evolved a model in which air plays the role of quenching gas and have found that in this type of discharge both atomic and molecular ions of mercury are present. Assuming the existence of both types of ions they have obtained the distribution function and deduced an expression for T_e/T_{eB} and have found that within the range of (B/P) values used here the experimental results are in quantitative agreement with the theoretical deduction. That the electron temperature decreases in presence of axial magnetic field in case of mercury discharge has also been shown by Franklin (1976), $C_1 = \left(\frac{e}{m}\frac{L}{v_r}\right)^2$ is evidently the square of the mobility of the electron in mercury air mixture at 1 torr. The value of mobility calculated from C_1 agrees in order of magnitude with that obtained experimentally by Nakamuru and Lucas (1978). Further the results show that frequency of ionization changes with the magnetic field as has been previously noted by Bickerton and von Engel (1956). It is also noted that $\frac{n_{eoB}}{n_{eo}} = \left[\frac{T_e}{T_{eB}}\right]^{1/2}$ and as experimentally we have found that T_e is $>$ T_{eB}, n_{eoB} will be $> n_{eo}$ which was previously found to be true in case of molecular gases, as determined by the probe method Sadhya, Jana and Sen (1979) and also by Cummings and Tonks (1941), in case of mercury arc plasma.

Table (8.16)

Magnetic field in Gauss	$\frac{B^2}{P^2} \times 10^{-6}$		$\sqrt{\frac{T_e}{T_B}}$ (expt)		$\frac{i}{i_B}$ (expt)		$\sqrt{\frac{T_e}{T_{eB}}}\ \frac{i}{i_B}$		C_1 from Fig. Ref [Sadhya & Sen (198	
	X	Y	X	Y	X	Y	X	Y	X	Y
0	0	0	1	1	1	1	1	1		
250	.44	.3	1.169	1.138	1.002	1.0014	1.17	1.14		
550	2.0	1.47	1.2218	1.2087	1.006	1.005	1.23	1.21	$.3\times10^{-7}$	$.39\times10^{-}$
835	4.7	3.4	1.2564	1.2686	1.0117	1.011	1.27	1.28		
1050	7.5	5.3	1.2915	1.302	1.0156	1.017	1.32	1.33		

X Corresponds to i = 2.25 amp. P_{air} = .08 torr. P_{Hg} = .3032 torr

Y Corresponds to i = 2.5 amp. P_{air} = .08 torr. P_{Hg} = .3731 torr.

(II) Dependence of the intensity of mercury triplet lines on discharge current and magnetic field in an arc plasma.

It has been shown by Sen and Sadhya (1986) that in case of triplet series of mercury $\lambda = 5461$ Å, $\lambda = 4358$ Å and $\lambda = 4047$ Å when subjected to an axial magnetic field from zero to 2000 gauss there is variation of intensity and the occurance of maxima in these lines. These variations were explained by considering the reabsorption of the spectral lines and a mathematical theory was formulated which could satisfactorily explain the observed results. The experimental investigation was continued by Sen and Gantait (1988) in case of the same triplet series of mercury in an arc where the spectral intensity variation was studied for variation of arc current from 2 A to 5 A and a transverse magnetic field varying from zero to 1.6 KG. The results for the variation of spectral intensity with arc current for three spectral lines $\lambda = 5461$ Å, $\lambda = 4358$ Å and $\lambda = 4047$ Å have been plotted. [in Sen & Gantait (1988)]. It is observed that the rate of increase of intensity $\frac{dI}{di}$ is different for the three wave lengths. For $\lambda = 4047$ Å, $\frac{dI}{di} = 0.2$ for $\lambda = 4358$ Å, $\frac{dI}{di} = 0.245$ and for $\lambda = 5461$ Å $\frac{dI}{di} = 0.31$.

The variation of the intensity of the spectral lines under a transverse magnetic field for three arc currents has been plotted Sen and Gantait (1988). There is always an increase in intensity as previously noted by Sen et al (1972), but in the investigation now under consideration, Sen and Gantait (1988) it is noted that below a certain value of the magnetic field a minimum i in the intensity is observed and the magnetic field at which this minimum occurs differs though by a small amount in case of all the three spectral lines investigated.

