CHAPTER VI

EVALUATION OF ELECTRON TEMPERATURE IN TRANSVERSE AND AXIAL MAGNETIC FIELD IN AN ARC PLASMA BY MEASUREMENT OF DIFFUSION VOLTAGE.

6.1. Introduction:

The investigation on the measurement of plasma parameters such as electron density, collision frequency of electrons with atoms and electron temperature and their variation with pressure, discharge current and external magnetic fields has been extensively investigated by the standard plasma diagnostic techniques in case of glow discharge but the corresponding data for arc plasma has been little reported so far. But Sen and Das (1973), Ghosal, Nandi and Sen (1976), (1978) and (1979); Sadhya and Sen (1980), Sen, Ghosh and Ghosh (1983); Sen, Sadhya, Gantait and Jana (1987); Sen and Gantait (1987); (1988), have investigated systematically the properties of arc plasma for the last few years. The aim of their investigations is to develop a consistent theory for the occurrence of arc plasma and to study the transition phase from glow discharge to arc plasma. Sen, Gantait and Acharyya (1988) have shown that the electron density and
electron temperature in an arc plasma can be measured by the Langmuir single probe method. It is known that in the positive column of a glow discharge or in an arc plasma, a radial electric field develops as a result of net charge separation due to different rates of diffusion of ions and electrons (ambipolar diffusion). Taking the radial profile of charge distribution as Besselian, electron temperature in glow discharge in air (pressure 1 torr) has been evaluated by Sen, Ghosh and Ghosh (1983), from the measurement of diffusion voltage. They also measured the variation of electron temperature in a magnetic field by placing the discharge tube in a transverse magnetic field ranging from 0 to 100G. The utilization of this method in case of arc plasma will be investigated in the present work taking into account the radial distribution of charged particles in an arc plasma as has been provided by Ghosal, Nandi and Sen (1978). Further the theoretical analysis carried out by Allis and Allen (1937), Tonks and Allis (1937) and Huxley (1937) show that the behaviour of the electrons with regard to electron temperature, the radial distribution of electrons, the current voltage characteristics and other properties will be different when the external magnetic field is transverse than when the field is axial. The results obtained by Sen, and Das (1973)
indicate that the theoretical expression deduced by Beckman (1948) and later on simplified by Sen and Gupta (1971) regarding the variation of electron density and electron temperature in a transverse magnetic field in glow discharge is valid in the case of arc plasma as well. The voltage current characteristics as has been observed by Sen and Gantait (1988) undergo a similar change for both the alignments of magnetic field but the transverse magnetic field has a more dominant effect on the properties of arc plasma than that of an axial magnetic field. Hence in the present investigation it is proposed to evaluate the electron temperature in an arc plasma by measuring the diffusion voltage and study its variation in both transverse and axial magnetic fields and provide a theoretical analysis of the observed results.

6.2. Experimental arrangement:

In this investigation for measurement of diffusion voltage in transverse magnetic field the arc tube of 41 cm length, 26.5 cm anode-cathode spacing, 2.2 cm inner diameter and 2.5 cm outer diameter was used and in case of axial magnetic field the arc tube is of 9.1 cm length, 6.2 cm anode-cathode spacing, 1.86 cm inner diameter and 2.16 cm outer diameter.
Both the arc tubes are made of pyrex glass. The arc is excited between two mercury pool electrodes fitted with two tungsten wires for external electrical connection by a 250V d.c. source from generator with a rheostat to control the current as recorded by an ammeter. The whole arc system is cooled by air coolers and two mercury electrodes by circulation of water. To maintain the pressure constant in the tube, dry air which acts as a buffer gas has been introduced by a variable microleak of a needle valve fitted in the vacuum arrangement. By a calibrated pirani gauge the pressure has been calibrated. For measurement of parameters in transverse magnetic field the portion of the positive column of the arc has been placed between the pole pieces of an electromagnet while for that in longitudinal magnetic field the whole arc tube has been inserted between the two pole pieces.

The electromagnet has been run by a stabilized d.c. power supply (Type EM20), and the magnetic field has been calibrated by a gaussmeter (Model G14). After every sequence of measurement the electromagnet is suitably demagnetised.
6.2.1. Transverse magnetic field:

For diffusion voltage measurement in transverse magnetic field two cylindrical probes (tungsten) of 0.8 cm length and 0.014 cm radius have been inserted parallel to one another one along the axis $r = 0$ and the other at a distance of 0.6 cm from the axis in the same cross sectional plane of the tube. But these two probes in case of axial magnetic field are of 0.53 cm in length while other specifications are the same as in transverse magnetic field. In the above two cases the output voltage at the two probes has been measured by a VTVM having an internal impedance of $100 \, M\, \Omega$. A low pass filter circuit has been provided at the output of the probes to prevent oscillation generated in the arc from reaching the VTVM, which records the magnitude of the diffusion voltage. The diffusion voltage has been measured as a function of the magnetic field with arc current as a parameter. Specifically for transverse magnetic field the diffusion voltage has been measured upto the magnetic field of 1000 gauss at three constant arc currents namely 2.5 A, 3.0 A and 3.5 A and in axial magnetic field upto 1010 gauss at three fixed arc currents namely 3.0 A, 4.0 A and 5.0 A.
Table 6.1

