INVESTIGATION ON SOME OF THE PHYSICAL PROCESSES OCCURING IN GLOW AND ARC DISCHARGE PLASMA

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I have pleasure to certify that Miss Chandana Acharyya has carried out the research work under my guidance for the thesis entitled 'Investigation on some of the Physical Processes occuring in Glow and Arc Plasma' in final form. She is submitting her thesis for the Ph.D.(Sc.) degree of the University of North Bengal. Miss Acharyya has fulfilled all the requirements for the submission of her thesis as laid down by the University. In character and temperament she is suitable for the submission of her above thesis.

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D E D I C A T E D

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CHAPTER I

REVIEW OF THE PREVIOUS WORK.

In this work it is proposed to study the physical processes occuring in a glow discharge and arc plasma and following lines of investigation have been undertaken:

1.1. Measurement of plasma parameters by probe technique

One of the standard methods for measurement of plasma parameters is the probe method and a variety of probes has been used to measure plasma properties. They all have the feature of being inserted into the plasma medium in order to sample plasma properties in a local region. Most probes perturb the plasma in some way, and care must be taken to ensure that plasma in the presence of the probe is the same as the plasma before the insertion of probe. The two simplest probes used in plasma measurements are (i) electrostatic (or Langmuir) and (ii) magnetic probes.

The electrostatic probe is used for the measurement of plasma properties because of its experimental simplicity and reliability. Generally a Langmuir probe is a thin insulated wire with a small exposed region at its end immersed in plasma to collect electrons or ions from the plasma, depending on the potential of the probe relative to the plasma potential. Usually some potential is applied to the probe from an external source relative to plasma potential and the resulting current flowing through the probe is recorded as a function of applied potential. Langmuir and Mott-Smith (1924) developed the theory of flow of current through such probes and the measurement of probe currents at different probe potentials can be used to obtain the values of the electron density, n_e , the ion density, n_i , the electron temperature T_e , the plasma potential V_p , the plasma floating potential V_f (i.e. the potential of the probe for zero net probe current), and the random electron and ion current densities J_{er} , J_{ir} .

If the potential of the probe is much larger than the local potential of the plasma, the probe attracts electrons and repels ions, forming a sheath region around the probes which is electron-rich, This sheath region is a few Debye lengths thick and occurs for the same reason that a given charged particle in a plasma is shielded; namely the range of the force field (potential) is limited by the tendency of the particles of opposite sign to cluster around a given charge. Thus the influence of a probe in a plasma is limited to a region about one Debye length from the probe. As the probes offer boundaries to the plasma and the properties of the plasma will change in the vicinity of the probe-boundaries, the whole probe theory becomes complicated.

In case of collisional plasma due to some secondary effects the sheath thickness increases with positive potential and electron current never saturates. The effect of ionisation on saturation probe current has been studied by Devyatou and Mal'kov(1984). They measured sink parameters for an infinite cylindrical probe and found that if the radius is small in comparison with the ionization length, then the sink parameter is determined by Bohm's expression (1949) in case of spherical probes. They considered the probe operation in presence of ionization and recombination processes in the bulk of the plasma.

According to Langmuir's probe theory the electron current through the probe is

$$I_e = I_{re} \exp. (- eV_p / KT_e) \quad . \; . \; . \; . \qquad (1.1)$$

where I_{re} denotes the random electron current and K is Boltzmann constant and T_e is the electron temperature.

$$I_{re} = \frac{1}{4} A_s n_e e \left(\frac{8 KTe}{m \pi} \right)^{1/2} \quad \ldots (1.2)$$

A_s represents the effective electron collecting area of the probe and n_e is electron concentration of plasma. Assuming Maxwellian distribution of electrons, eqn. (1.1) gives the value of electron temperature T_e by the slope of the line in partial attraction regime in a semilogarithmic plot of I_e against V_p. I_{re} is the electron saturation current at space potential which can be calculated from the intersecting point of the two tangents in the characteristics ($I_e - V_p$). The procedure of drawing the tangents were:

(i) Considering the distribution to be a Maxwellian one, the tangent in the partial electron attraction regime was plotted through more points of highly negative probe potential and eqn. (1.1) is valid for electron current which is small in comparison with I_{re} (Schott, 1968).

(ii) Another tangent was plotted in electron saturation current region in such a way that it passes through maximum number of points. The saturation current region consists of two parts:

(a) Due to the growth of collective area, electron current I_e increases linearly with probe potential. (b) When probe potential is made more positive, break away from this linear increase is found. In this region, the probe becomes hot and the probe sheath expands so much that for a large voltage drop across the sheath, the electrons can further ionize in their way to probe. At the time of plotting the tangent the points just below breakaway point were utilised.

The effective probe area A_s has been considered to be equal to $2\pi r_p l$, since $l/r_p \gg 1$ where l represents the cylindrical probe length and r_p is probe radius. Thus eqn. (1.2) provides the measurement of electron density. Clements, et al (1971) measured the ionization density on a plasma jet. In their investigation the current to a negative probe in an argon plasma jet shows a strong dependance on probe bias and is of the order of magnitude less than the convection/diffusion saturation current.

The probe current decreases when the probe is biased negatively due to the repulsion of electrons. The logarithmic slope of the characteristic will correspond to the local electron temperature in this portion.

The ion and electron current cancel each other at V_f the floating potential. No electrons can reach the probe if more negative potential to the probe is applied and hence ion saturation current is drawn. The electron temperature and density can be determined by measuring electron and ion saturation current. Cherrington (1985) described the use of electrostatic or Langmuir probes for the measurement of electron density and temperature in low pressure reactive plasmas. The effect of cooling on probe has been investigated by Clements and Smy (1973). Their theoretical predictions indicate that while cooling effects can be substantial, accurate electron temperature measurements can be obtained if the probe is sufficiently small or is moved through the plasma at sufficient velocity.

Since the very inception of Langmuir's (1924 - 1926) work, the probe theory has been developed in many fields. The probe theory depends on a number of parameters which measure the various domain at which electrostatic probe can be utilised. Taking λ , mean free path of charged species, for collision with neutrals, r_p , the probe radius and λ_D , Debye shielding length ($\lambda_D = 4.9(T_e/n_e)^{1/2}$ in cm), the probe theory was found approximately valid in the collision limit given by[$\lambda \gg r_p$, $\lambda \gg \lambda_D$] . Bernstein and Rabinowitz (1959), Lam (1965) and Leframboise (1966), computed some results on the above considerations. Also Su and Lam (1963) and Cohen (1963) computed the continuum regime given by [$\lambda \ll \lambda_D \ll r_p$] , Wasserstrom, Su and Probstein (1965); Chou Talbot and Willis (1966); Bienkowski and Change (1968); Chung, Tolbot and Touryan (1975) carried out some calculations in the intermediate cases and a systematic analysis of probe theories has been provided. The probe theory becomes simple when the Debye ratio, $\xi_p = r_p/\lambda_D$ is much greater than 10 according to Chen, Etievant and Mosher (1968). They enunciated that in case of thin sheath the charge collecting area is effectively close to the geometric area of the probe or when $\xi_p \ll 1$. In case of thick sheath, the probe current is determined by orbital motion theory of Langmuir. For a suitable selection of ξ_p it is to be noted that λ_D is the characteristic of plasma source, whereas r_p is set only by the physical properties of probe. To estimate the approximate range of Debye ratio, Lamframboise (1966) computed that orbital motion theory is accurate for cylindrical probes for $\xi_p < 5$ which can easily be satisfied in experiments but orbital motion approximation is valid for $\xi_p \ll 1$ in case of spherical probes.

Some assumptions given by Schott (1968) in his orbital motion theory are as follows:

(a) In absence of probe, plasma should be homogeneous and quasi neutral.

(b) The distribution of electrons and ions should be Maxwellian with temperature T_e and T_i respectively and $T_e \gg T_i$. Electron and ion mean free path (λ_e and λ_i respectively) should be large compared to their Debye shielding distances. The charged species striking the probe structure should be absorbed and not react with the probe material as such.

(c) The sheath around the probe should have a well defined boundary.

(d) The edge effects can be neglected without losing accuracy if the sheath thickness is small compared to the lateral dimensions of the probe.

The condition of Maxwellian velocity distribution is often not maintained in case of low pressure plasma. One of the main assumptions of the conventional Langmuir probe theory is the demand for a Maxwellian distribution function of charged particles. Allen (1974) discussed the classical probe theory due to Langmuir (1924). Langmuir assumed that the potential difference between the probe and plasma was confined to a space charge sheath adjacent to the probe. Thus if the electrons have a Maxwellian distribution Boltzmann's relation gives $Z_e = Z_o$ exp. (eV/KTe). T_e = electron temperature V = negative potential. Electron temperature and electron and ion densities can be determined from this simple theory. Johanning (1984) calculated probe currents for non-Maxwellian electron energy distributions. The classical Langmuir formula for the orbital motion - limited current of cylindrical probes is simplified. The author has shown that the electron current is independent of electron energy distribution if the mean electron energy E is constant. However, Druyvesteyn (1930) showed that the actual velocity distribution might be derived from the form of probe characteristics. The selection of probe material will be such that it is resistent to heat, chemical activation and sputtering. To avoid the secondary electron emission due to particle bombardment, the work function of the probe material must be large. Chung, Talbot and Touryan (1975) reviewed the informations and findings about the perturbations of plasma due to probe.

Kumer et al (1979) made measurements of plasma density in argon discharge by Langmuir probe and microwave interferometer method. The measurement of plasma density in an argon plasma at 0.1 - 1.0 torr has been made using the ion-current data obtained from a cylindrical Langmuir probe and using a microwave phase shift interferometer.

Sanders and Pfender (1984) used the electric probe for the measurement of anode fall and anode heat transfer at atmospheric pressure of arcs in argon for different arc configurations and water-cooled anode surface close to the probe. With the help of an adjustable fine wire probe penetrating through a small hole in the centre of a flat anode they measured probe potential and electron temperature in the anode boundary layers. Pasternak and Offenberger (1975) used double ended tungsten wire probes mounted on a shaft of a small water cooled d.c. motor inside the arc chamber. Using conventional probe theory, spatially resolved probe current measurements provided electron temperature and cross-sectional density profiles of arc.

The probe technique has been extensively used in r.f. plasma. Boschi and Magistrelli (1963) have studied the effect of a sinusoidal signal of large amplitude on the characteristics of a Langmuir probe. They measured the average values of the current collected by the probe and also determined the value of electron temperature, plasma density and plasma potential. Ciampi and Talini (1967) determined the spatial average plasma conductivity by a radiofrequency probe. They used cylindrical plasma which is radially inhomogeneous. In their work the real and imaginary part of the probe impedance versus the probing frequency are found numerically for inhomogenous plasma. An application of this method is carried out in a flow facility plasma jet with Q factor measurements from 0.5 to 1.5 MHz and average conductivity values from 75 to 100 Mho/m are obtained. Lindberg (1985) has critically analysed the fundamental HF probe circuits ranging from 100 MHz to a few GHz.

Langmuir probe measurement was also used in HF discharges by Spatenka and Sicha (1985) to give experimental evidence of the presence of heavy atomic or molecular negative ions in the created polymer thin film layers.

Langmuir probe characteristics in a plasma containing electrons with drift velocities has been studied by Sawada and Miura (1980). They analysed the probe characteristics and discussed several problems and made some observations on Langmuir probe technique.

Measurement of the electron distribution function was done by some authors using probe techniques. The axial distribution of floating potential along the tube has been observed by Maciel and Allen (1985). In the ionospheric studies by Peterson et al (1981) it was observed that the distribution function may be found by using data taken by probes whose dimensions are small compared with the Larmor radius. Stenzel et al (1983) enunciated a technique for measuring the distribution function in a laboratory plasma. They used a microchannel plate whose smallest dimension was small compared to the Larmor radius. In this technique current had been collected by the probe at various geometric orientations and the data had been unfolded by a computer. A method was presented by Eremeev and Novikov (1982) for calculating the distributed parameters of a partially ionised gas in the vicinity of electric probes of spherical and cylindrical shapes, in the presence of collisions between the charged components and the neutral background.

An extensive investigation on the measurement of electron temperature and electron density in low temperature plasmas in air, hydrogen, and nitrogen with the help of cylindrical probe has been carried out by Sadhya, Jana and Sen (1979), in this laboratory. Recently Karamar (1987) measured electron density and temperature in the space of the electron beam with the help of Langmuir double probe. He also extended his measurements concerning the energy in an energetic electron beam in the vicinity of the focus of the beam.

For the practical use of Langmuir probe in deposition plasma Felts and Lopta (1987) measured the electron temperature and plasma density of different depositing plasmas as function of power, pressure and flow using double floating cylindrical type electrostatic probes and compared the results using Laframboise's theory. They also found that probes are a useful tool for characterizing sputtering and polymer forming plasmas.

Diffusion process in plasma:-

It is known that the number of electrons in the positive column plasma is controlled by the loss to the walls of the discharge tube. Since the current is constant along the positive column and is carried largely by the electrons, the loss of electrons to the walls must be balanced by corresponding gain from ionization within the column. The production of electrons throughout the interior of the column and their higher diffusion rate cause a radial distribution of the electron density which is highest at the tube axis and lowest at the walls. This electron density distribution produces a radial electric field that influences the radial movement of the electrons and ions. The electron diffusion rate is slowed down and the ion rate is enhanced by the presence of this electric field. If the mean scattering length of the charged particles is small compared to the tube radius, an ambipolar diffusion coefficient can be defined. This coefficient describes the rate at which ions and electrons diffuse while satisfying the quasi-neutrality condition $n_e \approx n_i$. The result is that the ions and electrons diffuse together at a rate which is twice that for the free diffusion of ions. The radial distribution of ions and electrons is given in terms of the ambipolar diffusion coefficient D_a as

$$n = n(0)\, J_0\left(r\sqrt{\nu_i/D_a} \right) \qquad \ldots(1.3)$$

where $n(0)$ is the electron density at $r = 0$ where r is the radius of cylindrical column and J_0 is a Bessel function of zero order which for small values of $R\ (\nu_i/D_a)^{1/2}$ has a nearly parabolic dependence on r, i.e.

$$J_0(r) \approx 1 - (r/2)^2$$

where ν_i is the electron ionization frequency.