In order to take into account the effect of self absorption, we note as suggested by Sen and Sadhya (1986)

$$I_{ul} = (1 - A_s)\, I^0_{ul}$$

where A_S is the self absorption of the spectral line and I^0_{ul} is the intensity without self absorption

$$I^0_{ul} = n \frac{g_u}{Z_0} A_{ul}\, h \nu_{ul} \exp\left[-\frac{(E_u - E_l)}{K T_e}\right]$$

and $$A_s = f_{lu}\, \lambda_{ul}\, P\, n_1(0)$$

where f_{lu} is the absorption oscillator strength

and $$P = \frac{1}{3} \pi r_0 c \left[\frac{M}{2\pi K T_g}\right]^{1/2} R.$$

then $$\frac{I_{ul}}{I_{2.5}} = \left\{ 1 - f_{lu}\, \lambda_{ul} \frac{1}{3} \pi r_0 c \frac{M}{(2\pi K T_g)^{1/2}} \right\} \bar{C}$$

as $(1 - A_S)_{2.5}$ can be regarded as a constant and represented by $1/\bar{C}$

then
$$\frac{d}{di}\left(\frac{I_{ue}}{I_{2.5}}\right) = \frac{d}{di}\left(\bar{C} - \bar{C}\,\alpha\, T_g^{-1/2}\right)$$

where
$$\alpha = f_{en}\,\lambda_{ue}\,\frac{1}{3}\,\pi\, r_0\, c\,\frac{M}{(2\pi K)^{1/2}}$$

or
$$\frac{d}{di}\left(\frac{I_{ue}}{I_{2.5}}\right) = \frac{\bar{C}\,\alpha}{T_g^{3/2}}\,\frac{d\,T_g}{di}$$

Hence
$$\frac{d}{di}\left(\frac{I_{ue}}{I_{2.5}}\right)_{4047A^0} : \frac{d}{di}\left(\frac{I_{ue}}{I_{2.5}}\right)_{4358A^0} : \frac{d}{di}\left(\frac{I_{ue}}{I_{2.5}}\right)_{5461}$$
$$= \left(f_{en}\,\lambda_{ue}\right)_{4047A^0} : \left(f_{en}\,\lambda_{ue}\right)_{4358A^0} : \left(f_{en}\,\lambda_{ue}\right)_{5461A^0}$$

The values of f_{en} are provided by Gruzdev (1967)

$$\left(f_{en}\right)_{4047} = 0{\cdot}10, \quad \left(f_{en}\right)_{4358} = 0{\cdot}114, \quad \left(f_{en}\right)_{5461} = 0{\cdot}14.$$

Hence
$$\left(f_{en}\,\lambda_{ue}\right)_{4047} : \left(f_{en}\,\lambda_{ue}\right)_{4358} : \left(f_{en}\,\lambda_{ue}\right)_{5461}$$
$$= 0{\cdot}2 : 0{\cdot}24 : 0{\cdot}38$$

Whereas from our experimental data the ratio is 0.2: .245: 0.31.

In case of magnetic field we have

$$\frac{(I_{ue})_H}{I_{ue}} = 1 - f_{en}\,\lambda_{ue}\,P\left\{\frac{n_1(0)H - n_1(0)}{\frac{n_u(0)H}{n_u(0)}}\right\}$$

when a transverse magnetic field is present it has been deduced by Sen and Das (1973) that if n_H and n_0 are the electron densities in presence and in absence of magnetic field

$$n_H = n_0 \exp(-aH)$$

where $a = \dfrac{eE\,C_1^{1/2}\,r_0}{2KT_e\,P}$

where the symbols have their usual significance,

then $n_1(0)_H = n_1(0)\exp(-aH)$

$$n_u(0)_H = n_u(0)\exp(-aH)$$

then

$$\frac{(I_{ue})_H}{I_{ue}} = 1 - f_{en}\,\lambda_{ue}\,P n_1(0)\left\{\frac{\exp(-aH) - 1}{\exp(-aH)}\right\}$$