<table>
<thead>
<tr>
<th>Magnetic field in K.G.</th>
<th>Arc current = 2.5 A</th>
<th>Arc current = 3.0 A</th>
<th>Arc current = 3.5 A</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRH(exp.) in Volts</td>
<td>VRH deduced in Volts</td>
<td>VRH(exp.) in Volts</td>
<td>VRH deduced in Volts</td>
</tr>
<tr>
<td>0.28</td>
<td>0.7075</td>
<td>0.65</td>
<td>0.6091</td>
</tr>
<tr>
<td>0.45</td>
<td>0.9568</td>
<td>0.80</td>
<td>0.8134</td>
</tr>
<tr>
<td>0.56</td>
<td>1.1807</td>
<td>1.00</td>
<td>0.9963</td>
</tr>
<tr>
<td>0.68</td>
<td>1.4789</td>
<td>1.20</td>
<td>1.2413</td>
</tr>
<tr>
<td>0.80</td>
<td>1.8357</td>
<td>1.45</td>
<td>1.5337</td>
</tr>
<tr>
<td>0.90</td>
<td>2.1772</td>
<td>1.80</td>
<td>1.8137</td>
</tr>
<tr>
<td>1.00</td>
<td>2.5590</td>
<td>2.20</td>
<td>2.1265</td>
</tr>
</tbody>
</table>

6.3. Results and discussion

In transverse magnetic field:

The variation of diffusion voltage has been plotted in Fig. 6.1 for magnetic field varying from zero to 1.0 K.G. It is observed that the diffusion voltage increases with magnetic field for three fixed currents namely 2.5 A, 3.0 A, and 3.5 A. The values of diffusion voltages are entered in Table 6.1, for values of magnetic field used in the experiment. From the nature of the curves
Fig. 6.1.
it can be assumed that an empirical relation of the form
\[ V_{RH} = V_R \left[ 1 + m' H^2 \right] \]

where \( V_{RH} \) and \( V_R \) are the diffusion voltages with and without magnetic field and \( m' \) is a constant can represent the experimental results. We can estimate the value of \( m' \) by a statistical method, which is shown for a current of 2.5 A.

\[ V_{RH} = V_R \left[ 1 + m' H^2 \right] \]

\[ S = \sum \left[ V_{RH} - V_R - m' V_R H^2 \right]^2 \]

\[ \frac{dS}{dm'} = -2 \sum \left[ V_{RH} - V_R - m' V_R H^2 \right] V_R H^2 = 0 \]

\[ \sum_{i=1}^{i=7} V_{RH} H^2 = V_R \sum_{i=1}^{i=7} H^2 + m' V_R \sum_{i=1}^{i=7} H^4 \]

\[ m' = \frac{\sum_{i=1}^{i=7} V_{RH} H^2 - V_R \sum_{i=1}^{i=7} H^4}{V_R \sum_{i=1}^{i=7} H^4} \]

\( V_R = 0.55 \text{ volts} \)
\[ \sum_{i=1}^{i=7} V_{RH} H^2 = 6.8005 \]
\[ \sum H^2 = 3.5069 \]
\[ \sum H^4 = 2.425 \]

\[ m' = \frac{6.8005 - 1.928}{1.3338} = 3.6526 \]
The values of \( m' \) for arc currents of 3.0 A and 3.5 A can be estimated as follows:

For 3.0 A arc current

\[ V_R = 0.48 \text{ volts} \]

\[ \sum V_{RH} H^2 = 5.6761 \text{ and } \sum H^2 = 3.5069 \]

\[ \sum H^4 = 2.425 \]

Hence \( m' = \frac{5.6761 - 1.6833}{1.164} \)

\[ = 3.4302 \]

And for 3.5 A arc current

\[ V_R = 0.36 \text{ volts} \]

\[ \sum V_{RH} H^2 = 4.2399, \quad \sum H^2 = 3.5069 \]

\[ \sum H^4 = 2.425 \]

\[ m' = \frac{4.2399 - 1.2625}{0.873} \]

\[ = 3.41062. \]

To verify whether the assumed empirical relation for \( V_{RH} \) agrees with experimental results the calculated values of \( V_{RH} \) are compared with experimental results in table 6.1 for three arc currents. It is evident from
this table that the results are in good agreement with each other. Hence we can conclude that the variation of diffusion voltage in a transverse magnetic field can be represented as

\[ V_{RH} = V_R \left( 1 + m'H^2 \right) \quad \text{...(6.1)} \]

where the value of \( m' \) decreases with increase of arc current.