If the recombination rate at the walls is high, the electron density at that radius $r = R$ is essentially zero, So

$$J_0[R(\nu_i/D_a)^{1/2}] = 0$$

and it has the solution

$$R(\nu_i/D_a)^{1/2} = 2\cdot40, \text{ or } \frac{1}{\nu_i} = \frac{R^2}{(2\cdot40)^2 D_a} \qquad \ldots(1.4)$$

The term $1/\nu_i$ is the average time between ionizations. This time must equal the average time required for an electron to migrate to the wall, and this is what the right hand side of eqn.(1.4) represents.

Kosinar et al (1979) calculated the electric field, potential and charged particle concentration in a plasma sheath at an infinite electrically non-conducting plane. In the sheath, electrons were assumed to be distributed according to the Boltzmann law and the ions are accelerated in the sheath field and collide with the gas molecules.

Experimental measurements of the character of plasma diffusion was presented by Dremin and Stefanovskii (1979). It was noted that modulation of the curvature and torsion in such a system leads to the appearence of specific particle groups, analogous to the super-traped particles in the stellarators with helical windings. The method of determining plasma life times was discussed and results were used to calculate the diffusion coefficient of the plasma.

A new technique for temperature measurements in plasmas was described by Gouesbet and Valentin (1980). Its principle was to use the thermal diffusion of light particles added to the plasma as tracer.

Miyoshi and Ariyasu (1980) studied the energy distribution of electrons in hydrogen gas discharges. The energy distribution in the discharge was assumed as a balance between two processes. The first was an energy loss on collision between electron and molecule and the other was an energy gain from an electric field. The authors studied the relation between energy distribution and the discharge current, voltage and gas pressure etc. Experimental results were compared with those calculated by using the Boltzmann equation.

A method was proposed by Golubovskii (1981) in which the electron energy distribution function can be determined from probe current measurements at high pressure than are usually considered. The kinetic theory of electron current in a probe was developed for a diffusional regime, and it was shown that if the probe dimensions and the thickness of the discharges layer fulfil certain specific conditions, the distribution function is proportional to the first differential of the probe current with respect to probe potential.

In the ionospheric studies by Peterson et al (1981) it was observed that the distribution function may be found when dimensions are small compared to, or of the order of the Larmor radius of the particles being collected. Zasedka and Reztsov (1982) showed that spatial distribution of the electric field strength coincides with the spatial distribution of electron concentration and distribution of space charge density coincides with distribution of the electron concentration gradient.

A new technique has been developed by Kaya (1982) for the measurement of electron temperature. Its working principle may be stated as follows:

At two different potentials electron current is collected by the probe and measured, and the difference of the two potentials is proportional to the electron temperature. Sen, Ghosh and Ghosh (1983) measured electron temperature in glow discharge with the help of two probes (one at the axis and other at a short distance from the axis of the cylindrical tube in the same cross sectional plane). They measured diffusion voltage and determined electron temperature with previous knowledge of radial electron density profile.

Using probe measurements Maciel and Allen (1985) observed the axial distribution of floating potential along the tube.

An early problem of the transition from free to ambipolar diffusion of electrons has been re-examined by Dote (1985). Starting from the classical flow equations for electrons and positive ions and the continuity equations for charged particles, the authors have obtained a general characteristic equation of effective diffusion coefficient for electrons, where the results due to Allis have been corrected. The transition characteristics calculated from the above general equation have been extremely concrete and practical. Finally, this approach has been applied to glow discharge and an example of the characteristics has been presented as a function of plasma density for various values of electron temperature.

1.2. Measurement of diffusion coefficient of electrons in plasma.

Diffusion is a phenomenon in which charged or uncharged particles move from points of high concentration to those of low concentration. Considering the process of diffusion as due to collision of electrons with atoms it can be shown that the diffusion coefficient of electrons can be calculated to be

$$D_e = \frac{v_r \lambda_e}{3}$$

where v_r is their mean random velocity and λ_e the mean free path of the electrons. Terloud and Rietjens (1963) measured the diffusion coefficient of a highly ionized cesium vapour plasma by means of Langmuir probes and microwaves transmission. The results are compared with calculations in which the diffusion coefficient is assumed to be inversely proportional to the ion density. They observed that the decay of the electron temperature is more rapid than can be expected on the basis of elastic collision losses. When the density is decreased to an extent where collisions of ions with atoms becomes predominant, the diffusion coefficient becomes independent of n_i where n_i is the ionic concentration.

Crompton and Sutton (1952) experimentally determined the value of diffusion coefficient in case of nitrogen and hydrogen. They used two diffusion chambers with different dimensions, each was mounted in a pyrex glass envelope. One chamber was constructed of nichrome with a central disk of radius, $b = 0.5$ cm., height $h = 1.0$ cm. and annulus of outer radius $c = 1.5$ cm. whereas in the other the metal was silvered brass and a further division was made in the collecting electrode so that $b = 0.5$ cm. or 1 cm., $h = 2.0$ cm., $c = 2.6$ cm. A manometer using Apiezon oil of measured density was used to measure the pressure of the gases inside the chamber. The necessary voltages for the electrodes of the diffusion chamber were obtained from a stabilized d.c. power supply with a voltage divider across the output, which could be varied from 0 to 300 V. They found the value of diffusion coefficient $D = 1.34 \times 10^5 \, cm^2 sec^{-1}$ for hydrogen at

$$\frac{E \text{ (electric field)}}{P \text{ (Pressure)}} = 0.05 \, V/cm.$$

and drift velocity $v_d = 2.0 \times 10^5$ cm/ sec.

For nitrogen the value of $D = 3.69 \times 10^5 \, cm^2 sec^{-1}$ for $E/P = 0.05$ and $V_d = 2.4 \times 10^5$ cm/sec. Crompton and Sutton (1952) calculated the value of D for different values of E/P and v_d for both the cases.

An experimental investigation of the electron temperature dependence of the ambipolar diffusion coefficient and electron ion recombination coefficient in the afterglow of plasma produced in neon has been made by Hess (1965). By means of a microwave cavity technique the electron density was measured as a function of time during the afterglow period of a d.c. discharge while at the same time the electron energy was increased by the power level of a microwave signal. It was found that the ambipolar diffusion coefficient D_a increases with increasing electron temperature T_e following the relation:

$$D_a \propto (1 + T_e/T_g),$$

while the recombination coefficient decreases with increasing electron temperature. Shimahara and Kiyama (1969) measured the diffusion coefficient of a plasma by the correlation of density fluctuation. An investigation was made by Kando et al (1972) in which anomalous diffusion coefficient changes in an axially decaying collisional plasma when the main mode of the instability is suppressed by the feedback technique.

Using microwave diagonostic technique in a afterglow discharge Mentzoni (1964) measured the rate of diffusion for the low current discharge. He obtained

$D_a P = 110 \pm 10\ cm^2 sec^{-1}$ and for high current discharge $216 \pm 20\ cm^2 sec^{-1}$ at pressure below 1 mm. Hg.

1.3. Measurement of electron atom collision frequency in an arc plasma by radio frequency coil probe in presence of a longitudinal magnetic field.

In plasmas continuous scattering of each particle to new directions and velocities by other particles due to many body interactions of different types occur. But these being very complicated processes it is difficult to make a quantitative analysis. However, to classify them and to find out which of them is relatively more effective, it is possible and useful also to find the statistical average of these effects.

In plasmas there are different types of collision between the particles viz.

1. Collisions among neutral particles,
2. Collisions among charged particles, and
3. Collisions between neutral and charged particles.

The collision frequency ν is the product of the number density of the colliding particles, the collision cross section and the mean value of the relative velocity. In our present investigation collisions between neutral and charged particles are taken into account to determine collision frequency in an arc plasma.

Though probe method is used for the measurement of electrical conductivity of a plasma it is not adequate due to formation of a cold boundary around its structure in case of hot plasma according to Lin et al (1955) and so unable to provide proper information on the conductivity. It is also noted that probe method is not suitable in flowing plasma, plasma jets and field free plasma. But the coil probe technique is in general a suitable means to measure conductivity.

The magnetic field linked with a solenoidal r.f. electric field induces solenoidal current into the plasma under investigation and the effect is reflected back into the probe coil; this is the fundamental principle of a r.f. coil probe diagonostic technique. Hence sometimes this method is termed an induction or magnetic flux method.

An experimental observation was made by Lin, Resler and Kantrowitz (1955) for the measurement of electrical conductivity of highly ionised argon from the search coil (probe)pick up of electromagnetic disturbances produced by the passage of shock waves through it. By solving an integral equation of the first kind with the response function $V_{l}(S-\xi)$ as the Karnel, where $S \longrightarrow$ the position of shock front with respect to the probe at a given time and $\xi \longrightarrow$ the axial coordinate of any point with respect to the shock front, the conductivity distribution $\sigma(\xi)$ (axial) could be determined. During each shock large signals were found to pass through the search coil, when a steady magnetic field was put off. According to them it was due to electrostatic effects. But it was pointed out by Ghosal, Nandi and Sen (1976) that this effect was due to stray capacitance effect. In fact those pick ups were due to the formation of finite capacitance between the search coil and the gas inside the shock tube. Lamb and Lin (1957) obtained identical results. Lin et al (1955)eliminated these effects by designing a centre tapped search coil arrangement.

An experiment was performed by Blackman (1959) to reduce the inductance of a coil wound around a plasma column by the shielding effect in the electrically conducting plasma. The frequency of a circuit has been changed by the reduced inductance. With the help of the above idea Savic and Boult (1962) devised a frequency modulation circuit to determine gas conductivity and boundary layer thickness in a shock tube.

Rosa (1961) made a different approach where the coil was embedded in the insulated wall of MHD generator and resonated into a condenser and the method yielded results on conductivity of the gas.

With the help of immersive method where the coil probe was kept inside the plasma, some authors viz. Moulin and Masse (1964), Stubbe (1968) and Jayakumar et al (1977) and Olson and Lary (1961, 1962, 1963) showed that the immersive method was more sensitive to variations in plasma conductivity than non-immersive method. On the contrary, Donskoi, Duaev and Prokif'ev (1963) adopted a non-immersive type method to estimate electrical conductivity of heated gas streams. The technique rested on the measurement of electrical circuit parameters, effective inductance, circuit resistance, Q-factor, mutual inductance etc. of tank circuit.

The results of electrical heat conductivity derived from the Boltzmann equation with Grad's method of orthogonalized moments retaining the coupling between diffusion and heat fluxes had been expressed by Suchy (1985). These are calculated for Coulomb interaction potentials screened with the Debye - Huckel length.

The electrical conductivity of the conducting medium however, was determined by Koritz and Keck(1964) from a measurement of Joule Losses produced by alternating magnetic field of a coil surrounding it. In this regard a number of authors viz. Tanaka and Vsami (1962), Gourdin (1963) Khvashchtevaski (1962) made a conductor approximation for plasma which means that when an alternating electrical voltage is impressed upon it, the plasma is considered to offer no resistance and a.c. conductivity essentially becomes the d.c. conductivity. They argued that if the change in magnetic flux linked with a coil, when plasma is in its core, be measured, it may be possible to estimate d.c. conductivity for a range of frequencies. They put an expression for a.c. conductivity

$$\sigma_{a.c} = \frac{ne^2}{m\nu}\left(\frac{\nu^2}{\nu^2+\omega^2} - j\,\frac{\omega\nu}{\nu^2+\omega^2}\right)$$

where m and e are the electronic mass and charge, n the electron density, ν the electron atom collision frequency and ω is the angular frequency of the r.f. field imposed. The imaginary term corresponds to inherent plasma reactance developed due to mass inertia.

Tanaka and Hagi (1964), however, projected the effect of inductance change in a different way. If the plasma is conductive, the imposed radio frequency field may induce eddy currents and will dissipate energy in the region where they flow. As a result the magnetic flux will be screened off from the region. Hence it will cause a reduction in the effective inductance of the net work and will result in a shift in resonance frequency. Though all the active coil probe experiments discussed so far utilise the shift in either inductance or resistance of the coil probe due to plasma in one way or other, experimental results have been explained theoretically from different approaches leading to some exclusiveness of each problem.

Akimov and Konenko (1966) scrutinised the validity of the two similar coil probe techniques for determining plasma conductivities and discussed various possibilities. They gave stress on the works of Blackman (1959) and Donskoi et al (1963); their observations are also useful to the study of electrical conductivity from a shift in resonance frequency or quality factor Q of the coil within which plasma is kept. In contrast to the prediction of Tanaca and

Hagi (1964), the test object in the coil may change the oscillator frequency for some ranges of conductivities. Hausler (1957) and lateron Ghosal, Nandi and Sen (1976) showed that the shift in frequency is due to the capacitative effect of the test object on the coil. A conductor in the vicinity of a coil increases its stray capacity as a result of which the oscillator frequency decreases. Actually plasma conductivity averaged over the cross sections differ from calibrating curves, due to radial nonuniformity of the plasma. However, Ghosal, Nandi and Sen (1978) asserted that even if the skin depth is much larger than the plasma tube radius, the disagreement is expected to exist since coil probe technique gives information on moments of conductivity distribution of different order.