$$= 1 - \alpha\exp(-2aH) + \alpha\exp(-aH)$$

$$\frac{d}{dH}\frac{(I_{ue})_H}{I_{ue}} = 2\alpha a\exp(-2aH) - \alpha\exp(-aH)$$

or $H_{min} = \dfrac{\log_e 2}{a}$

The numerically calculated value of H_{min} comes out to be 201.4 gauss which is in close agreement with experimental values. This shows that self absorption plays a dominent role with regard to variation of arc current and superposition of a magnetic field also. From the expression for $(I_{ul})_H / I_{ul}$ it is evident that $(I_{ul})_H / I_{ul}$. is a function of $n_1(0)$ the electron density and will increase with smaller values of $n_1(0)$, that is for low current which is also corroborated by experimental results.

(III) Persistence of afterglow maintained by a radiofrequency field in a mercury arc.

A new phenomena has been observed in a mercury arc plasma when it was noted that by applying a radio-frequency field to a mercury arc the persistence time of afterglow increased manifold after the main arc current is switchedoff. In two research publications Sen et al (1986, 1987) the results have been discussed in detail. The afterglow being considered here is different from that considered hitherto in the sense that whereas in a normal afterglow the decaying time is of the order of few microseconds or less in our experiments the glow was allowed to continue for a few tens of seconds by applying a radio frequency field which provided additional ionization and allowed the plasma to decay at a much slower rate. The experimental results have been described in detail in the above mentioned papers, Sen et al (1986, 1987).

The variation of persistence time with arc current (2 A to 4.5 A) and the variation of persistence time with arc duration time for arc currents 3, 3.5 and 4 A are shown in the papers Sen et al (1986, 1987). The variation of persistence time with the variation of input radio-frequency voltage (150 volts to 350 volts) and the variation of persistence time with magnetic field (0 to 1.5 KG) have also been plotted.

The main conclusions which can be drawn from these results are as follows:

a) The persistence time increases with the arc current.

b) The persistence time increases with the excitation time of the arc, and also increases for all values of excitation time for increasing arc current.

c) The persistence time increases linearly with the increase of the radiofrequency voltage input.

d) The persistence time increases with the increase of the external magnetic field showing saturation for high values of magnetic field.

e) It has further been noted that when there is no arc discharge the rectified output voltage of the oscillator is 260 volts, as the arc is switched on it drops to 13 volts and when the arc is switched off it immediately rises to 100 volts and gradually rises with time until the original voltage is restored when the glow vanishes.

The reason for the persistence of glow after extinction of the main current may be due to the fact that the flow of arc current has built up a sufficiently high electron density. Since in the absence of the a applied r.f. field the glow - instanteneously vanishes when the arc current is cutoff we find the presence of r.f. field enhances the persistence time of the after glow and this is ascribed to fresh ionization produced by the r.f. field and the loss of electrons may be due to diffusion recombination and attachment. The rate of ionization will be given by ν_n' where ν' is the frequency of ionization by the radio frequency field and is the electron density at the instant of extinction of the arc. If δ denotes the confined loss processes combined then we get

$$\frac{\partial n}{\partial t} = (\nu_n - \delta)$$

As the rate of ionization process will increase with i.e. with arc current the time of persistence will naturally increase with arc current. Further the effect of increase of arc current will gradually heat the glow plasma and since according to Kihara (1952)

$$\nu = N \frac{3\sigma}{C_i} \frac{K T_e}{m} \exp\left[- \frac{m v_i^2}{2 K T_e}\right]$$

where σ, C_i are molecular constants introduced by Kihara, N is the number of molecules at 1 torr and T_e is the electron temperature and as shown by Persson (1961)

$$T_e = T_g + \frac{M}{3K}\left(\frac{eE}{m \nu_m}\right)^2$$

which indicates that T_e increases with T_g and Kihara's expression shows that ν increases which increases the persistence time. To explain the increase of persistence time with the applied voltage of the r.f. field we note that

$$\nu = \frac{3 e E \sigma}{C_i (3 \lambda P)^{1/2}} \exp\left[- \frac{m c_1^2 N (3 \lambda P)^{1/2}}{2 e E} \right]$$

which indicates that ν will increase with the increase of E and consequently the persistence time.