In glow discharge the radial distribution profile of charged particle density has been taken to be Besselian. It has been shown by Ghosal, et al (1978) that the radial distribution function for the azimuthal conductivity for an arc plasma is of the form

\[ \sigma_r = \sigma_0 \left[ 1 - \left( \frac{r}{R} \right)^{2n} \right]^n \quad \text{...(6.2)} \]

where \( \sigma_0 \) is an axial conductivity, \( \sigma_r \) is the conductivity at a distance \( r \) from the axis of the tube, \( R \) is the arc tube radius and \( n \) is a constant which has been shown to be

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

where \( a' \) is an experimentally measured quantity that changes with arc current. It has been shown by Sen et al (1983) that the diffusion voltage \( V_R \) is
\[ V_R = - \int \frac{dne}{ne} \frac{KTe}{e} \quad \ldots(6.3) \]

and as the electron density is proportional to conductivity we can write from eqn. (6.2)

\[ ne = n_o \left[ 1 - \left( \frac{r}{R} \right)^2 \right]^n \quad \ldots(6.4) \]

Beckman (1948) has deduced that in presence of transverse magnetic field the radial electron density is decreased. Sen and Gupta (1971) have shown that Beckman's expression can be stated as

\[ neH = ne \exp(-aH) \quad \ldots(6.5) \]

where \( neH \) and \( ne \) are the electron concentrations in the presence of and in absence of magnetic field respectively, and

\[ a = \frac{eEC_1^{1/2} r}{2KTeP} \quad \ldots(6.6) \]

where \( E \) is the axial voltage drop per unit length and

\[ C_1 = \left( \frac{e}{m} \cdot \frac{L}{v_r} \right)^2 \]
where \( L \) is the mean free path of the electrons at a pressure of 1.0 torr, \( K \) is the Boltzmann constant, \( T_e \) is the electron temperature, \( v_r \) is the random velocity of electrons and \( r \) is the distance of the second probe from the probe at tube axis and \( P \) is the vapour pressure of mercury.

In presence of magnetic field diffusion voltage is given by

\[
V_{RH} = - \int \frac{dn_{eH}}{n_{eH}} \frac{K T_{eH}}{e}
\]

with the help of eqns. (6.4) and (6.5) it follows that

\[
V_{RH} = - \frac{K T_{eH}}{e} \int \left( \frac{\left( n_{eH} \right)_0}{n_{eH}} \right) \frac{d \left\{ n_0 \left( 1 - \frac{r^2}{R^2} \right)^n \exp(-aH) \right\}}{n_0 \left( 1 - \frac{r^2}{R^2} \right)^n \exp(-aH)}
\]

\[
= - \frac{K T_{eH}}{e} \left[ n \log \left( 1 - \frac{r^2}{R^2} \right) - aH \right]
\]

Hence

\[
T_{eH} = \frac{e}{K} \left( \frac{V_{RH}}{2n \log \frac{R}{\sqrt{R^2-r^2}} + aH} \right) \quad \ldots (6.7)
\]
And when $H = 0$ it reduces to

$$T_e = \frac{e}{K} \frac{V_R}{2n \log \frac{R}{\sqrt{R^2 - r^2}}} \ldots (6.8)$$

From eqns. (6.7) and (6.8)

$$\frac{T_eH}{T_e} = \frac{VRH}{VR} \frac{2n \log \frac{R}{\sqrt{R^2 - r^2}}}{(2n \log \frac{R}{\sqrt{R^2 - r^2}} + aH)}$$

Putting the value of $VRH$ from eqn. (6.1)

$$\frac{T_eH}{T_e} = \left(1 + m'H^2\right) \frac{X}{X + aH}$$

where $X = 2n \log \frac{R}{\sqrt{R^2 - r^2}}$

and $\frac{T_eH}{T_e} = \frac{1 + m'H^2}{1 + aH/X} \ldots (6.9)$

Therefore, with the values of $m'$ and $a/x$ from eqn. (6.9) $T_eH/T_e$ can be estimated for different values of $H$.