With the help of either immersive or non-immersive probes many workers as well as Hollister (1964), Murino and Bonoma (1964) determined the average (bulk) conductivity, because in every case the test plasma was radially nonuniform. Ciampi and Talini (1967, 1969), investigated the interaction of solenoidal electric field in conjunction with radially nonuniform plasma in a very generalised way. They put forward an equation for a radial profile of conductivity as

$$\sigma(r) = \sigma_0 \left[1 - m\left(\frac{r}{R}\right)^n\right] \quad \ldots(1.5)$$

In the analysis however, the authors only considered a low frequency approximation whose displacement current has been ignored and hence for the radio frequency, conductivity becomes the d.c. conductivity. With a prior knowledge of conductivity profile, a measurement of m & n from equation (1.5) at any frequency provides the value of axial conductivity σ_0. This observation was however valid for limited range of frequencies. In this range the above measurement for the unknown plasma and for a homogeneous medium of conductivity $\bar{\sigma} = h\sigma_0$ gives the same result. Hence with connection to resistive or inductive measurement plasma simulates a homogenous medium and according to authors $\bar{\sigma}$ can be interpreted as a spatial average conductivity. Thus two averages σ^* and σ^{**} were obtained according to the resistive and inductive measurements respectively as given below:

$$\sigma^* = \frac{4}{R^4}\int_0^R \sigma(r)\,r^3\,dr$$

$$\sigma^{**} = \frac{3}{4}\left[\frac{4}{R^4}\int_0^R \sigma(r)\,r^3 dr\right]^2 + \frac{3}{4}\,\frac{6}{R^6}\int_0^R r^5 dr\left[\frac{4}{r^4}\int_0^r \sigma(r)\,r^3 dr\right]^2$$

With the help of measured Q factor and a calibration curve to find the first average conductivity σ^* Ciampi and Talini (1967) carried on an experiment in a flow facility plasma. Later on they (1969) elaborated their theory and measurement to incorporate the collision frequency. Ghosal, Nandi and Sen (1976, 1978) also pointed out that the expression of the two meaningful averages (σ^* and σ^{**}) and the relevant frequency and conductivity ranges could be obtained in a simpler way. The authors performed an experiment where they utilised a probe coil technique and concluded that the conducting medium forms a transformer where the primary and the single turn secondary are the coil and the conducting medium (plasma).

Ghosal, Nandi and Sen (1976) pointed out that, the loss of r.f. power of the resonant circuit due to the presence of plasma column within a coil was affected by two factors (i) eddy current loss and (ii) capacitative by pass. With the help of a composite equivalent circuit the authors concluded that the reflected resistance in the primary due to the eddy current flowing through the plasma is significant in the arc region and obtained an expression for effective resistance R' as

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

where R_0 is the radio frequency resistance of coil, ω the angular frequency, M, the mutual inductance and R_1 is the mutual plasma resistance. Taking the plasma to be of uniform conductivity, the authors obtained an expression for the azimuthal conductivity

$$\sigma_s = \frac{\pi(\alpha - 1)}{\ell \omega^2 M^2} R_0$$

where α a dimensionless quantity denoting the ratio of the radio frequency current in absence and in presence of the discharge and 'ℓ' is the equivalent length of the coil inductance formed between the coil and the plasma. In their next paper, however, they pointed out that an arc cannot be considered as a uniform medium from the point of view of conductivity and charge density. They started with a generalised radial conductivity distribution and determined experimentally a quantity which is a function of the assumed conductivity and determined experimentally a quantity which is a function of the assumed conductivity distribution. With a consideration of 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 for this annular cylindrical plasma under the above condition has been shown to be $\omega^2 M^2(r)/R(r)$, 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. They provided an expression for the reflected impedance as

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

where $\sigma(r)$ denotes the azimuthal conductivity of the plasma at a distance r from the axis. Hence the total effective impedance becomes

$$R' = R_o + \frac{\omega^2 \ell}{2\pi}\int_0^R \frac{M^2(r)\sigma(r)}{r}\,dr \qquad \ldots(1.6)$$

where R is the tube radius. Here $M(r)$ can be simplified as $M(r) = Kr^2$ where K is a constant which depends on the number of terms of the primary coil. Accordingly eqn. (1.6) can be reduced to

$$\alpha - 1 = \frac{\omega^2 K^2 \ell}{2\pi R_0} \int_0^R r^3 \sigma(r)\, dr \qquad \ldots(1.7)$$

And further

$$\int_0^R \sigma(r) r\, dr = I / 2\pi E \qquad \ldots(1.8)$$

where I is the arc current and E is the axial voltage drop per unit length. Using eqn. (1.7) and (1.8)

$$\frac{\int_0^R r^3 \sigma(r)\, dr}{\int_0^R r\sigma(r)\, dr} = \frac{\alpha - 1}{f^2 K^2 \ell} \; \frac{E}{I} R_0 \qquad \ldots(1.9)$$

where f is the frequency of the radio frequency current.

Ghosal et al (1978) assumed $\sigma(r)$ to be of the approximate form

$$\sigma(r) = \sigma_0 \left[1 - \left(\frac{r}{R}\right)^2\right]^n \qquad \ldots(1.10)$$

where n is a constant. From eqn. (1.9) and (1.10)

$$n = \frac{R^2}{a} - 2$$

where $a = \frac{\alpha - 1}{f^2 K^2 \ell} \frac{E}{I} R_o$ ...(1.11)

And from eqn. (1.8) and (1.10) the expression for axial conductivity is

$$\sigma_o = \frac{I/E}{2\pi} \frac{2(n+1)}{R^2} \qquad ...(1.12)$$

Ghosal, Nandi and Sen (1978) also obtained the identical result as given by Ciampi and Talini. Gantait (1988) performed experiment to observe variation of σ_o with arc tube radius, and obtained that σ_o decreases exponentially with the increase of R. An emperical relation of σ_o with R has been given

$$\sigma_{o(R)} = \sigma_{o\langle R \rightarrow o \rangle} \exp(-\beta R).$$

where β is a constant and $\sigma_o\langle R \rightarrow o \rangle$ the axial conductivity at $R \longrightarrow 0$.

It is to be noted that on the basis of average conductivity model [Stokes (1965, 1969)] the nature of conductivity profile could not be obtained from the Q factor measurement alone. The profiles of the type treated by Ciampi and Talini (1967), the difference between the azimuthal average and the axial conductivity can be as much as a factor of 5 and if the profile constants m and n are varied indefinitely the aforesaid factor may be extremely larger. The selection of the profile demands that the plasma fills the available volume and it may be approximate for an ordinary discharge plasma but may not be true for other situations such as flow facility plasma, plasma jets, metal arc etc. where the errors may become higher as the plasma conductivity may vanish at some distance away from the (tube) wall.

Moskvin and Chegnokova (1965) measured temperature on an argon plasma; they found a peak conductivity of roughly 3000 mho/m, falling approximately to zero at a radius 33 mm. Stokes (1969) theoretically calculated the azimuthal average that should be measured for the Moskvin-Chesnokova plasma stream assumed to be exhausting along a 2 cm. diameter tube. This is given to be approximately 100 mho/m, It is observed that the axial conductivity is 30 times higher than the apparent average.

Uramoto (1970) described a method for determining the electron-neutral collision frequency in a low density plasma. In the experiment the author used a radio frequency signal of constant frequency and voltage applied between plane probes while the density is varied to determine an antiresonance point. The above method is sensitive to external circuit impedance and avoids the perturbing effect of the strong r.f. field at resonance. Ghosal, Nandi and Sen (1978) estimated the azimuthal average $\overline{\sigma}_{\phi}$, volume average $\overline{\sigma}_{vol}$ and the axial conductivity σ_{o} of mercury arc discharge and found that axial conductivity can be ten times the aximuthal average value.

Effective collision frequencies in a weakly ionized turbullent plasma had been measured by Spence and Roth (1986) using resonant absorption of an extraordinary wave, propagating across a plasma column. They measured the attenuation and phase shift of a transmitted wave in a swept frequency measurement using an HP8510 network analyser.

Expressions were obtained by Pleshanov (1968) for longitudinal and transverse conductivity and an anisotropy angle for anon-quasi neutral plasma. It was shown that the transverse conductivity of such plasma is finite in super high magnetic field and consequently the specific power output may be unlimited, in contrast with the case of quasineutral plasma which has a finite output.

Pytte (1969) developed a method for the calculation of the conductivity tensor, including collisional contribution associated with a wave in a plasma in a magnetic field. The author calculated electron current contribution in terms of Landau collision. Nicol et al (1971) determined the collision frequency and collision model in flame plasmas by means of magnetic field dependent microwave absorption and dispersion. They used acetylene-oxygen and acetylene-air flames burning through an x-band wave guid resonator parallel to the microwave electric field vector and perpendicular to an external magnetic field to study electron cyclotron resonance. The authors found that the absorption and dispersion are slowly decreasing functions with the magnetic field strength. It was also observed that the collision frequency amounts to 210 ± 4 GHz for the acetylene-oxygen flames and 249 ± 4 GHz for the acetylene-air flames.

Seashottz (1971) performed an experiment on "effect of collisions on Thomson scattering in a magnetic field with unequal electron and ion temperatures and electron drift". The author observed that collision frequency decreases when magnetic field influence is reduced.

1.4. Plasma parameters from diffusion voltage measurements both in transverse and longitudinal magnetic field.

The effect of a magnetic field on the breakdown condition of a gas was calculated by Wehrli (1922) and obtained that λ , the mean free path of the electron assumed constant for all the electrons changes to λ' as in presence of magnetic field the electrons describe a cycloidal path.

$$\lambda' = \lambda\left[1 - \frac{eH^2\lambda}{8Em}\right] \qquad \ldots(1.13)$$

where e is the charge and m is the mass of the electron, H is the magnetic field in gauss and E is the voltage per unit length of the tube. The author concluded that the effect of magnetic field is equivalent to an increase of pressure P_e to P_{eH} where

$$P_{eH} = \frac{P_e}{\left[1 - eH^2\lambda/8Em\right]} \qquad \ldots(1.14)$$

where P_e is the effective gas pressure. By taking electron energy and drift velocity into consideration, Blevin and Haydon (1958) derived a new expression for equivalent pressure and showed that a transverse magnetic field effectively increases the gas pressure from P_e to P_{eH} so that

$$P_{eH} = P_e \left(1 + C_1 H^2 / P^2 \right) \qquad \ldots(1.15)$$

where $C_1 = \left(\frac{eL}{mv_r}\right)^2$ involving random velocity distribution of electrons is assumed constant within certain limit of H/P. From the concept of equivalent pressure, the variation of Townsend's first ionization coefficient in a transverse magnetic field can be explained in high (E/P) region in which the distribution of electrons is assumed to be Maxwellian with a constant average collision frequency. Haydon et al (1971) critically analysed the velocity distribution for electrons in presence of magnetic field and found it not to be Maxwellian, so that in case of application of the concept of equivalent pressure for electron behaviour in gases like hydrogen as studied by the authors, the collision frequency is required to be taken as energy dependent. Heylen and Bunting (1969) formulated an equivalent reduced electric field concept in a constant electric field. In transverse magnetic field, the transverse and perpendicular mobilities and their ratio for electrons have been explained assuming Maxwellian velocity distribution.

The average electron collision frequency was observed to vary with electron energy. In case of molecular gases such as oxygen, air and nitrogen the results were experimentally verified.

The mobility of electrons in the direction of the electric field in presence of a magnetic field is reduced and Townsend and Gill (1937) obtained

$$\mu_H = \frac{\mu}{1+\omega_H^2 \tau^2} \qquad \ldots(1.16)$$

where $\omega_H = \frac{eH}{mc}$ and τ represents the time between two successive collisions. In presence of magnetic field Blevin and Haydon (1958) deduced an expression for mobility by considering the bulk properties of electron avalanche and is given by

$$\mu_H = \frac{\mu}{1+C_1 H^2/P^2} \qquad \ldots(1.17)$$

The eqn. (1.17) was verified experimentally by Sen and Gupta (1964) by computing the values of electron mobility in air discharge in presence of magnetic field and over a wide range of pressure.

The effect of magnetic field on electron mobility in a d.c. arc plasma was studied by Hasem(1984) and he showed that the decrease of electron mobility in the magnetic field may be due to hindering of the upward motion of excited particles (ions, excited atoms, and molecules) in the magnetised plasma.

Ecker and Kanne (1964) studied theoretically the effect of a transverse magnetic field on a cylindrical plasma column. In the formulation of the basic equation to describe the collision dominated positive column in a transverse magnetic field, Ecker and Kanne calculated the expression for electron temperature under the assumption that electron heat conduction is small in comparison to collision (elastic) losses and the energy conservation law (for electrons) balances the energy gained in the electric field with energy loss due to collisions with neutral particles. For this balance equation in a real plasma Ecker and Zöler (1964) put a criterion as

$$\lambda_e < 2R\gamma^{1/2} \qquad \ldots(1.18)$$

where λ is the mean free path (electrons) R is the discharge tube radius and γ is the fractional loss of electrons in an elastic collision. This condition is not achieved in normal discharge and appeared in practice only in case of high current and relatively high pressure discharge (arc). The authors investigated the problem mainly for two cases: firstly collision free limit where Langmuir theory of free fall is valid and secondly in collision dominated region where Schottky's ambipolar diffusion theory applies. They found that magnetic field does not change the temperature in the collision dominated discharges and gave a linear perturbation treatment taking small values of magnetic field.

Marchetti et al (1984) used a self consistent mode coupling theory to calculate the coefficient of self diffusion in a three dimensional classical one component plasma subjected to an external magnetic field. They found a Bohm like behaviour for asymptotically large fields for diffusion in the plane perpendicular to the magnetic field.