It is further observed that persistence time increases with the increase of the magnetic field. Further it is observed that the intensity of afterglow increases with the increase of the magnetic field which is inconformity with our previous observation (Sen, Das & Gupta, 1972) and shows that the afterglow is mainly due to radiofrequency discharge. The results in presence of magnetic field also help us to identify the loss mechanism to a certain extent. The magnetic field affects the loss due to diffusion according to the expression

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

where $\omega_B = \left(\frac{eH}{m}\right)$ the cyclotron frequency and is the time for collision between charged particles and neutral atoms. As diffusion decreases but the ionization frequency remains almost unaffected in presence of magnetic field it appears that $\partial n/\partial t$ increases which will increase the persistence time of afterglow.

It is difficult to isolate the various loss processes in a decaying plasma but the above analysis shows that diffusion is one of main mechanisms of the loss process, but a more detailed analysis o of the decaying plasma by standard techniques will be required before the role of the different possible decay processes can be ascertained.

(IV) Intensity measurement of spectral lines with increasing arc current in an arc plasma.

The enhancement of intensity of the spectral lines $\lambda = 5465.5$ Å, $\lambda = 5209.1$ Å in case of silver arc, $\lambda = 5218.2$ Å and $\lambda = 5153.2$ Å in case of copper arc and $\lambda = 5369.9$ Å $\lambda = 5018.4$ Å, $\lambda = 4383.5$ Å in case of iron arc with increasing arc current from 2.5 Å to 7 Å has been investigated. As noted earlier by Sen and Sadhya (1986), Sen and Gantait (1988) it has been observed that not only there is variation in the intensity profiles of spectral lines of different elements but there is variation in the rate of increase of intensity among the spectral lines of the same element with the increase of the discharge current.

The variation of intensity of spectral lines with arc current in case of Ag-Ag, Cu-Cu and Fe-Fe electrodes has been plotted in a least square fitted line Sen, Acharya, Gantait (1989) and the estimated slope of enhancement of the intensity ratio has been calculated statistically and the results are entered in table (8.18).

In case of optically thick plasma Sen and Sadhya (1986) have shown that

$$I_{ul} = (1 - A_s) I_{ul}^{0}$$

where

$$As = \frac{f_{en}\ \lambda_{ue}\ P\ n_e^0}{}$$

$$P = \frac{1}{3}\pi\ r_0\ c\left[\frac{M}{2\pi K T g}\right]^{1/2} R$$

where the symbols have their usual significance as in the earlier section $I_{ue}^{0} = n\ \frac{g_u}{Z_0} A_{ue}\, h\nu_{ue} \exp\left[-\frac{E_u - E_l}{K T_e}\right]$ If I_0 denotes the intensity of the spectral line at the initial current

$$\frac{I_{ue}}{I_0} = \frac{(1-As)_i}{(1-As)_0}\ \frac{n_i}{n_0}$$

$$= \bar{c}\left[1 - As\right]_i = c\left[1 - \alpha\, T_g^{-1/2} n_e^0\right]$$

$$\alpha = f_{en}\ \lambda_{ue}\ \frac{1}{3}\pi\ r_0\ c\left(\frac{M}{2\pi K}\right)^{1/2} R.$$

$$\frac{d}{di}\left[\frac{I_{ue}}{I_0}\right] = \frac{1}{2}\bar{c}\,\alpha\left[T_g^{-3/2}\frac{dT_g}{di}\, n_e^0 - 2\, T_g^{-1/2}\frac{dn_e^0}{di}\right]$$

$$n_e^0 = \frac{1}{\mu e E \pi R^2} \quad \& \quad \frac{dn_e^0}{di} = \frac{1}{\mu e E \pi R^2}$$

$$\frac{d}{di}\left[\frac{I_{ue}}{I_0}\right] = \frac{1}{2}\frac{\bar{C}_\alpha}{T_g^{1/2}}\left[\frac{1}{T_g}\frac{dT_g}{di}\, n_e^0 - \frac{2 n_e^0}{i}\right]$$