In the present investigation the value of 'a' given in the expression (6.6) has been estimated for
three arc currents, when arc current is 2.5 A, with
\[ E = \frac{37}{26.5} \text{ volts/cm}, \quad r = 0.6 \text{ cm}, \quad C_1 = 2.0 \times 10^{-6}, \]
\[ p = 0.3731 \text{ torr}, \] when arc current is 3.0 A, with
\[ E = \frac{35.5}{26.5} \text{ volts/cm}, \quad r = 0.6 \text{ cm}, \quad C_1 = 0.5946 \times 10^{-6}, \]
\[ P = 0.3731 \text{ torr}; \] similarly for arc current 3.5 A with
\[ E = \frac{34.0}{26.5} \text{ volts/cm}, \quad r = 0.6 \text{ cm}, \quad C_1 = 0.49 \times 10^{-6}, \]
\[ P = 0.3731 \text{ torr} \] (values taken from an earlier paper (Sadhya and Sen, 1980) and \( T_e = 10131 \) °K for arc current 2.5 A, \( T_e = 9573 \) °K for arc current 3.0 A, and \( T_e = 9000 \) °K for arc current 3.5 A, given by Sen, Gantait and Acharyya (1988), the values of 'a' becomes \( 1.83 \times 10^{-3} \) while for 3.0 A and 3.5 A arc currents it becomes \( 1.013 \times 10^{-3} \) and \( 0.937 \times 10^{-3} \) respectively taking the corresponding values of the above quantities. And the values of \( x = 2n \log \frac{R}{\sqrt{R^2-r^2}} \) can easily be calculated with the knowledge of quantitative value of \( n \). Some values for \( n \) were obtained by Ghosal, et al (1978), but a measurement of \( n \) for a wider range of current (2.2 A to 5.0 A) has been performed in this laboratory by Gantait (1988). Some of these values have been taken to calculate the value of \( X \). The plotting of \( n \) with arc current has been reproduced in Fig. 6.2.
Fig. 6.2.

Arc current in Amps.
Taking the values of $R$, the inner tube radius 1.1 cm. and $r$, the separation between the two probes 0.6 cm. And with $n = 1.7149, 1.7446$ and $1.8158$ the value of $X$ is found to be $0.60707, 0.61759$ and $0.64279$ for arc currents 2.5 A, 3.0 A and 3.5 A respectively. Therefore, putting these values in eqn. (6.9) the values of $T_{eH}/T_e$ have been calculated and the results plotted in Fig. 6.3. Each curve shows a minimum around 200 - 300 gauss of magnetic field.

6.3.1. Axial magnetic field:

In case of axial magnetic field it has been shown by Sen and Gantait (1988) that the conductivity of an arc plasma can be represented by

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

where $\sigma_H$ and $\sigma_0$ are the conductivities with and without magnetic field and the values of $\alpha$ have been calculated for three arc currents 3, 4 and 5 amp by the statistical method. Hence in case of axial magnetic field we can write that

$$n_{eH} = n_0 \exp (-\alpha H)$$
Fig. 6.9.
then

\[ V_{RH} = - \int \frac{d n_{eH}}{n_{eH}} \frac{K_{TeH}}{e} \]

\[ = - \frac{K_{TeH}}{e} \int \frac{d \{ n_0 (1 - \frac{r^2}{R^2}) \} e^{-\alpha H}}{n_0 (1 - \frac{r^2}{R^2}) e^{-\alpha H}} \]

\[ = - \frac{K_{TeH}}{e} \left[ \log (1 - \frac{r^2}{R^2})^n + \log e^{-\alpha H} \right] \]

\[ T_{eH} = \frac{e/K}{2n \log \frac{R}{\sqrt{R^2 - r^2}} + \alpha H} \]

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

\[ \frac{T_{eH}}{T_e} = \frac{V_{RH}}{V_R} \frac{2n \log \frac{R}{\sqrt{R^2 - r^2}}} {2n \log \frac{R}{\sqrt{R^2 - r^2}} + \alpha H} \]

\[ \ldots (6.10) \]

The values of \( V_{RH} \) in axial magnetic field as measured experimentally have been plotted against the corresponding values of the magnetic field in fig. 6.4. The values of \( \alpha \) as provided by Sen and Gantait (1988) are 0.2859, 0.2744 and 0.2714 respectively for three arc currents 3 A, 4 A and 5 A.
Diffusion voltage in volts.

Magnetic field in KG.

Fig. 6.4.
The values of $\frac{T_{eH}}{T_e}$ calculated from eqn. (6.10) have been plotted against magnetic field in fig. 6.5. A comparison with the results entered in Fig. 6.3 for transverse magnetic field shows that whereas in case of transverse magnetic field a minimum is observed for $\frac{T_{eH}}{T_e}$ for all the three arc currents a maximum in the value of $\frac{T_{eH}}{T_e}$ is observed for axial magnetic field almost in the same region of magnetic field. After attaining the minimum value $T_{eH}$ increases almost linearly with the magnetic field when it is transverse whereas it decreases with magnetic field when the magnetic field is axial.

In a two-fluid model we may assume that two distinct temperatures $T_e$ (for electron) and $T_g$ (for gas) exist. The difference between these two temperatures can be derived from an energy balance equation leading to

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

where symbols have their usual significance (Hirsh and Oskam, 1978). It follows that

$$T_e (T_e - T_g) = C \lambda e^2 E^2$$

where $C = \frac{\pi m_g e^2}{24 m_e k^2}$

$$\ldots (6.11)$$
Fig. 65.
In presence of magnetic field eqn. (6.11) can be modified as

$$TeH \left( TeH - Tg \right) = C \frac{\lambda^2_{eH}}{E_H^2} \ldots (6.12)$$

From eqn. (6.11) and (6.12) we get

$$\left( TeH - Te \right) \left( TeH + Te - Tg \right) = C \left[ \frac{\lambda^2_{eH}}{E_H^2} - \frac{\lambda^2_e}{E^2} \right]$$

with approximation that

$$TeH + Te \approx 2Te$$

$$\left[ \frac{TeH}{Te} - 1 \right] = \frac{C}{Te^2 \left( 2 - Tg/Te \right)} \left[ \frac{\lambda^2_{eH}}{E_H^2} - \frac{\lambda^2_e}{E^2} \right] \ldots (6.13)$$