(B) Diffusion in longitudinal magnetic field:

If a magnetic field acts parallel to the axis of the positive column, the effective diffusion coefficient Da is reduced to

$$D_b = D_a / \left(1 + \frac{\omega_{ce}^2}{\nu_c^2}\right)$$

Here $\omega_{ce} = \frac{Be}{m}$ and ν_c is the electron collision frequency. Thus it is evident that as the magnetic field is increased, the rate of electron diffusion is decreased. In a longitudinal magnetic field, the ions being more massive will be less constrained then electrons from radial diffusion. However, the electric field created by radial distribution of the electrons still tends to restrain the ions. Thus the ions as well should diffuse at approximately the same rate as those of electrons.

The 'normal' distribution both for electrons and ions is not altered when it is subjected to a longitudinal magnetic field. Tonks (1941) approximated the dispersal effect along a plasma column in longitudinal magnetic field. Radial electron and ion distribution's solution is the sum of a series of zero order Bessel functions. The 'normal' distribution along the length of the positive column remains unchanged in the first term, while successive terms decrease with distance along the column at rates which are complicated functions of T_e , the electron temperature and the magnetic field strength, H. Davies(1953) also found that the electron velocity distribution in longitudinal magnetic field is Maxwellian. An investigation was carried by Vorobjeva et al (1971) in mercury vapour arc subjected to an axial field ($H \leq$ 800 Oe) and found that Maxwellian distribution holds good for electron velocity. The energy gained by electrons in electric field balanced by losses in elastic collision is not fulfilled in case of low pressure diffused mercury arc, according to Ecker and Zöler (1964) as observed from Ellenbaas - Heller heat balance equation. On the otherhand, Ghosal, Nandi and Sen (1979) showed that for such a discharge, the energy consumed by the discharge is lost primarily in ionising collisions and a major part of ionising particles is lost through ambipolar diffusion to the wall of the discharge tube. There is some inadequacy in defining an arc. But for some criteria of arc such as (a) relative high current density, (b) low cathode fall, (c) high luminosity of the column defined by Pfender (1978) dominate the discharges in a low pressure mercury arc. Generally, in these discharges, the volume ionization is balanced by diffusion of charged particles. Inspite of diffusion, recombination of charged particles plays a vital role in their loss mechanism. Recombination becomes more significant than diffusion in an active discharge for the high value of electron temperature with respect to ion temperature. Hoyaux (1968) enunciated that normal ambipolar diffusion prevails for the column which is sufficiently long with respect to its radius at low magnetic fields. But above a certain magnetic field, plasma turbulence progressively sets in and leads to an abnormal loss of particles and an increase in voltage drop. There are two known types of diffusion: (1) In low pressure region Langmuir free fall diffusion is effective and (2) in high pressure region Schottky's ambipolar diffusion is dominant. Franklin (1976) described an ion fluid model relating the two domains in the transition region. A balance between particle loss and generation processes predicts the determination of electron temperature.

Franck et al (1972) carried on an experiment to determine electron temperature T_e in longitudinal magnetic field. He found that when a longitudinal magnetic field is superimposed on a low pressure plasma, reversal of the radial ambipolar electric field takes place at a definite magnetic field B_r. He found the value of electron temperature from the value of B_r. Marhic and Kwan (1977) found that both electron temperature and electron density change. From radiation profiles vander Sijde (1972) found change of temperature and density profile for a hollow cathode argon arc in axial magnetic field ($H \leq 1250$ G). In a longitudinal magnetic field Wienecke (1963) found an increase of pressure in the hot region of a cylindrical symmetric arc. The author observed that the forces exerted by the field on charged particles modify diffusion current and hence field.

The electron diffusion across and along the field becomes anisotropic and reduction of radial diffusion results due to application of magnetic field on a cylindrical plasma column. The plasma adjusts to this new situation by decreasing its ionization frequency which is determined by electron temperature and hence the change of electron temperature occurs. So a reduction of diffusion loss results due to decrease in electron temperature or axial electric field. Considering Langmuir free fall model Self (1967) estimated the influence of longitudinal magnetic field on a cylindrical plasma column. Also, taking the ion fluid model Franklin (1976) investigated the properties of cylindrical plasma subjected to an axial magnetic field, and his investigation is applicable both in high and low pressure regions. He showed that ambipolar diffusion will be reduced by the application of a longitudinal magnetic field due to the reduction in radial diffusion of charged particles.

Geissler (1970) observed the disagreement between experimental data and ambipolar theory in case of a finite length of cylindrical column with non-conducting walls and placed in an axial magnetic field in high pressure region. The diffusive decay of a weakly ionised gas in a finite length cylinder having non-conducting walls was analysed by

Chekmarev et al (1977) in presence of longitudinal magnetic field and observed that ambipolarity of diffusion exists in magnetic field too. Previously, Franck et al (1972) pointed out how the magnetic field influences the ambipolar diffusion.

Electronic and ionic diffusion reduce when a magnetic field is increased. The variation of electron and ion diffusion across a magnetic field can be shown classically as

$$D_{e,i1} = \frac{D_{e,i}}{1 + b_{e,i} H^2} \quad ...(1.19)$$

where $b_{e,i}$ is the square of the mobility of respective species. The electron diffusion is reduced more than ion diffusion, as the electron mobility is large than ion mobility by a term 10^2 to 10^3 at a given pressure. Due to increase of magnetic field the radial component of electric field vanishes for $D_{e1} = D_{i1}$ at a particular magnetic field H_r. While studying the problem of plasma instability, the anomalous behaviour of plasma column in longitudinal magnetic field has been studied mostly in noble gases. Hoh and Lehnert (1960) studied the influence of longitudinal magnetic field in hydrogen, helium and krypton, confined in non -

conducting and long discharge tubes, so that the diffusion can be neglected at the ends. They found that the radial diffusion across the axial magnetic field decreases classically upto H_{cr} and above H_{cr} the diffusion increases with magnetic field. An interpretation of anomalous behaviour of diffusion has been given by Kadomtsev and Nedospasov (1960) by considering an instability in the form of helical wave which will be created by axial electric field for high values of magnetic field. This instability enhances the effective ambipolar diffusion with increasing magnetic field by $E \times H$ drift which pushes the electrons to outward radial direction and amplify the diffusion. H_{cr} is calculated from the measurement of pressure. Janzen et al (1970) observed in neon gas that the instability depends on the length of the discharge tube. No instability is observed in short length ($L \leq 15$ cm.) discharge tube. In case of long discharge tubes Deutsch and Pfau (1976) observed an anomalous increase of diffusion in noble gases in weak discharges and in presence of axial magnetic field ($H \ll H_{cr}$). Sato (1978) interpreted the same results as that of Deutsch and Pfau in terms of self excited ionization waves.

In axial magnetic field there is another weak instability in quiescent plasmas. This instability is known as drift dissipative instability according to Timofeev (1976). These instabilities are regarded as high current convective instabilities for active discharges.

The problem of longitudinal diffusion of electrons in a plasma in an external magnetic field was solved by Sestak and Forejt (1986) in case of electron ion plasma and that of a plasma of identical particles by Bychkov et al (1980) who analysed the relation between the energy dependence of the elastic scattering cross section of the electron and the kinetic coefficients of electrons moving in a gas in a constant electric field. They computed the relation which depends upon the electron velocity distribution function. The representation obtained is used to establish the energy dependence of the elastic scattering cross section of the electron and to calculate diffusion coefficient in presence of longitudinal magnetic field.

In this laboratory Sen and Jana (1977) investigated the current voltage characteristics of glow discharge in presence of axial magnetic field. They observed that the discharge current increases with the increase of magnetic field for the range of pressure

0.685 torr to 0.925 torr. The results showed that the radial distribution of electron follows zero order Bessel function and is valid in magnetic field also. Considering the physical processes involved in a mercury arc discharge taking air as buffer gas Sadhya and Sen (1980) described a model in which air behaves as a quenching gas. They obtained the distribution function of both types of ions (atomic and molecular) and developed an expression for T_e/T_{eH}, where T_e is electron temperature without longitudinal magnetic field and T_{eH} is electron temperature with longitudinal magnetic field. The experimental results were in quantitative agreement with theoretical deduction within the range of (H/P) values studied.

Cohen and Sultorp (1984) calculated the longitudinal self diffusion coefficient for a magnetised plasma considering the kinetic theory in the weak coupling approximation.

1.5. Radio frequency breakdown of gases in presence and in absence of magnetic field.

Ionisation and subsequent breakdown of a gas subjected to uniform a.c. field differ in many important aspects from ionisation and subsequent breakdown by uniform d.c. field. The charged particles in the bulk of the gas are accelerated when a high frequency or microwave electric field is imposed across a gas. It is well known that electrons are always present in a given volume of a gas due to cosmic radiation; and through these electrons the transfer of energy from the applied electric field of any kind to the volume of the gas results. The electrons are accelerated much faster than ions because of their lighter mass and as a result, the energy transferred from the imposed electric field to the electrons is so much larger that we can neglect the motion and subsequent effects on the heavier particles. In an ac field, the direction of the force on the electron alters and the electrons will oscillate within the bulk of the gas provided the vessel-walls are sufficiently far apart. It is the prime feature that characterises high frequency or microwave discharges from low frequency or d.c. discharges.

Actually at high frequencies and in the absence of any gas atoms, the electrons would oscillate out of phase with field and no energy would be transferred. But in presence of gas atoms electrons accelerated by electric field collide frequently with the gas atoms and hence change the phase condition. It results a net transfer of energy from the field to the electrons and electrons lose energy by collisions with the gas atoms. However, in a favourable situation an electron may gain sufficient energy to exceed the excitation energy level of the atom and lose most of its energy. It results in subsequent radiation when it returns to its ground state. It is noteworthy that the electrons lose energy not only by elastic collisions but also by inelastic collisions. The resulting energy distribution of electrons may produce sufficient number of electrons having energy comparable to ionization energy of the gas atoms so that they may ionise the atoms. When this occurs we have multiplication of electrons and the process may be a cumulative one. It is also very important to note that the electrons at the same time may undergo loss due to diffusion to the walls, recombination with the positive ions, or by attachment to neutral atoms or molecules. A balance equation of these productions and loss rates determines the electron density of the steady state discharge and it in turn characterises the electrical properties of the same. If the electric field is sufficiently large, the electron density attains very large value with a luminous glow in the bulk of the gas and hence causes breakdown of the gas.

The general characteristics of the breakdown curves have been investigated by several workers. Gutton and Gutton (1928) determined the potentials between external electrodes required to start the discharge in hydrogen at low pressures with oscillations of wavelengths between 3 to 5620 meters whereas Krichner (1930) utilised internal electrodes for breakdown purposes. Townsend and Gill (1938) considered only the motion of free electrons in the gas under the influence of an alternating electric field ignoring wall and electrode processes and space charge effects. Thomson (1930) carried an extensive work on the electrodeless ring discharge and latter (1937) derived an elementary theory regarding each electron as oscillating about a mean position in the gas.

In order to ionise the gas electron must at some point in its trajectory attain enough energy for ionization and it must strike a molecule before it returns this energy again to the field. If $E_o \cos\omega t$

be the magnitude of the imposed field, the energy acquired in time 't' by an electron from the field must be equal to or greater than the ionization energy eV_i of the gas atom (V_i is the ionization potential of the gas atoms or molecules). According to the second criterion, the distance traversed by the electron in time t must be either equal to or smaller than the mean free path λ_e of the electron in the gas. Only those electrons which start with zero initial velocity and in zero phase of the applied field can participate in the motion.

Several authors found double minimum in the striking potential as a function of pressure. Gutton and Gutton (1928) characterised the double minimum as due to resonance phenomenon in the gas. Gill and Donaldson (1931) reported that when the field is directed along the tube only one minimum appears, but when it is across the tube, another minimum, at high pressure appears. According to them at high pressure the cloud of electrons oscillates with an amplitude less than the width of the tube, ionization in the gas being balanced by diffusion. On the contrary when pressure decreases, the electrons acquire more energy from the field out of their long free paths and hence the striking field slowly become smaller. However, the amplitude of electron oscillation becomes larger and larger and ultimately the amplitude becomes approximately equal to the distance between the walls. As a result, the loss of electrons increases sharply and a much greater field is necessary to initiate the desired discharge. Similar work had been reported in this context by Thomson (1937), Zouckerman (1940), Githens (1940), Chenot (1948) and Pim (1948, 1949).

Hale (1948) reported his measurements in argon and xenon over the range of 5 Mc/s. to 50 Mc/sec. and pressures varying from 20 to 50 micron. He pointed out that the breakdown field for high frequency field is determined by those electrons in the gas which succeed in acquiring ionizing energy in one mean free path. The value of the electronic mean free path is deduced from kinetic theory which entails some doubts. Actually an effective mean free path is needed in this case because the electronic mean free path changes with the energy of the electron and as the energy of the electron varies between zero and ionizing energy. Also the assumption that the probability of ionization becomes a maximum when the electron gains the ionizing energy is not supported by experimental results by Smith (1930). According to Smith (1930) the efficiency of ionization increases quite rapidly with increasing electron energies slightly above the ionizing energy.

From a different approach Gill and von-Engel (1948) carried on experiments where they measured the starting potential of a h.f. discharge as a function of frequency (wavelength) of the imposed field in gases at very low pressure, of the order of 10^{-3} mm. Hg. From these results Gill and von-Engel, put forward a theory of the initiation of the discharge. It is noted that the starting field is independent of the gas and the pressure, but depends upon wavelength of the applied field and the dimension and material of the vessel, although the fully developed discharge shows the spectrum of the gas.

Townsend and Williams (1958) studied the breakdown condition in air and hydrogen for values of p.d. = 15 mm cm of Hg and frequency 5 MHz to 70 MHz. They found double minima, the first minimum was not very sensitive to breakdown voltage and gas pressure as in lower frequency of the applied field.

Cooper (1947) carried on investigation in ultra-high frequency breakdown of air in coaxial lines and waveguides for separation between 0.1 cm and 0.3 cm and over the pressure range of 20 cm to 760 cm. It was found that the breakdown field to be 70% of the d.c. field at two wavelength namely 10.7 cm and 3.1 cm. Posin (1948) carried on similar experiment for 3.0 cm as Herlin and Brown (1948).