The quantity within the brakket will be a constant for all the spectral lines and we get

$$\frac{d}{di}\left[\frac{I_{ue}}{I_0}\right]_{\lambda_1} : \frac{d}{di}\left[\frac{I_{ue}}{I_0}\right]_{\lambda_2} = (\lambda_{ue} f_{en})_{\lambda_1} : (\lambda_{ue} f_{en})_{\lambda_2}$$

The calculations based on the above equation have been entered in Table (8.18)

Table 8.18

Arc electrode	Wavelength Å	$\frac{d}{di}\left(\frac{I_{ul}}{I_o}\right)_{exp}$	f_{lu}	$\frac{\frac{d}{di}\left(\frac{I_{ul}}{I_o}\right)_{\lambda 1}}{\frac{d}{di}\left(\frac{I_{ul}}{I_o}\right)_{\lambda 2}}$	$\frac{(f_{lu}\lambda_{ul})_{\lambda 1}}{(f_{lu}\lambda_{ul})_{\lambda 2}}$
Silver	5645.5	0.4903	0.5771	0.91	0.99
Silver	5209.1	0.5398	0.6102		
Cupper	5218.2	0.7422	0.4593	0.93	0.97
Cupper	5153.2	0.7941	0.4771		
Iron	5364.4	2.041	0.2536	2:0.82	1:92:6
Iron	5014.9	0.8342	0.0835	:1	:1
	4383.5	1.0187	0.1620		

It is evident from the results that the agreement between theoretical and experimental results is very close in case of all the three arcs investigated. We can thus conclude that selfabsorption plays a dominent role in determining the intensities of spectral lines in case of optically thick plasmas and particularly its effect on intensity variation when the arc current is changed.

(K) Heat Flow processes in the positive column of a low pressure mercury arc.

The heat transport properties of confined electric arc plasma (i.e. the electric arc burning in a tube with cold walls) have been investigated by a number of investigators during the past few decades. The assumed Elanbaas Heller heat balance equation expressing simply the balance of three terms:

1. Heat generation by Joule effect,
2. Heat transfer by thermal conduction
3. Heat transfer by radiation.

However, they were able to show that the radiation loss was a few percent of the total loss, In general, the electrical conductivity assumes a radial distribution within the arc tube but for simplification they assumed the "Channel Model" (Hoyaux, 1968) for the electrical conductivity distribution within the arc. Goldstein and Sekiguchi (1958) have done elegent experiments employing microwave technique to determine thermal conductivity of a decaying glow discharge plasma where the plasma constituents were also in thermal equilibrium.

It is worthwhile to mention at this stage that no reference in the literature is available where the process of heat flow in a confined low pressure arc (where the electrons are far from being in thermal equilibrium with the heavier constituents) has been adquately studied. The present section is devoted to study semi-emperically the heat flow processes occuring within a low pressure mercury arc plasma.

Ghosal et al, 1978, have shown that when an arc is formed within a tube, the current density is not uniform throughout the cross-section but is maximum at the axis and minimum at the periphery. This phenomena gives rise to selective self-heating at the axis of the arc plasma. The arc continuously absorbs power from the source and gives it away to the surroundings. One might therefore be tempted to consider that the mechanism of selective self-heating might be employed to determine the thermal conductivity of the plasma. There are justifications in neglecting the effect of radiation and convection in the case of low temperature arcs but nevertheless it is worthwhile to mention that in this case the process of heat flow requires close observations. In a weakly ionised plasma both the electronic and molecular contributions to thermal conductivity are to be considered. One might predominate substantially over the other depending on the electron temperature, temperature gradients (electron temperature and gas temperature etc). There might be present another mechanism of heat flow other than thermal conduction, radiation and convection, which arises due to the fact that electron density distribution within the arc may cause diffusion and energy might be carried away by the electrons. In contrast to the case of high pressure arc this mechanism of heat flow might play a significant role in case of low pressure arcs.