It has been deduced by Sen and Gantait (1988) that in presence of magnetic field

$$E_H = E \left( 1 + mH \right)$$

and

$$\lambda^2_{eH} = \frac{\lambda_e}{\left( 1 + C_1 H^2 / p^2 \right)^{1/2}}$$

[ Blevin and Heydon (1958), Sen and Ghosh (1963)]

where $C_1$ is the same constant as introduced in
eqn. (6.6) eqn. (6.13) can further be simplified as

\[
\frac{T_e H}{T_e} = 1 + \beta \left[ \frac{m^2 H^2 + 2 m H - C_1 H^2 / p^2}{1 + C_1 H^2 / p^2} \right]
\]

where \( \beta = \frac{C e^2}{T_e^2} \left[ 2 - \frac{\beta g}{T_e} \right] \)

then

\[
\frac{1}{T_e} \frac{d T_e H}{d H} = \frac{\beta \left[ m C_1 p^2 - (m^2 - C_1 p^2) H - m \right]}{\left[ 1 + C_1 H^2 / p^2 \right]} = 0
\]

Hence

\[
H = \frac{(m^2 - C_1 p^2) + \sqrt{m^4 + \frac{C_1^2}{p^4} + 2m^2 \frac{C_1}{p^2}}}{2m C_1 / p^2} \quad \ldots (6.14)
\]

where negative sign before the radical has been discarded for the same reasoning as before. With simplification

\[
H = \frac{m}{C_1 / p^2} \quad \ldots (6.15)
\]

In order to find whether the value of \( H \) corresponds to minimum or maximum equation (6.14) has been differentiated again so as to yield

\[
\frac{1}{T_e} \frac{d^2 T_e H}{d H^2} = \frac{-2 \beta}{(1 + C_1 H^2 / p^2)^3} \left[ (1 + C_1 H^2 / p^2) \left\{ 2 m C_1 H / p^2 + \frac{C_1}{p^2} - m^2 \right\} - \left\{ m C_1 H / p^2 + \left( \frac{C_1}{p^2} - m^2 \right) H - m \right\} 4 C_1 H / p^2 \right] - \frac{2 \beta}{(1 + C_1 H^2 / p^2)^2} \left[ (1 + C_1 H^2 / p^2) \left\{ 2 m C_1 H / p^2 + \frac{C_1}{p^2} - m^2 \right\} - \left\{ m C_1 H / p^2 + \left( \frac{C_1}{p^2} - m^2 \right) H - m \right\} \right] \]

\[
= \frac{-2 \beta}{(1 + C_1 H^2 / p^2)^3} \left[ (1 + C_1 H^2 / p^2) \left\{ 2 m C_1 H / p^2 + \frac{C_1}{p^2} - m^2 \right\} - \left\{ m C_1 H / p^2 + \left( \frac{C_1}{p^2} - m^2 \right) H - m \right\} 4 C_1 H / p^2 \right] - \frac{2 \beta}{(1 + C_1 H^2 / p^2)^2} \left[ (1 + C_1 H^2 / p^2) \left\{ 2 m C_1 H / p^2 + \frac{C_1}{p^2} - m^2 \right\} - \left\{ m C_1 H / p^2 + \left( \frac{C_1}{p^2} - m^2 \right) H - m \right\} \right]
\]
Putting the value of

\[ H = \frac{m}{c_1 / p^2} \]  (eqn. 6.15)

\[ \frac{1}{T_e} \frac{d^2 T_{eH}}{d H^2} = 2\beta \left[ m^2 - \frac{c_1}{p^2} + \frac{m^4 p^2}{c_1} + \frac{m^6 p^4}{c_1^2} + \ldots \right] \]

In case of axial magnetic field \( m = 0.295 \times 10^{-3} \)
(Sen and Gantait (1988)) and \( c_1 = 0.125 \times 10^{-6} \)
(Sadhya and Sen, 1980)

\[ \frac{1}{T_e} \frac{d^2 T_{eH}}{d H^2} = 2\beta \left[ 0.087 \times 10^{-6} - 1.358 \times 10^{-7} + 5.4 \times 10^{-9} + \ldots \right] \]

= negative quantity.

In case of transverse magnetic field \( m = 5.55 \times 10^{-3} \)
and \( c_1 = 2.8 \times 10^{-6} \) (Sen and Das, 1973).

\[ \frac{1}{T_e} \frac{d^2 T_{eH}}{d H^2} = 2\beta \left[ 30.8 \times 10^{-6} - 30.4 \times 10^{-6} + 31.15 \times 10^{-6} + 970.3 \times 10^{-6} + \ldots \right] \]

= a positive quantity.