Brown and McDonald (1949) provided the theoretical interpretation and experimental investigation of breakdown of gases in cylindrical cavities and between coaxial cylinders at the wavelength of 9.6 cm. The theoretical interpretation is based on the criterion that at the point of breakdown ionization rate is equal to the rate of loss due to diffusion. Other electron removal processes namely attachment and recombination are considered to be negligible for the type of discharge. By analogy with the first Townsend coefficient for d c ionization where the electron loss is governed by mobility, the high frequency ionization coefficient is controlled by diffusion.

Holstein (1946) pointed out that the energy distribution of electrons in a h.f. field is closely the same as that of electrons in a static field equal in magnitude to the rms value of h f field. He interpreted the breakdown criterion having a general character introducing direct current analogy. He then obtained a relation between the breakdown field E, the gap length d and the gas pressure p as

$$(Pd)^2 = \frac{\pi^2 KT_e}{e(E/P)(\alpha/P)}$$

where α is the Townsend's first ionization coefficient, e and T_e the charge and temperature of electron and K is the Boltzmann constant.

Margenau and Hartman (1948) analysed the methods for determining the electron energy distribution theoretically.

Kihara (1952) introduced a molecular model for collision processes between gas molecules and charged particles and obtained an absolute expression for mobility coefficient, diffusion coefficient and electron temperature in terms of some molecular constants and some measurable parameters.

Taillet and Brunet (1965) investigated the physical mechanism of high frequency discharges - maintained by resonance. It is concluded that when a r f discharge is excited with a frequency $\omega/2\pi$ higher than collision frequency ν_c , a resonance due to dispersive properties of the plasma can control the steady state of the discharge and determine the value of the electron density for a given geometry and frequency.

In high frequency discharge, besides two general types of electron loss mechanisms (mobility and diffusion), there may be another type of loss mechanism due to formation of negative ion in some gases. Negative ions appear in gases under two conditions:

(i) They may be generated in the bulk of the gas through attachment of free electrons to atoms and molecules (largely and through dissociation of molecules in a polar phase of electron impact).

(ii) They may appear in the gas by interaction of fast particles of atomic mass with surfaces or by liberation from hot surfaces. Attachment of electrons causes loss of the former as ionising agents which in turn enhances the rate of carrier loss by recombination.

In a series of works Loeb (1921, 1923, 1924) worked out the possible theories of formation of negative ion from electron and neutral molecules.

The breakdown of gases by h f electric fields in conjunction with a steady constant magnetic field has also been investigated by Townsend and Gill(1938) who calculated the effect of magnetic field on the h f breakdown of a gas in a magnetic field.

In discharge vessels, where the electric and magnetic field are in the direction of the axis of the tube, the rate of diffusion of electrons to the surface of the tube is diminished by the action of the magnetic force and hence the breakdown field decreases. If the electric and magnetic fields are perpendicular to each other, not only diffusion is decreased, but for certain value of magnetic field and applied frequency resonance will occur (when $\omega = \omega_b$, the electron cyclotron frequency). Actually it indicates that the magnetic field reverses the direction of electrons, without loss of energy, as the imposed electric field reverses. Although the magnetic field supplies no energy to the electron, it nevertheless changes its direction so that the electron may acquire energy from the electric field provided that the motion is not frequently interrupted by collisions with gas molecules.

Townsend and Gill (1938) tested experimentally the theoretical investigation by measuring the electric field required to start a discharge in dry air in a large spherical bulb 13 cm in diameter in presence of transverse magnetic field. They performed the above experiment at 30 MHz and 48 MHz and over the range of pressure from few micron to 240 microns. A decrease of starting field was found for values of pressure less than the minimum without magnetic field and increase of starting field for values of pressure greater than that at which the breakdown voltage become minimum when the magnetic field was employed. Brown(1940) carried on some extension of the similar work to the case of hydrogen and reported similar results therein.

Lax, Allis and Brown (1950) performed experiments and explained theoretically the breakdown voltage of a gas excited by a microwave field in presence of transverse magnetic field. They used helium gas containing a small admixture of Hg vapour and obtained breakdown curves for different values of pressure. The breakdown voltage becomes minimum for a magnetic field which is independent of the pressure of the gas.

Ferritti and Veronesi (1955) determined breakdown voltage in air using cylindrical electrodes at 10 MHz and 30 MHz.frequencies varying magnetic field from zero to 800 gauss. The pressure of the gas was maintained at 0.1 mm, 0.5 mm and 10 mm Hg. and in all sets of observation breakdown voltage decreased in presence of magnetic field.

Deb and Goswami (1964) investigated the electrical breakdown in a high frequency electrodeless discharge at low pressure subjected to a steady magnetic field and pointed out that with increase in α the ratio of cyclotron frequency to the frequency of the applied field, the breakdown field tends to increase and the main region of the curve is displaced towards longer wavelengths.

Bengall and Haydon (1965) investigated the pre-breakdown ionization in nitrogen gas to show that the influence of a transverse magnetic field is equivalent to an increase in the gas pressure from p to $p_{eH} = p\,(1 + \omega_B^2/\vartheta_C\ \ )^{1/2}$ where ω_B is the electron cyclotron frequency and ϑ_C is electron molecule collision frequency.

In a coaxial resonator in the presence of longitudinal magnetic field Ivanov and Gavrilova (1972) carried on investigation of high frequency single electrode discharge. They pointed out that under certain conditions the losses due to high frequency single electrode discharge become large and are governed mainly by the secondary emission coefficient of the electrode material and by the ratio of frequencies ω and $\omega_b (= eH/m)$.

Grollean (1974) studied high frequency resonance discharge in hydrogen in static magnetic field. It was shown experimentally that the gas pressure, the amplitude of the electromagnetic field and the angle between the direction of the static magnetic field and the discharge axis are the most important parameters.

Though a fairly large amount of work in resonance magnetic field was reported, little work has been done so far in which non-resonant magnetic field is employed. Sen and Ghosh (1963) investigated the breakdown in air and nitrogen in crossed non-resonant magnetic field using the radio frequency field of frequency 8.1 MHz and 7.15 MHz respectively over the pressure range of few microns of Hg to 500 microns of Hg. They obtained a family of curves for different steady magnetic fields whose values lie within 100 gauss. It was noticed that each curve, for a steady crossed magnetic field, has got a minimum breakdown voltage at certain pressure which shifts to higher pressure as the magnetic field is increased. An increase of breakdown voltage was also observed on the imposition of perpendicular magnetic field. Sen and Gupta obtained the breakdown characteristics in non-resonant magnetic field varying from 0 to 120 gauss in helium, neon and argon and obtained the same results as Sen and Ghosh (1963), the frequency of the applied h f field was 4 to 12 MHz. With the help of theory by Kihara (1952) for breakdown of gases by radiofrequency field and equivalent pressure concept introduced by Blevin and Haydon (1958) with the variation of mobility and diffusion coefficients in a magnetic field, an expression for the breakdown voltage of gases by r.f. field was developed by Sen and Ghosh (1963) to explain their experimental results.

Sen and Bhattacharyya (1969) calculated the values of α/P at different E/P values from the r.f. breakdown measurements in case of air, oxygen and carbondioxide within the pressure range 1 to 6 mm of Hg and in transverse magnetic field from 0 to 1800 gauss.

It was noticed that the α/P values calculated from Brown's theory of diffusion controlled breakdown are in better agreement with the results obtained in the literature than those calculated from Kihara's theory. Kumar et al (1971) studied the breakdown phenomenon of air in presence of axial magnetic field over the pressure range 5 to 115 mtorr.

Ram and Sarkar (1971) investigated the r f (16 MHz) breakdown characteristics of argon in presence of low (0 to 180 gauss) longitudinal and high (100 to 1500 gauss) non-resonant transverse magnetic field. But in transverse magnetic field the breakdown voltage was found to increase upto a certain magnetic field and decreased with increase of magnetic field above 40 mm Hg.

Sen and Jana (1977) established the validity of diffusion theory in radio frequency breakdown in molecular gases in axial magnetic field.

Radiofrequency breakdown characteristics at 55 MHz frequency of air have been studied in the presence of a parallel low intensity magnetic field over the pressure range of 5 to 15 mtorr by Kumar et al (1971). The breakdown potential has been found to decrease with increase in magnetic field. This decrease is much prominent at the lowest pressure. It has also been found that the variation of breakdown potential with pressure shows broad minimum in low magnetic field. This change becomes almost linear beyond 80G. Thus an appreciable reduction in diffusion loss of electrons under the above mentioned condition has been observed experimentally.

Bhattacharyya and Das (1974) studied the breakdown potential in air over the pressure range of 50 to 300 micron under the simultaneous action of an r f (5.7 MHz) and a variable transverse d c field (0-30 V/cm). The breakdown potential is always higher than that in the absence of d c field for all values of pressure and the pressure at which the breakdown voltage becomes minimum always shifts to higher pressures with the increase in the d c field. It is assumed that electrons are lost not only by diffusion but also due to mobility due to application of d c field. Bhattacharyya and Das (1977) investigated the variation of breakdown potential of dry air, oxygen and hydrogen using r f electric field (6.2 MHz) over the range of gas pressure 0.5 to 8.0 torr also in presence of uniform (350 G, 500 G) transverse magnetic field. The theory of breakdown using high frequency electric field has been modified for crossed r f electric and steady magnetic fields to explain the results.

Bhattacharyya and Das (1982) investigated the variaton of radio frequency (8.9 MHz) electric field breakdown of gases like air, hydrogen and oxygen for gas pressures of 0.25, 0.5 and 0.3 torr respectively, in the presence of transverse magnetic field varying from 0 to 3000 gauss. For each gas a minimum value of the breakdown field is found at a certain value of the magnetic field, both values being different for each of the three gases. In this investigation they obtained a second breakdown field of much lower magnitude in a strong magnetic field when the electron cyclotron frequency is much higher than the electron - neutral collision frequency, both being much higher than the frequency of the applied field. By considering the average motion of the electrons in a very strong magnetic field, transverse to an electric field of small magnitude, linear relations are obtained between the second breakdown field and the corresponding magnetic field.

Recently Whang and Noh (1986) reported that breakdown of N_2 gas by 13.56 MHz electric field is very different from that under steady fields. The second order differential equation derived from the Boltzmann equation is used for the electron distribution function. The ionization rate and diffusion coefficient are calculated using kinetic theory. They conclude that the breakdown condition is that the number of electrons provided by ionization equates the number diffusing to the walls of the discharge vessel. They calculated the breakdown electric field using computer and compared the results with experimental values.

1.6. Spectroscopic investigation of the intensities of spectral lines in a plasma.

Spectroscopy is a very wide subject in itself, having well developed applications to nearly all categories of plasma research. The various methods of spectral diagnostics are based on established relationships between plasma parameters and radiation characteristics such as intensity, absorption coefficient and spectral line broadening. The spectral study of the radiations given off by a plasma can be a ready source of information about its state. However the spectroscopic technique is a more accurate diagonostic technique than dc probe method, r f probe method and microwave technique.

Plasma parameters viz. electron temperature and electron density of glow discharge can be determined from the relative intensities of radiation. Frequently relative measurements are not only technically simpler, but they are also the only possible means from the theoretical point of view.

In the absence of equilibrium, the population density of the first excited states is lower because of the emitted radiation; the concentration of free electrons and ions is lower than at equilibrium, for example, as a result of diffusion losses;

near the ionization limits of atoms and ions equilibrium assemblies of levels are formed (Saha's relationship is fulfilled beginning with the S-level of the atom and the t^+ level of the ion). Experimentally the following measurements are possible :

(a) relative intensity of two or more lines;

(b) relative intensity of atom and ion lines or lines from ions of different charge;

(c) relative intensity of the continuum at two wavelengths;

(d) relative intensity of lines and continuum.

Formulae for determining the plasma temperature by these methods are

(a) $$\frac{I_p}{I_s} = \frac{A_p g_p \lambda_s}{A_s g_s \lambda_p} \exp\left(-\frac{E_p - E_s}{KT}\right);$$

(b) $$\frac{I_p}{I_s^+} = \frac{A_p g_p \lambda_{s^+} Z_+ n_o}{A_{s^+} g_{s^+} \lambda_p Z_o n_+} \exp\left(-\frac{E_p - E_s^+}{KT}\right);$$

(c) $$\frac{I_{K1}}{I_{K2}} = \frac{\xi_1}{\xi_2} \exp\left[\frac{hC(\lambda_2 - \lambda_1)}{\lambda_1 \lambda_2 KT}\right];$$

(d) $$\frac{I_p}{I_{K2}} = 2{,}15 \cdot 10^{10} \frac{A_p g_p}{\lambda_p \xi_2} \cdot \frac{n_o}{n_e n_+} T^{1/2} \exp\left(-\frac{E_p}{KT}\right)$$

The accuracy of the temperature determination is the higher the greater the energy difference

$$\Delta T/T = (KT/\Delta E)[\Delta(I_1/I_2)/(I_1/I_2)]$$

Theoretically, the accuracy of the measurements is a minimum for method (a), a maximum for method (b).

For practical realization some modification are to be considered.

1) With method (a) it is sometimes possible to select lines, that are similar in wavelengths, intensity profile and this increases the accuracy of the measurement.

2) Method (b) is applicable only in the limited temperature range where one can match atom and ion lines of comparable intensity.

3) With method (c) it is necessary to compare sections of the continuum which differ strongly in wavelength and intensity and this creates some difficulties, furthermore, the values of the factor ξ are rarely known with high precision;

4) Method (d) is convenient only in that it allows to select a line and the adjoining continuum for measurements. However, in many instances the intensity of the continuum is small, or the accuracy with which its absolute value is known, is insufficient.