Theoretical consideration

The heat flow processes in the positive column of a low pressure mercury arc has been considered in a detailed mathematical analysis by Ghosal, Nandi and Sen (1979). Considering the one dimensional case and assuming that the charged particles are undergoing ambipolar diffusion in the Z direction the steady state perturbed distribution function f_{e_1} may be given by the relation

$$v_Z \frac{\partial f_{e0}(Z, v_x, v_y, v_z)}{\partial Z} + \frac{e E_Z}{m_e} \frac{\partial f_{e0}}{\partial Z} = -\nu_{me} f_{e_1}$$

where f_{e0} and ν_{me} are the equilibrium distribution function and electron atom collision frequency respectively and E_Z is the field produced in the Z direction due to diffusion of charged particles. The equilibrium distribution function is assumed to be Maxwellian

$$f_{e0}(Z\, v_x\, v_y\, v_z) = \phi(Z) \left(\frac{m_e}{2\pi K T_e}\right)^{3/2} e^{-\frac{m_e v^2}{2 K T_e}}.$$

where $\phi(z)$ is related to electron density by

$$n(z) = n_0\,\phi(z) = n_0\left[1-\left(\frac{r}{R}\right)^2\right]^n.$$

the radial particle distribution formula introduced by Ghosal, Nandi and Sen (1976).

The authors assumed that the total heat flow is due to heat conduction by electrons, heat flow due to ambipolar diffusion and heat flow due to neutral particles the contribution by the ions being considered small in comparison to that of electrons so that $H = H_e + H_D + H_n$, Ghosal et al (1979) calculated that

$$H_e = -\frac{5}{2}\frac{n_0}{m_e}\frac{K^2}{\nu_{me}}\phi(r)\,T_e\frac{dT_e}{dr}$$

$$H_D = -\frac{5}{2}n_0 K T_e \frac{\mu_i}{\mu_e} D_e \frac{d\phi(r)}{dr}.$$

$$H_n = -K_n\frac{dT_n}{dr}.$$

assuming cylinderical symmetry Z can be replaced by radial variable r, and other symbols have their usual segnificance.,

If Q_0 is the total rate of heating inside the plasma column of unit length it has been calculated that $$\overset{o}{Q}_0 = \overset{o}{Q}_e + \overset{o}{Q}_D + \overset{o}{Q}_n$$

where it has been shown that

$$\overset{o}{Q}_e = \frac{5}{2}\,\pi\,\frac{K^2}{e^2}\cdot\frac{\sigma_0}{\Lambda}\,T_e\left(T_{n0}-T_{nw}\right).$$

$$\overset{\circ}{Q}_D = 5\pi \frac{\mu_i}{\mu_e} \frac{K^2}{e^2} \frac{\sigma_0}{\Lambda} T_e^{\,2}$$

$$\overset{\circ}{Q}_n = 2\pi \frac{K_n}{\Lambda} (T_{n0} - T_{nw})$$

where σ_0 is the axial electrical conductivity, μ denotes the mobility T_{n0} and T_{nw} is the temperature at the axis and at the wall respectively and

$$\Lambda = \frac{\int_0^R r\,\sigma(r)\,dr/r\,dr}{\int_0^R r\,\sigma(r)\,dr}$$

The experimental procedure has been described in the paper by Ghosal, Nandi and Sen (1979). The experimental values of σ_0 and Λ for three arc currents are σ_0 = 6.26 mhos/cm for 2.3 amp. arc current, σ_0 = 18.05 mhos/cm for 3.1 amp. and σ_0 = 26.55 mhos/cm for 4.0 amp and Λ = 0.8800, 1.0561 and 1.0676, for the three discharge currents. From these data and actual measurement of temperature at the axis and at the wall of the discharge tube the following table has been prepared Table (8. 19).

This table shows that electronic thermal conductivity is below 30% of the total flow rate for 2.3 arc current and at lower electron temperature this still further decreases and in the present situation heat is mainly carried away to the wall due to ambipolar diffusion.

It has further been shown that

$$\mathring{Q}_D = 5\pi \sqrt{\frac{m_e}{m_i}} \; \frac{K^2}{e^2} \; \frac{\sigma_0}{\Lambda} \; \frac{T_e^{5/2}}{T_n^{1/2}} \; \frac{q_e}{q_i}$$

where q_e / q_i is the ratio of electron atom to ion atom cross section. From this taking the Brode's value of electron atom collision cross section q_i is found to be 16.78×10^{-15} sq.cm. This is quite in agreement with mercury atom atom collision cross section which is 8.059×10^{-15} sq.cm. This method enables one to calculate electron atom collision cross section for energies of electrons below those reported by Brode (1953) and Massey (1969).