We can thus conclude that in case of an axial magnetic field a maximum in the value of \( T_{eH} \) whereas in case of transverse magnetic field minimum in the value of \( T_{eH} \) is expected when the magnetic field is varied. The experimental results support these theoretical deductions.
Further the values of $H_{\text{max}}$ where the electron temperature becomes a maximum in the axial magnetic field and the values of $H_{\text{min}}$ where the electron temperature becomes a minimum in a transverse magnetic field have been calculated for three different arc currents from the respective values of $m$ and $C_1$ and the results entered in Table 6.2. The corresponding values of mercury vapour pressure have been taken from the earlier paper by Sadhya and Sen (1980).

**Table 6.2**

**Axial Magnetic Field.**

<table>
<thead>
<tr>
<th>Arc current in amps.</th>
<th>$H_{\text{max}}$ Exp. K.G.</th>
<th>$H_{\text{min}}$ calculated K.G.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.31</td>
<td>0.3285</td>
</tr>
<tr>
<td>4</td>
<td>0.2</td>
<td>0.2818</td>
</tr>
<tr>
<td>5</td>
<td>0.142</td>
<td>0.201</td>
</tr>
</tbody>
</table>

**Transverse magnetic field**

<table>
<thead>
<tr>
<th>Current</th>
<th>$H_{\text{max}}$ Exp. K.G.</th>
<th>$H_{\text{min}}$ calculated K.G.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.288</td>
<td>0.2735</td>
</tr>
<tr>
<td>3</td>
<td>0.201</td>
<td>0.181</td>
</tr>
<tr>
<td>3.5</td>
<td>0.188</td>
<td>0.132</td>
</tr>
</tbody>
</table>
The quantitative agreement between the experimental and calculated values is not very satisfactory as is to be expected due to some uncertainty in the values of $C_1$ which is the square of the mobility of the electrons at a pressure of one torr. There is lack of experimental data in literature regarding the mobility of electrons in mercury vapour but the order of magnitude of $C_1$ is of the right order as is found in McDanial (1964). However, the agreement between the experimental and calculated values of $H_{\text{max}}$, or $H_{\text{min}}$ is of the right order of magnitude.

Taking the expression for electron temperature which is derived by considering the arc plasma as a two fluid system it has been possible to derive an expression for variation of electron temperature with magnetic field and it is found that the theory predicts that in an axial field electron temperature becomes a maximum at a certain magnetic field and then decreases whereas it shows a minimum and then increases with magnetic field when the field is transverse. The experimental results confirm the validity of the theory. Further the electron temperature from diffusion voltage measurements and assuming the radial distribution of charged particles in an arc plasma as provided by Ghosal, Nandi and Sen (1978) give the correct order of magnitude for electron temperature
thereby providing the validity of the proposed radial distribution function, and the measurement of diffusion voltage in an arc plasma can be an alternative diagnostic tool for measurement of electron temperature. As has been noted by Franklin (1976) electron temperature decreases with the axial magnetic field for higher values of magnetic field in glow discharge and similar results have also been obtained in the present investigation on arc plasma with the exception that for smaller values of magnetic field a maximum in the value of $T_{eH}$ has been found. In transverse magnetic field the electron temperature increases with higher values of magnetic field after attaining a minimum for smaller values at magnetic field.
References:


Please Note:—

Due to short period, the reprints could not obtained from Publishers. The copy of the galley proof is enclosed.
Evaluation of electron temperature in transverse and axial magnetic fields in an arc plasma by diffusion voltage measurement

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The diffusion voltage in a mercury arc plasma has been measured for arc currents from 2.5 A to 5 A in transverse and axial magnetic fields from zero to 1.1 kG. Assuming the radial distribution of charged particles proposed by Ghosal et al. (1978) and utilizing the method of Sen et al. (1983), the ratio of electron temperatures with and without a magnetic field has been evaluated. It becomes a maximum in an axial field and then decreases, whereas it shows a minimum in a transverse field and then increases. An expression for the ratio of the electron temperature with and without a field has been deduced that explains these results. Quantitative agreement between experiment and theory is fairly satisfactory.