The local thermodynamic equilibrium model(LTE) and corona equilibrium model (CE) are the main two models of equilibrium plasma. In LTE model, a unique temperature exists in plasma which determines the velocity distribution function for electrons. The analysis of the state of the plasma is particularly simple in this equilibrium since it is only such local plasma parameters as electron density, electron temperature and composition that determine the relevant populations. Collisional processes are usually more important in establishing LTE than radiative processes, since most plasma of interest are optically thin to internal radiation (except perhaps for the resonance lines). Consequently collisional de-excitation rates must exceed radiative decay rates for true LTE. According to Boltzmann distribution law energy of every particular kind is distributed over all particles in the gas and Saha equation is the result in case of ionization in this equilibrium. In equilibrium plasma it is possible to apply methods (a), (c) and (d). Method (b) requires the use of some model for an equilibrium population distribution, for example the model of coronal equilibrium, which is valid at low n_e.

By using $n_e \geqslant 10^{14} E_2{}^3 (KT)^{1/2}$ [for the equilibrium population of the first (and higher) excited states (excitation energy E_2) with respect to the ground state] , it is possible to determine the minimum energy (equatum number) of the level beginning with which methods (a) and (d) are applicable. A decrease in the range of population equilibrium decreases the value of ΔE , that can be utilized in measurements. If the continuum intensity is not very large (precisely in this case it is frequently necessary to deal with non-equilibrium conditions, since intensity $I_e \sim n_e{}^2$ and nonequilibrium increases with lower n_e), large values of ΔE can be obtained with method (d). In fact Park (1968) described the spectral line intensities to determine the electron temperature in a nonequilibrium nitrogen plasma. In this work the relative populations of excited states of atomic nitrogen in a collision-dominated nonequilibrium plasma for given ratios of nonequilibrium ground state number density and given electron temperatures consisting of atoms, single charged ions and electrons are calculated by the method of Bates, Kingston and Mcwhirter (1962).

From the resulting populations, the spectral intensities of two prominent visible lines are calculated assuming the plasma to be optically thin for these lines. It is shown that with the exception of a decaying plasma at temperatures greater than $8000^{o}K$, the calculated nonequilibrium intensities disagree with the equilibrium spectral line intensities that would be conventionally employed to determine the temperature of a plasma in equilibrium. Gruzdev et al (1974) investigated an He plasma with high ionization at atmospheric pressure for the investigation of equilibrium establishment. They showed that for a laboratory plasma with ionization $\chi > 0{\cdot}1$ at atmospheric pressure and T_e 3000^{o} - $4000^{o}K$ ionization equilibrium is not achieved due to the unbalanced radiative decay of the resonance state of He 1 resulting an its overpopulation and under population of He III.

To investigate the temperature dependence of spectral lines intensity emitted by thermal plasma, Bielski (1966) presented the temperature dependence of atom, ion and electron concentrations and provided a graphical method of determining the temperature T_m at which the intensity of a spectral line reaches a maximum value under condition when the sum of atom and ion concentrations is constant (independent of temperature). This method can be applied to the lines emitted by atoms and ions of any multiplicity of ionization. Another investigation has been made by Pacheva et al (1970) to measure electron temperature in a hollow cathode discharge tube by the method of relative line intensities. An analytical method developed by Gratreau (1973) which provides a simultaneous determination of both electron temperature T_e and density n_e of a dense plasma by using time - resolved relative spectroscopic measurements of lines from He-like and H-like ions.

Griem (1964) calculated the number density of electrons to obtain complete LTE. The expression of electron density is given by

$$n_e \geqslant 9\times 10^{17} (E_2/\chi_H)^3 (KT_e/\chi_H)^{1/2} \text{cm}^{-3} \quad \ldots (1.20)$$

with E_2 the energy of the first excited and χ_H the ionization energy of hydrogen and K is the Boltzmann constant. Griem considered that the collisional excitation rate is ten times the radiative rate from that level for lowest excited state. Hey (1976) modified this criterion by considering finer values of Gaunt factor appearing in collisional excitation rate coefficient and incorporating the effect of metastable-metastable collisions.

Wilson (1962) provided an equation for LTE to be valid as

$$n_e \geqslant 6 \times 10^{13} \chi_i^{3} (KT_e)^{1/2} \, cm^{-3} \quad \cdots (1.21)$$

χ_i is the excitation energy of atom in eV. From these criteria, Elton (1970) has given a single criterion for electron density necessary to maintain complete LTE in the discharge tube as

$$n_e \geqslant C (KT_e)^{1/2} \chi_i^{3} \, cm^{-3} \quad \cdots \quad (1.22)$$

where C is a constant equal approximately to 1.4×10^{13}, assuming complete trapping of resonance lines and 1.4×10^{14} assuming no trapping whatsoever.

LTE can be expected to hold for stationary and spatially homogeneous plasmas, if collisional processes with electrons obeying Maxwellian distribution dominate in the rate equations. The principal quantum numbers of states for which radiative decay and collisional excitation rates are comparable often exceed a critical value but radiative decay rates decrease with principal quantum number. In these circumstances it is logical to relate density states above the critical level with each other and in the same way to electron density in a complete LTE system. Richter (1968) showed that the ground level is over-populated by a factor, though the occupation number for states over this critical level are as in LTE with temperature, T_e. Due to this reason the critical level is in partial LTE. With quantum number p for a level, the electron density in partial LTE approximated by Griem (1964) is

$$n_e \geqslant 7\times10^{18}\ \frac{Z^7}{p^{8.5}}\left(KT\grave{e}/\chi_H\right)^{1/2}\ \mathrm{cm}^{-3} \quad \dots (1.23)$$

here Z is the charged state of atom. This estimation is valid only for hydrogen ions. For other atoms, p is identified as effective quantum number of the level defined as

$$P_{eff} = Z\left(\frac{R}{T_\infty - T_p}\right)^{1/2} \quad \dots (1.24)$$

where R is Rydberg constant, T_∞ is the ionization limit, T_p is the temperature value of the level p and for neutral atoms Z = 1. Introducing semi-emperical formula of excitation rate coefficient, Drawin (1969) corrected eqn. (1.24). Fujimoto (1973) considered LTE on the basis of a collisional radiative model for hydrogen ions which is identical with that enunciated by Griem.

LTE does not prevail in low electron concentration. It is possible to obtain equilibrium here whereby the collisional excitation and ionisation is balanced by radiative decay and recombination respectively. Solar corona is an example of this kind of equilibrium (CE), so is known as corona equilibrium (CE) model. In CE, the allowed spectral lines emitted from the population of an excited level is governed by collisional excitation from ground level as it is the faster process than the spontaneous radiative decay. For all excited levels CE to be valid is given by Wilson (1962) as,

$$n_e \leq 1.5 \times 10^{10} \chi_i^{-0.5} (KT_e)^4 \text{ cm}^{-3} \quad \cdots (1.25)$$

Wilson also described a semi-corona (SC) domain when CE is valid except for levels close to ionisation limit.

The criterion for SC domain in case of ions without metastable levels is

$$n_e \leq 10^{11} \chi_i^{1.5} (KT_e)^2 \text{ cm}^{-3} \quad \ldots (1.26)$$

Another condition for CE has been proposed by Mcwhirter (1965) and Fujimoto (1973) interpreted CE in terms of a collisional radiative model. It is necessary to mention that when all the above criteria do not apply for an actual plasma, all of the collisional and radiative rate processes are to be considered for a particular level. In transition region (fromSC to partial LTE) this is important. Fujimoto (1979) adopted this transition region through quasi saturation phase by ladder like (stepwise) excitation mechanism.

The following two assumptions are made to handle spectroscopic problem easily.

(A) Optically thin plasma is taken because the radiation generally treated in terms of optical path and the absorption of radiation is negligible. Both for CE and LTE light sources above 10,000^{o}K are transparent in the central parts of the line [except for resonance line (Lochte-Holtgreven, 1968)] .

(B) The electrons are assumed to obey Maxwellian distribution for simplification. In spectroscopic methods a knowledge of electron energy distribution function 'f' is involved directly in the collision integrals. An equilibrium of Maxwellian type velocity distribution is established by the collisional effects of free electrons in an active plasma.

But due to the presence of electric field in the discharge or elastic collisions of electrons, this equilibrium may be destroyed. The distribution function $f(\vec{r},\vec{v},t)d\vec{r}d\vec{v}$ denotes the number of electrons at position $\vec{r}$ in $d\vec{r}$, with velocity $\vec{v}$ in the range $d\vec{v}$ at time t. This function satisfies Boltzman transport equation in which the rate change of the number of electrons in $d\vec{r}$ $d\vec{v}$ is equal to the net flow of electrons into this volume element. From the velocity of electrons, the flow in position space occurs. On the otherhand acceleration due both to collision with gas atoms and the applied electric field can be derived from the velocity space. For that reason the distribution function is taken almost spherically symmetric in velocity space to avoid mathematical complexity.

Thus the Boltzman equation is solved and the distribution function of unknown form is obtained numerically by taking first two terms of an expansion in spherical harmonics. In case of high ionization plasma, the solved distribution function differs a little from a Maxwellian one. But von-Engel (1965) assumed that the energy distribution of electrons in a gas moving in an electric field is approximately Maxwellian in nature. In case of small degree of ionization the socalled non-Maxwellian interactions of electrons with other particles result in elastic and inelastic collisions. Thus energy exchanges between charged, excited and neutral particles takes place due to these collisions and conversions between potential and kinetic energies occur. These energy transformations effect the distribution function, 'f'.

For inelastic collisions, it is the electrons in the tail of the distribution that participate in energy exchange. In case of low temperature plasma, some high energetic electrons in the tail is lost due to inelastic collisions. The functional nature is not altered for non-ionised bulk electrons. This phenomenon led von-Engel (1965) to consider energy distribution to be Maxwellian (mainly for helium gas).

In case of free electrons obeying Maxwellian velocity distribution, Elton (1970) framed up four criteria as follows:

$$t_{ee} \ll t_{ff}\, ,\, t_{eh}\, ,\, t_{part}\, ,\, t_{inel} \qquad \ldots(1.27)$$

For a specific experiment, the energy relaxation time for colliding electrons, T_{ee} must be less than:

(1) t_{ff} , the energy decay time for free processes,

(2) t_{eh} , the characteristic electron heating time,

(3) t_{part} , the characteristic time for particles, and lastly,

(4) t_{inel} , the relaxation time for electron impact including atomic processes such as excitation, ionization etc. The radiation of plasma is increased, when the number density is high so that criteria (1.27) are fulfilled. Griem(1964) described that the laboratory plasmas that emit enough light for spectroscopic observations are sufficiently dense and long lived so that electrons velocity distribution at any instant of time and at any point in space is Maxwellian.

In the investigation of plasma diagonostics Evans (1974) enunciated that plasma parameters can be deduced from radiation generated within it and emitted, or from the changes undergone by radiation introduced into the plasma but derived from an independent source. He found that the distribution of electrons amongst the possible levels in a population of excited atoms or ions immersed in plasma is determined by collisions with other particles and by radiation processes. The local thermodynamic equilibrium (LTE) model and the steady state corona model are used to predict the electron distribution.

The use of an optical spectrographic system in the study of a CF_3H plasma process has been investigated by Frieser et al (1980).

Golovistskii et al (1987) determined the plasma discharge parameters of gas mixtures containing helium in narrow tubes by spectroscopic technique. They come to the conclusion that a significant advantage of spectroscopic methods for plasma diagonostics over probing technique is the fact that all spectroscopic measurements are done in a non-contact fashion and are done without disturbing the plasma at all. The proposed spectroscopic method is suitable for quite a wide group of plasmas in which the only condition is that the plasma be optically thin for the helium lines whose lower levels are metastable. If the concentration of metastable helium atoms is somehow measured by self absorption for example, then this method becomes universal. A significant achievement of this method is also the fact that it can be applied for plasma diagonostics to any gas discharge devices, which lack any adaptations for plasma diagonostics.

1.7. Dependence of spectral intensities on arc plasma

To interpret results obtained from some typical plasma light sources as examined by common spectroscopic instruments, some knowledge about atomic parameters such as oscillator strength, line width and continuum emission coefficient are needed. The classicial treatment of light absorption by harmonic and anharmonic electron oscillators had led to definition of a dimensionless constant, absorption oscillator strength, f_{lu} expressing the absorptive power for each characteristic frequency as a fraction of the total absorptive power of the electron. The expression for f_{lu} has been given by Kuhn (1964) as

$$f_{lu} = A_{ul} \left(g_u / g_l \right) / 3\gamma$$

where $\gamma = 8\pi^2 e^2 / 3mc\lambda^2$

where A_{ul} denotes transition probability and g_u and g_l levels are statistical weights of upper and lower levels. The statistical weights are related to the inner quantum number of a level

$$g_L = 2J_L + 1$$

and to the quantum number of a term

$$g_M = (2L+1)(2S+1)$$

Another factor, self absorption, plays a vital role in determining the intensities of spectral lines. Cowan and Dieke (1948) explained that the self absorption within a gas layer of uniform excitation temperature has the effect of levelling out all intensity differences. This often causes serious difficulties in determining the ratios of strength of spectral lines in multiplets and hyperfine multiplates.

Self absorption is by no means restricted to absorption lines i.e. lines connected with the ground level. Also lines whose lower state is metastable often show marked self absorption or even self reversal. In quantitative studies of spectral line profiles it is essential to take self absorption into consideration.

Measurements have been made by Fowler and Duffendack (1949) regarding the intensity of radiation from the low voltage arc in helium as a function of gas pressure, tube current and tube potential. The experimental results indicate that the radiation is the result of a primary electron process and this process has been generally assumed to be direct.