Table 8.19

Discharge current	σ_0 mho/cm	n	Λ
2.3	6.26	2.293	0.8800
3.1	18.05	3.859	1.0561
4.0	26.55	3.984	1.0676

CONCLUSION

A general review of the experimental results regarding the electrical and optical properties of arc plasma that have been measured in this laboratory and also those of other workers has been presented. From these data we can conclude the following:

a) Both the glow discharge and arc plasma react almost in a similar way under the effect of an external magnetic field whether longitudinal or transverse. Specially when the arc current is of the order of a few amperes. The mathematical analysis of the behaviour of a glow discharge under an external field is also valid in case of an arc plasma.

b) The main difference between a glow discharge and arc plasma lies in the radial distribution of charged particles. In case of glow discharge the distribution is Bessalian whereas in case of arc plasma the distribution is given by $n_r = n_0 \left[1 - \left(\frac{r}{R} \right)^2 \right]^n$. where the symbols have been explained in the text.

c) It has been shown that Langmuir's single probe method can be utilized for calculating electron density and electron temperature in arc plasma as well.

d) By utilizing the new distributionfunction electron temperature in an arc plasma in both transverse and longitudinal magnetic field has been measured and their variation with arc current has been explained. The new distribution function has also been utilized in conjunction with a longitudinal magnetic field to calculate the collision cross section.

e) The investigation of Hall effect in an arc plasma enables us to calculate electron density and mobility of electrons provided that the change of main arc current is taken into consideration due to imposition of the magnetic field.

f) Considering the physical processes involved in a mercury arc discharge where the buffer gas is air and pressure low a model has been developed in which air plays the role of a quenching gas and it has been found that in this type of discharge both atomic and molecular ions of mercury are present.

g) The role of self absorption of spectral lines in arc discharge has been analytically established and experimental results support the theoretical analysis.

h) The after glow investigation in an arc plasma in presence of a radiofrequency field enables one to identify the different loss mechanism.

i) The measurement of heat conductivity in an arc plasma shows that in the process of heat conduction the process of ambipolar diffusion has a major role to play.

References

1. Voltage current and power relation in an arc plasma in a transverse magnetic field, S.N.Sen and R.P. Das, International J.Electronics, 34, 527, 1973.
2. Azimuthal radiofrequency conductivity measurement in an arc plasma by studying the eddy current effect, S.K.Ghosal, G.P.Nandi and S.N.Sen, International J. Electronics, 41, 509, 1976.
3. Radial distribution function for the azimuthal conductivity of an arc plasma, S.K.Ghosal, G.P. Nandi and S.N.Sen, International J.Electronics, 44, 409, 1978.
4. Heat flow process in the positive column of a low pressure mercury arc, S.K.Ghosal, G.P.Nandi and S.N.Sen, International J.Electronics, 47,415,1979.
5. Mercury arc plasma in an axial magnetic field, S.K.Sadhya, and S.N.Sen, International J.Electronics, 49, 235, 1980.
6. Enhancement of spectral intensities of mercury triplet lines in longitudinal magnetic field, S.N.Sen, and S.K.Sadhya, Pramana, J.Phys. 26, 205,1986.
7. Hall effect in an arc plasma, S.N.Sen & B.Ghosh, Proc. Ind. Natn. Sc.Acad., 51A, 346, 1985.

8. Persistence of afterglow maintained by a radio-frequency field in a mercury arc, S.N.Sen, S.K.Sadhya, M.Gantait, D.C.Jana; Intnl. J.Electron., 63, 55, 1987.

9. Dependence of the intensity of mercury triplet lines on air charge current and transverse magnetic field in an arc plasma, S.N.Sen & M.Gantait, Ind.J.Pure & Appl. Phys. 25, 165, 1987.

10. Persistence of agterglow maintained by a radiofrequency field in a mercury arc, S.N.Sen, S.K.Sadhya, M.Gantait, D.C.Jana, Proc. Ind. Acad.Sci. 53A, 469, 1987.