1. Introduction

Extensive measurements of plasma parameters such as electron density, electron collision frequency with atoms, electron temperature and their variation with pressure, discharge current and external magnetic fields have been made by the standard plasma diagnostic techniques for glow discharges, but the corresponding data for an arc plasma has been little reported so far. For the last few years we have made a systematic investigation of the properties of the arc plasma (Sen and Das 1973), Ghosal et al. 1976, 1978, 1979), Sadhya and Sen 1980, Sen et al. 1983, Sen 1987, Sen and Gantait 1987, 1988. The aim of these investigations has been to develop a consistent theory for the occurrence of an arc plasma and to study the transition phase from a glow discharge to an arc plasma. In a recent communication (Sen et al. 1988) we have shown how the electron density and electron temperature in an arc plasma can be measured by a Langmuir single probe method. It is well known that in the positive column of a glow discharge, or in an arc plasma, a radial electric field develops as a result of net charge separation owing to different rates of diffusion of ions and electrons (ambipolar diffusion). Sen et al. 1983 evaluated the electron temperature in a glow discharge in air (pressure 1 torr) from the measurement of diffusion voltage, taking the radial profile of the charge distribution to be basselian. They also measured the variation of electron temperature in a magnetic field by placing the discharge tube in a transverse magnetic field (0 to 100 G). The utilization of this method in the case of an arc plasma has been investigated in the present work employing the radial distribution function of charged particles in an arc plasma due to Ghosal et al. (1978).

The well-known theoretical analysis carried out by Allis and Allen (1937) and others shows that the behaviour of the electrons (and consequently the electron temperature, the electron radial distribution, the current–voltage characteristics and other parameters) is different for transverse and axial magnetic fields. The results obtained by Sen and Das (1973) indicate that the theoretical expression deduced by

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Beckman (1948), later simplified by Sen and Gupta (1971), regarding the variation of electron density and electron temperature in a transverse magnetic field in a glow discharge is also valid in the case of an arc plasma. Further, it has been observed by Sen and Gantait (1988) that the voltage–current characteristics undergo a generally similar change for both alignments of magnetic field, but that a transverse magnetic field has a stronger effect than an axial magnetic field. In the present investigation, we have evaluated the electron temperature in an arc plasma by measuring the diffusion voltage, have studied its variation in both transverse and axial magnetic fields, and have made a theoretical analysis of the observed results.

2. Experimental arrangement

For the investigation of an arc plasma, a mercury arc was utilized. For the measurement of diffusion voltage in a transverse magnetic field, an arc tube of 41 cm length, 26.5 cm anode–cathode spacing, 2.2 cm inner diameter and 2.5 cm outer diameter was used. In the case of an axial magnetic field, an arc tube is of 9.1 cm length, 6.2 cm anode–cathode spacing, 1.86 cm inner diameter and 2.16 cm outer diameter was used. Both tubes were made of pyrex. The arc was excited between two mercury pool electrodes (fitted with two tungsten wires for external electrical connection) by a 250 V DC generator with a rheostat to control the current. The whole arc system was cooled by air and the two mercury pool electrodes by circulating water. To maintain the pressure constant in the tube, dry air which acts as a buffer gas was introduced by a variable microleak needle valve fitted in the vacuum arrangement. The pressure was measured by a calibrated pirani gauge. For measurement of the parameters in a transverse magnetic field, a portion of the positive column of the arc was placed between the pole pieces of an electromagnet while for that in a longitudinal magnetic field the whole arc tube was inserted between the two pole pieces.

The electromagnets were run by a stabilized DC power supply (Type EM20), and the magnetic field calibrated by a gauss meter (Model G14). After every sequence of measurements, the electromagnet was demagnetized.

For diffusion voltage measurement in a transverse magnetic field, two cylindrical tungsten probes of 0.8 cm length and 0.014 cm radius were inserted parallel to one another, one along the axis \( r = 0 \) and the other at a distance of 0.6 cm from the axis in the same cross-sectional plane of the tube. In an axial magnetic field, they were 0.53 cm long, the other specifications being the same as for the transverse magnetic field. The diffusion voltage was measured as before (Sen et al. 1983).

3.1 Results and discussion

3.1. Transverse magnetic field

The variation of the diffusion voltage is shown in Fig. 1 for magnetic fields varying from zero to 1.0 kG. It may be seen that the diffusion voltage increases with magnetic field for three fixed currents, namely 2.5 A, 3.0 A, and 3.5 A. The values of the diffusion voltage are entered in Table 1. From the nature of the curves it can be
assumed that an empirical relation of the form \( V_{RH} = V_0[1 + m'H^2] \), where \( V_0 \) and \( V_{RH} \) are the diffusion voltages with and without a magnetic field and \( m' \) is a constant, represent the experimental results. We can estimate the value of \( m' \) by a statistical method, essentially as described before by Sen and Gantait (1988).

The value of \( m' \) for arc currents of 2.5 A, 3.0 A and 3.5 A are 3.6526, 3.43021 and 3.41062, respectively. To verify whether the assumed empirical relation for \( V_{RH} \) agrees with experimental results the calculated values of \( V_{RH} \) are compared with the experimental results in Table 1. They are in good agreement and we can conclude that the variation of the diffusion voltage in a transverse magnetic field can indeed be represented by

\[
V_{RH} = V_0(1 + m'H^2)
\]

where \( m' \) is a function of the arc current.