From the experiment of Fowler and Duffendack (1949) it is evident that the line intensities depend on arc current linearly. In previous experiment Duffendack and Koppius (1939) investigated the variation of intensity with abundance in gas mixtures. Over the range in densities investigated, the curves were found to be of the saturation type. This saturation was interpreted as the complete utilization of available primary electrons in inelastic impacts direct excitation being regarded as the source of the radiation. A new spectroscopic method of high pressure arc diagnostics has been described by Teh-Sen. Jen (1968). In this investigation general properties of the resonant line spectral profile emitted by high pressure arcs are investigated. The shape of the strongly broadened and greatly reversed profile is studied using the computed Dlines profiles from sodium d.c. arcs and the relationship to the key plasma parameters has been established. It is found that the relative intensities at the lateral peaks of the resonant profile are proportional to the corresponding intensities in the Planck spectrum for an effective central temperature T_e. This T_e is uniquely related to the actual central temperature with only slight dependence upon the shape of the temperature profile.

Ovechkin et al (1969) calculated the mean optical density indicated by Bartels' model using graphs of relative intensities as a function of distance. The slope of all curves is similar and points to a proportionality between the line width and the square root of the distance from centre. The mean optical density of plasma decreases with the reduction of Cu atom concentration when the self attenuation mainly takes place in the source central zone.

Emission in the near ultraviolet from transient arcs between gold electrodes carrying arc currents in the range 0.8 - 1.75 A was studied by Boddy et al (1969). Analysis of the intensities of the Au I lines was carried out in terms of a model involving two distinct zones. There is intense emission from the second positive system of nitrogen. Temperature of the order of 6000°K is obtained from the analysis of the rotational fine structure of the (0,0) band. In another investigation, the radial temperature distributions are measured spectroscopically for the current range of 5 - 570 Amp. in steps of between 5 and 50 amp. by Schade (1970) in case of cylindrical nitrogen arc (1 atom, 5 mm Ø). At the highest current of 570 Amp. the temperature attains a maximum 26000°K corresponding to a degree of ionization of 11.5%.

Auzinya et al (1979) described a spectroscopic method for measuring the temperature in an argon and air arc at atmospheric pressure. Accuracy of methods for measuring temperature in an argon-air arc depends on concentration of argon. On the basis of obtained results, the method of measuring the temperature in an argon - air arc is determined.

Drouet et al (1986) measured the arc - current distribution at the anode in vacuum at low pressure. In this investigation the arc was triggered by a laser pulse between a 3 mm outer diameter copper cathod and a 90 mm outer diameter brass anode formed from nine concentric rings, connected to the power supply through individual current transformers to allow simultaneous monitoring of the current in each ring. Measurements are reported for arc currents of 58, 137 and 204 Amp. electrode separation of 10, 15, 25, 35 and 45 mm and gas pressures from 10^{-6} to 10 torr during current pulse between 0.025 and 1 ms.

Rocca et al (1981) discussed the effect of an axial magnetic field on the spontaneous emission from an argon hollow cathode discharge and variation of spectral intensity with discharge current. In their investigation the longitudinal magnetic field is shown to decrease the effective density of beam electrons in the negative glow.

In our laboratory Sen et al (1987) investigated experimentally the variation of intensity of mercury lines with discharge current varying from 2.5 Amp. to 5 Amp. under transverse magnetic field varying from zero to 1.6 KG. The increase was found to be linear. The increased intensity shows a minimum around 200 - 250 G, but for smaller values of arc current, the effect of magnetic field is more prominent.

1.8. Investigation of glow discharge plasma subjected to the discharge of a bank of condensers.

Analysis of wire explosion phenomenon by electrical and optical method has been utilised by many authors. Nevodichanski et al (1968) considered the axial light emission of plasma created during an electrical explosion of thin metallic cylinders. It is shown that depending on the pressure, the intensity curve of the light emission from plasma shows a series of local peaks which are either due to the cumulative effect of converging shock waves or due to the pinch effect. Skowronek et al (1970) discussed the influence of plasma frequency on the light emitted by an exploding ionized gaseous filament. In their experiment a very dense and easily reproducible plasma was generated by the explosion of a thin pre-ionised gaseous column. The optical thickness of the discharge was measured by means of laser and the absorption coefficient was found to be higher than 18 cm^{-1}. The spectral brightness of the discharge is measured from wave lengths 0.2μ to 4.8μ. The instantaneous spectral distribution shows an abrupt drop in the near infrared at 1μ. This is interpreted as being due to the plasma frequency with a corresponding electron density of $(1 \pm 0.2) \times 10^{21}$ cm^{-3}.

Pinch effect of metal plasma obtained by exploding wire has been studied by Aycoberry et al (1962). Through a thin metallic wire a 1 μF , 100 KV capacitor was discharged with ringing frequency of 200 Kc/s. Pinch effect during the first micro seconds had been observed by exploded wire, and current and voltage were recorded by oscilloscope.

In the study of exploding wire phenomenon an electrolytic capacitor of large capacitance 400 to 500 μF charged upto several hundreds of volts was used as the source of energy by Iguchi and Kawamada (1967).

In 1962 Vitoviskii and co-workers reported that the soft X-ray was generated from wires exploded in vacuum. Handlestenerhag and co-workers (1971) observed that from exploding tungsten wires in vacuum X-rays were emitted. They showed that X-rays were emitted near the melting point of the wire. Vitkovitsky and co-workers (1962) explained that the emission of X-rays was due to the result of decelerated electrons initially emanated from the early onset of ionization. Qualitative explanation for the emission of hard X-rays was made by Stenerhag and co-workers (1971) by using a model based on thermoionic electron emission from the wire.

The duration times and the initiation mechanism of the restrikes of thin tungsten wires exploded in air was investigated by Vlastos (1968). He concluded that the restrikes of tungsten wires are always generated at the exterior wire explaining the dwell times of wire at high voltages. Vlastos's experimental arrangement consisted of a capacitor 9.6 μF, an inductance 26 nH and a resistance 13 mΩ. Coaxially symmetric exploding wire gap; a height of 150 mm, an outer diameter of 530 mm; an inner diameter of 500 mm and four symmetrically placed circular quartz windows with diameters of 70 mm. By utilising a specially constructed manipulator the wire could be mounted in the gap under vacuum. The gap was evacuated by a rotary vacuum pump with a displacement at speed of 9 m^3/h a oil diffusion pump with a capacity of 150 liter/sec. The final vacuum was found to be about 5×10^{-5} torr. The condenser bank charging voltage was measured by an ammeter connected in series with a resistance of 300 m$\Omega \pm 2\%$. The current was measured by a Rogowsky coil and a passive RC integrator. A probe with a rise time of about 2 n sec. was used for the current derivative. The rotating mirror streak camera of maximum resolution of 2.6 mm/μ sec. was synchronized with the voltage and current recordings. The Kerrcell shutter cameras had constant exposure time of 30 and 50 n sec. respectively. By means of simultaneous oscillographic recordings of the current and the signals from the monitors of the cameras, the exposure times were determined. The importance of Vlastos's observation was that due to mechanical or electrical properties of thin tungsten wires it produces a slow condenser banks at low voltages.

In case of glow discharge the enhancement of spectral line by shock waves was observed by Miyashiro (1984). In his investigation fast electric discharge is generated across a shock wave. The lower pressure around the cathode in front of the shock wave enables electrons to strongly diffuse radially and therefore the glow is maintained with little constriction even at high average pressure. Experimentally it is seen that the glow diameter, discharge fluorescence and current are enhanced by the shock wave.

Enhanced radiative temperature has been observed by Skarsgard et al (1969) at the plasma frequency in nearly Maxwellian helium afterglow plasmas. These measurements confirm the predicted bremsstrahlung emission from plasma oscillations generated by suprathermal electrons.

Enhancement of electrical conductivity in a gas was enunciated by August (1967). He performed an analytical and experimental investigation to investigate the plasma characteristics induced in air by alpha particle emissions for radioisotope material. Primary ionization caused by collisions produce sufficiently energetic electrons to cause secondary ionizations. Associated with these induced levels of electron energy are reduced probabilities that the freed electrons will be lost through attachment and dissociative recombination processes, thereby attaining an appreciable level of electrical conductivity in the gas. He estimated an average electron density through an ionized air layer adjacent to an alpha particle emitting surface having 2 millicurrents per inch^2 to be 10^9 - 10^{10} e/cm^3 and its graded distribution normal to the surface was also estimated.

The local dependence of the rise time of the emissive line intensities of Ne in a cylindrical hollow cathode has been measured by Yamashita et al (1980) as a step towards studying the mechanism of emission. The temporal change of the intensities at the central axis portion shows a clear initial peak enhancement and then a decrease to the stationary state.

The rise time of the intensity at the central axis portion is always a few microseconds faster than the edge portion.

Decker et al (1981) used fast 200 KV capacitor bank as a current source for a dense plasma focus. They described a fast high voltage, high impedance capacitor band designed as a current source for a dense plasma focus with a voltage of 200 KV, initial current rise 2 x 10^3 A/S, current rise time $\leq$ 500 ns and impedance 35 MΩ. The bank consists of 50 parallel storage modules which are connected by parallel plate transmission lines.

Scope and Object of the Present Work:-

In the present investigation both immersive and non-immersive diagonostic techniques have been adopted. We utilize (a) spectroscopic method, (b) r f coil and capacitor probe in conjunction with longitudinal magnetic field under the scheme of non-immersive diagonostic technique, and (c) single probe and (d) probes of different constructional geometry and different modes of insertion under immersive scheme.

Though a large amount of work has been carried out regarding breakdown of gases and consequent production of plasma, measurement of plasma parameters, waves and oscillations in a plasma and other allied problems, still the nature of some of the physical processes occuring in a plasma during the period of its formation and maintenance have not been adequately investigated. The physical processes occuring in the initiation and maintenance of an arc plasma are still not properly understood. Further the phase of transition from glow to arc should be investigated in order to develop a theoretical basis for the occurance of arc plasma. In this compilation some of the associated problems have been investigated.

(i) Measurement of plasma parameters in an arc by probe method

(ii) Measurement of plasma parameters in an arc plasma by diffusion voltage measurement.

In order to develop a generalized theory for the occurance of arc plasma and to investigate the transition of glow discharge to arc plasma experimental and analytical investigation has been undertaken by Sen and some of his research fellows (1973, 1976, 1978, 1979, 1980, 1985, 1986, 1987), during last few years. Actually to develop the theory for the occurance of arc plasma, a large collection of data regarding plasma parameters and their variation in a perturbing field is necessary. It is therefore, worthwhile to study whether the Langmuir single probe technique can be utilised for measurement of arc plasma parameters. This will also show the validity of Langmuir probe theory in the arc plasma region. Besides there is an important mechanism by which charged particles are lost in a plasma, and the process is known as ambipolar diffusion. Hence besides the experiment for Langmuir probe an experiment has been set up to measure the resultant diffusion voltage in an arc. The process of diffusion is basically connected with the radial distribution function of charged particles and an expression for the radial distribution function of conductivity in an arc plasma has been provided by Ghosal, Nandi and Sen (1978). The object is to analyse the experimental results by utilizing the new distribution function. This experiment can also show the validity of distribution function as proposed by Ghosal, Nandi and Sen (1978). This experiment may be extended in presence of different buffer gases, at different pressures and with different tube radii.

(iii) Measurement of electron atom collision frequency in an arc plasma by radio-frequency coil probe in conjunction with a longitudinal magnetic field:-

There are some standard methods for calculating the electron atom collision frequency in glow discharges but the corresponding results in case of an arc plasma have been little reported so far. The electron atom collision frequency is an important parameter and its variation with pressure and arc current will provide information regarding the collisional processes in an arc plasma. In carrying out this investigation it has been argued that an external magnetic field can be used as a probe.

Here the theory developed by Ghosal, Nandi and Sen (1976, 1978) regarding the radial distribution of conductivity of an arc plasma has been modified due to its tensorial behaviour when the arc is placed in a longitudinal magnetic field. A working formula has been developed to measure the electron atom collision frequency where the magnetic field has been used as a probe.

The present study is to explore 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 can be determined. The relevant theory has been developed taking the effect of radial distribution of conductivity into account.

(iv) Evaluation of electron temperature in transverse and axial magnetic field in an arc plasma by measurement of diffusion voltage:

In this laboratory Sen, Ghosh and Ghosh (1983) developed a method to evaluate the electron temperature in air glow discharge (pressure 1 torr) from the measurement of diffusion voltage taking the radial profile of charge distribution as Besselian. 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). In case of the arc plasma this technique has been utilized considering radial distribution of charged species as provided by Ghosal, Nandi and Sen (1978). Analytical expressions have been deduced to calculate the ratio T_{eH}/T_e where T_{eH} and T_e are electron temperature with and without magnetic field from measured values of diffusion voltages in presence of an external magnetic field. Further it has been observed by Sen and Gantait (1988) that the voltage current characteristics 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 the aim 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.

(v) Breakdown of argon under radiofrequency excitation in transverse magnetic fields.

The object in this section of the work is to study the physical processes involved when a gas breakdown under the simultaneous presence of a radio-frequency and a transverse magnetic field.

The breakdown characteristics of argon gas under radiofrequency excitation over a frequency range and for small H/P (ratio of magnetic field to gas pressure) values have been calculated on a theoretical model suggested by Hale (1948). Taking the concept of equivalent pressure into account in presence of magnetic field, breakdown voltage has been calculated as a function of frequency for different gas pressure and magnetic fields. On the basis of this model, it is also possible to calculate the minimum breakdown field (volts cm^{-1}) in presence of magnetic field without much mathematical complexity. The theory developed both from the basic equation of motion of electrons in presence of crossed electric and magnetic field and also by using the equivalent pressure concept in presence of magnetic field will help in understanding the processes involved in the discharge and also the range of validity of equivalent pressure concept.