11. Voltage current and power relation in an arc plasma in a variable axial magnetic field, S.N.Sen & M.Gantait, Pramana, J.Phys. 30, 143, 1988.

12. Voltage current characteristics of low current arcs in air with metal electrodes, S.N.Sen, M. Gantait and D.C.Jana, Ind.J.Phys. 62B, 78, 1988.

13. Conductivity and power relation in an arc plasma in a transverse magnetic field, S.N.Sen & M.Gantait, Ind. J. Pure & Appl.Phys., 26, 477, 1988.

14. Measurement of plasma parameters in an arc plasma by single method, S.N.Sen, M.Gantait & C.Acharyya, Ind.J. Pure & Appl.Phys. Communicated for publication.

15. Measurement of electron atom collision frequency in an arc plasma by radio frequency coil probe method in conjunction with a magnetic field, S.N.Sen, C. Acharyya, M. Gantait, S.K.Ghosal, G.P.Nandi, and B.Bhattacharjee, Communicated for Publication.

16. Evaluation of electron temperature in an arc plasma by measurement of diffusion voltage in a transverse and axial magnetic fields, S.N.Sen, C.Acharyya, and M.Gantait, Communicated for publication.

17. Intensity measurement of spectral lines with increasing arc current in arc plasma, S.N.Sen, C.Acharyya, M. Gantait & B.Bhattacharjee, Communicated for publication.

SUMMARY AND CONCLUSION

In this present work, Investigation on the physical properties of Glow discharge and Arc plasma have been investigated and mathematical analysis of the observed result has been given. The summary of the total work is mentioned below:

A) Heat flow process in the positive column of a glow discharge

The electronic thermal conductivity of ionised gases such as air, hydrogen, nitrogen and oxygen has been measured for discharge currents varying from 2mA to 8 mA. The problem of heat flow processes in the positive column of the glow discharge has been investigated utilizing the first order perturbation technique to Boltzmann Transport equation incorporating the radial distribution of charged particles which is assumed to be Bessalian.

The loss is due to heat conductivity of electrons, ions and neutral particles and also due to ambipolar diffusion of electrons. The experimental results enable us to calculate separately the centribution of different processes and it is observed that the major part of the heat loss is due to diffusion. Further from the experimental results it has been possible to calculate σ_{ia} the ion atom collision cross section.

B. Evaluation of Electron Temperature in Glow Discharge from Measurement of Diffusion Voltage.

It is shown that the electron temperature in a cylindrical glow discharge column can be evaluated by measuring the radial diffusion voltage due to charge separation. The effect of a transverse magnetic field on electron temperature has also been investigated.

C. Determination of plasma parameters by propagation of Sonic waves through an ionised gas.

The measurement of the attenuation constant of a propagating sonic wave through ionised air at different discharge currents varying from 1 mA to 8 mA and taking the values of electron temperature for different (E/P) values from literature, the ion atom collision frequency, drift velocity, mobility and ion atom collision cross section have been obtained utilizing the dispersion relation of ion acoustic waves at frequencies much below the ion plasma frequency. The values are consistent with literature values. The experiments were done in different gases.

D. Effect of capacitor bank discharge on low temperature plasma.

The effect of discharge of capacitor bank (which was charged to a high potential) through a glow discharge in air and hydrogen has been investigated. The object of this experiment is to study the changes in electrical conductivity and hence of electron density and the corresponding electron temperature in the glow discharge plasma when a bank of high voltage high capacity condensers is discharged through a glow discharge. It has been found that electron density increases almost in a linear way with the increase of input energy whereas electron temperature shows a sudden increase and then remains practically constant with further energy input. Considering various types of ionization processes in a discharge where additional energy has been fed in, a qualitative explanation of the observed results has been presented. The analysis of the data will enable us to understand the interation between an ionized gas and a high current pulsed discharge.

E. Hall Effect in an Arc plasma.

The Hall voltage in a mercury arc plasma carrying a current of 3 amps., with a background air pressure of 0.2 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 et al from the theoretical formulation of Beckman, 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.

F. Out line of a generalised theory of arc plasma from experimental results.

The summary and conclusion has been mentioned at the end of chapter VIII.