We can find values of the electron temperature with \( (T_{eH}) \) and without \( (T_e) \) a magnetic field from the measured values \( V_{RH} \) by procedures closely comparable with

![Figure 1. Variation of diffusion voltage with magnetic field for different arc currents (transverse magnetic field).](image)

<table>
<thead>
<tr>
<th>Magnetic field (kg)</th>
<th>( V_{RH} ) (exp.)</th>
<th>( V_{RH} ) deduced from (1)</th>
<th>( V_{RH} ) (exp.)</th>
<th>( V_{RH} ) deduced from (1)</th>
<th>( V_{RH} ) (exp.)</th>
<th>( V_{RH} ) deduced from (1)</th>
</tr>
</thead>
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<tr>
<td>0.28</td>
<td>0.80</td>
<td>0.7075</td>
<td>0.65</td>
<td>0.6091</td>
<td>0.45</td>
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<td>0.8134</td>
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<tr>
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<td>2.5900</td>
<td>2.20</td>
<td>2.1265</td>
<td>1.65</td>
<td>1.5878</td>
</tr>
</tbody>
</table>

Table 1.
those used before by (Sen et al. 1988) via the relation

\[
\frac{T_{\text{eff}}}{T_e} = \frac{1 + \frac{m' H^2}{x}}{1 + \frac{\alpha H}{x}}
\]  

(2)

where

\[ a = \frac{e R C_1^{1/2}}{2 K T_e P}, \quad C_1 = \left( \frac{e}{m} \frac{L}{v_t} \right)^2 \quad \text{and} \quad x = 2n \log \left( \frac{R}{(R^2 - r^2)^{1/2}} \right) \]

The value of \( a \) was calculated from the data obtained earlier (Sadhya and Sen 1980, Sen et al. 1988), and the values of \( x \) from the values of \( n \). Some values of \( n \) were obtained by Ghosal et al. (1978), and measurement of \( n \) for a wider range of current (2.2 A to 5.0 A) have been made in this laboratory by Gantait (1988). Plots of \( n \) versus arc current are shown in Fig. 2. Values of \( T_{\text{eff}}/T_e \) are plotted in Fig. 3. Each curve shows a minimum around 200–300 G.

3.2. Axial magnetic field

Values of \( V_{\text{RH}} \) in an axial magnetic field are plotted against the corresponding values of magnetic field in Fig. 4. Following a procedure in essence the same as that of § 3.1, we obtain the results plotted in Fig. 5. In the two-fluid model proposed by

![Figure 2](image1.png)

Figure 2. Variation of \( n \) with arc current.

![Figure 3](image2.png)

Figure 3. Variation of \( T_{\text{eff}}/T_e \) with magnetic field (Transverse magnetic field).
Hirsh and Oskam (1978), energy balance considerations in the absence of a magnetic field lead to the equation

\[ \frac{T_e - T_s}{T_e} = \frac{\pi m_e}{24m_e} \frac{\lambda_e^2 e^2 E^2}{K^2 T_e^2} \]  

(3)

and when a magnetic field is present

\[ \frac{T_{eh} - T_s}{T_{eh}} = \frac{\pi m_e}{24m_e} \frac{\lambda_{eh}^2 e^2 E_{H}^2}{K^2 T_{eh}^2} \]  

(4)

Putting

\[ E_{H} = E(1 + mH) \]

(Sen and Gantait 1988) and

\[ \lambda_{eh} = \lambda_e \left( 1 + C_1 \frac{H^2}{P^2} \right) \]

(Blevin and Haydon 1958, Sen and Ghosh 1963) we get from (3) and (4)

\[ \frac{T_{eh}}{T_e} = 1 + \beta \left[ \frac{m^2 H^2 + 2mH - C_1 \frac{H^2}{P^2}}{1 + C_1 \frac{H^2}{P^2}} \right] \]

where

\[ \beta = \frac{\pi m_e e^2 E^2 \lambda_e^2}{24m_e K^2 T_e^2 2 - \frac{T_s}{T_e}} \]
The value at which $T_{eh}/T_e$ will either show a maximum or minimum will be $H = m/C_1/p^2$.

It can be shown that

$$\frac{1}{T_e} \frac{d^2 T_{eh}}{dH^2}$$

will be negative for an axial magnetic field and positive for a transverse magnetic field, which explains the occurrence of the maxima and minima in the two cases.

Further, the values of $H_{max}$ where the electron temperature becomes a maximum in the axial magnetic field and the values of $H_{min}$ where the electron temperature becomes a minimum in a transverse magnetic field have been calculated for three different arc currents from the respective values of $m$ and $C_1$. The results are shown in Table 2. The mercury vapour pressures are taken from an earlier paper by Sadhya and Sen (1980).

Quantitative agreement between the experimental and calculated values, as distinct from qualitative agreement, is only moderately satisfactory as is to be expected owing to uncertainty in the values of $C_1$. However, the agreement between the experimental and calculated values of $H_{max}$ and $H_{min}$ is of the correct order of magnitude.

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**REFERENCES**