(vi) Intensity enhancement of spectral lines with increasing of arc current in arc plasma:-

It has been shown by Sen and Gantait (1987) that the intensity of spectral lines increases linearly with the increase of current in a mercury arc but the rate of increase is different for different wavelengths. The phenomena has been explained by the principle of self absorption of the spectral lines as has been done in the case of glow discharge, by Sen and Sadhya (1985), who deduced a detailed mathematical analysis to explain the results. In order to extend the results in case of other metallic arcs and to investigate whether it is the case in general, the present investigation has been undertaken.

An analytical expression for the ratio of intensity of the spectral lines with increasing arc current has been deduced assuming self absorption which predicts results in close agreement with those observed experimentally. In this experiment it is proposed to show how self absorption plays a dominant 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. This work can however be extended in case of vacuum arcs where pressure can be monitored systematically.

(vii) Investigation of glow discharge plasma subjected to the discharge of a bank of condensers:-

Discharge of a series of bank of condensers charged to high voltages has been utilised to create a transient high density plasma in a rarefied gas. The phenomena has been ascribed to the process of thermal ionization. Little work has been reported when a bank of condenser discharges take place through a steady state discharge. The object is to study how the physical processes are affected and how the plasma parameters change when the glow plasma receives a transient burst of energy. A spectroscopic method has been adopted for measurement of the intensity of spectral lines in a glow discharge when a bank of condensers discharges through it. A quantitative measurement of electron density and temperature is made in air and hydrogen glow raised to highly conducting condition by discharge of the bank of condensers. It is also noteworthy to state that this work can be performed in different gases with a broader interest of transient plasma heated to a very high value of electron temperature.

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CHAPTER II

THE EXPERIMENTAL SET UP.

2.1. Introduction:-

In this dissertation experimental observation and theoretical interpretation of some of the physical processes occuring in the glow and arc discharge plasma both in the absence and in the presence of either transverse or longitudinal magnetic field have been undertaken. In this investigation the plasma parameters of the glow (excited by ac and rf sources) and arc discharges have been estimated utilizing different techniques, electrical and spectroscopic under immersive and non-immersive probe schemes.

For the study of plasma behaviour we utilise the positive column of the discharges excited by ac and rf discharges, low pressure mercury arc and metal arcs in air with three different types of electrodes (i) silver-silver, (ii) copper-copper and (iii) iron-iron.

To study the effect of magnetic field a low pressure plasma with a low input energy has been taken, because plasma transport properties will be more influenced by the magnetic field as in low pressure discharge the mean free times of the plasma species are large. It is also worthwhile to note that in case of low pressure arc, before any set of observations is made, a steady state of the discharge has initially been achieved, there after the plasma parameters under interest have been investigated.

2.2. Discharge tubes&arc tubes:

Discharge tubes used in experimental measurements were constructed of pyrex glass. For glow discharge measurements the tubes were fitted with steel electrodes to minimize the sputtering yield. The external voltage has been applied to two circular parallel plate electrodes for breakdown. All arc tubes in which experiments have been carried out are also made of pyrex glass. The arcs have been produced between two mercury pool electrodes (fitted with two tungsten wires for external electrical connections) by a 250 volt dc source from a d c generator. Fig. 2.1 shows the design and construction of all arc tubes used in the laboratory. They are fitted to simple traps so that the mercury vapour going out of the discharge tube could condense smoothly and could return to the tube. Otherwise, it was observed that mercury would condense in the connecting rubber tubes and a mercury plug would be formed in

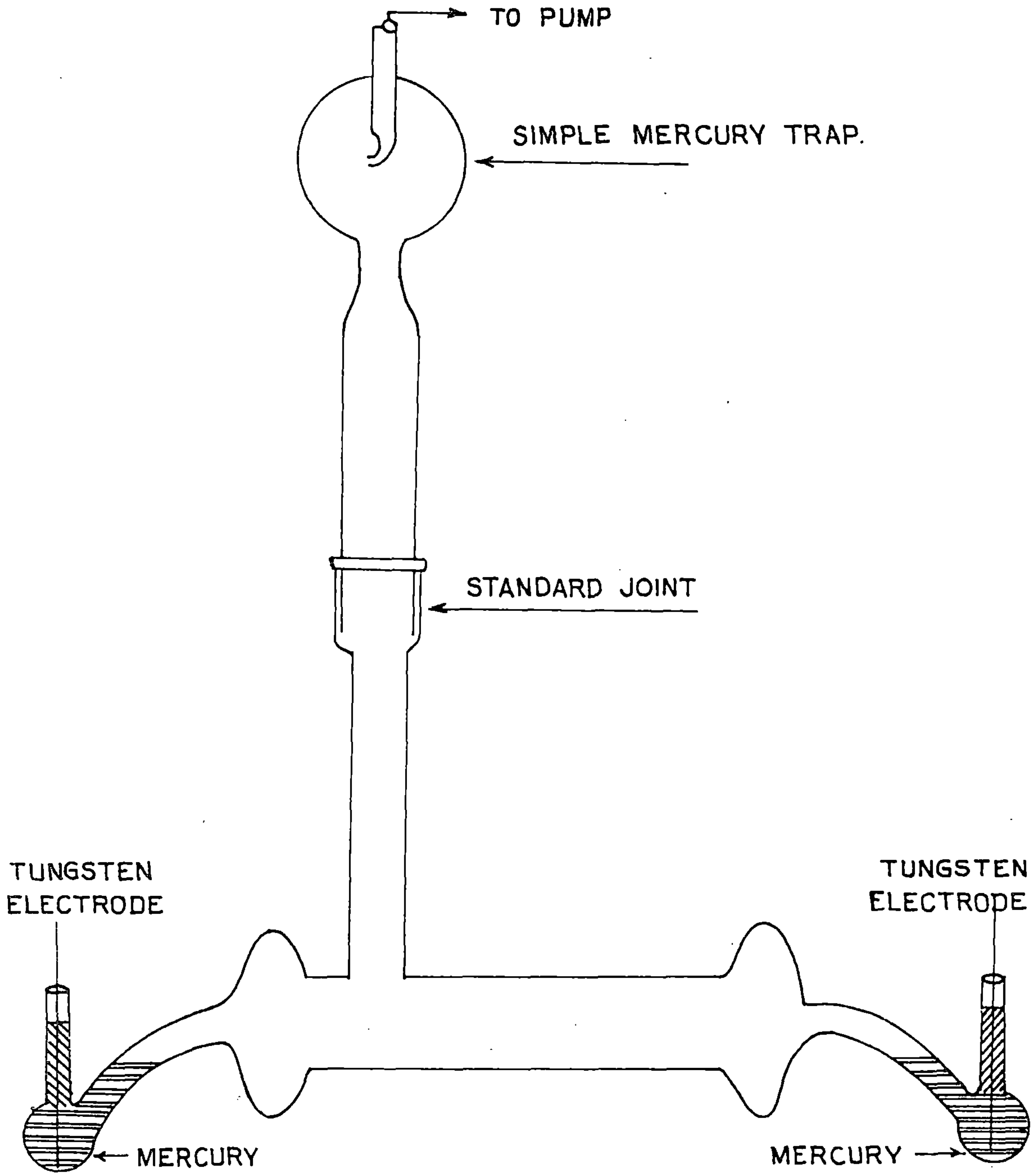

FIG. 2.1. DIAGRAM OF A MERCURY ARC TUBE.

the passage and thereby would disturb the vacuum system. The whole arc system is cooled down by air coolers and two mercury pool electrodes by circulation of water.

2.3. Cleaning and processing of arc tube:

For the preparation of mercury arc the arc tube is thoroughly washed and cleaned with dilute chromic acid and then with NaOH solution. The tube is then washed several times with distilled water and then with dehydrated benzene. The tubes are then heat baked in an electrical oven. Triple distilled mercury is then poured into the tube to the desired level. The tube is then connected to a double stage rotary vacuum pump and a vacuum of the order of 10^{-2} torr is achieved.

2.4. Preparation of gases for glow discharge:

For measurements where air acts as a buffer, air has been passed through dilute solution of caustic potash to remove traces of CO_2 and is then washed with water by passing through series of wash bottle containing cold water to remove traces of coustic potash, dust particles and organic matters. It has been dried by passing through a tower of fused $CaCl_2$ and finally through P_2O_5. Then air is introduced to a discharge tube and controlled through a needle valve. Hydrogen gas is prepared from electrolysis of a solution of pure barium hydroxide in between platinum electrodes in a U-tube. For hydrogen, the gas evolved from the cathode was passed through a hard glass tube containing copper spiral heated electrically. The gas is next passed through the same arrangement described above. After purification has been done in stated manners the gases are stored in a round bottomed glass flask which is connected to the discharge tube.

For usual discharge tubes, after several days of run for outgassing and observation purposes, the glass wall would become coated by impurity materials due to sputtering of the cathode. For that reason steel electrodes are used.

2.5. Measurements of pressure:

By utilizing Mcleod gauge the pressure of the gas in the discharge tube is measured. As shown in fig. 2.2, a parallel line is used for the measurement of pressure in the discharge tube. At the junction between these two vacuum lines the pressure is the same and if the conductance of the two lines are identical, the pressure in the discharge tube would be equal to that at the Mclead gauge. Dushman and Lafferty (1962) have discussed that effective pumping speed, S_{eff} is given

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C} \qquad ...(2.1)$$

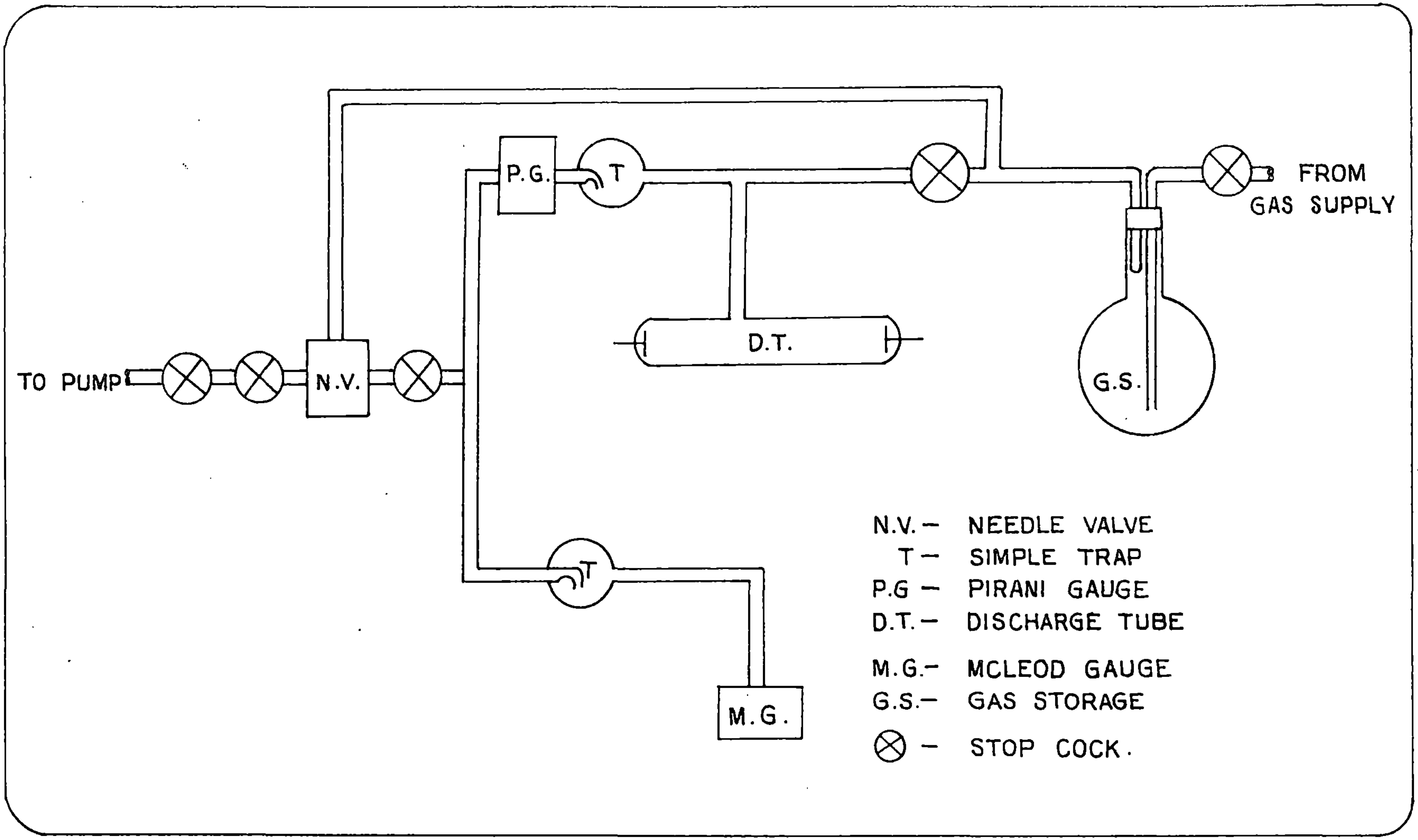

FIG. 2·2. DIAGRAM OF A GLOW DISCHARGE TUBE.

where S is the speed of the pump (50 litres/min) and C is the total conductance of the line. For viscous flow, conductance of a line is given by

$$C = 2{\cdot}84 \frac{a^4}{l} P_2 \text{ litre/Sec.} \quad \ldots(2.2)$$

where a and l are the radius and length of the tubes and P_2 is the upstream pressure. The parallel lines as shown in fig. 2.2 are identical as far as possible. The lines are made of rubber and polythene pressure tubes. The needle valve is placed in between the junction of identical lines and the pump for the same reason. A pirani gauge is used in the discharge tube line and through it the pressure of air can be compared. In glow discharge tubes, the order of pressures ranges from 1 to 10^{-1} torr.

In case of arc, a pirani gauge has been used in the arc tube line and through it the pressure of background dry air (buffer gas) has been measured. A needle valve has been placed in the arc tube line to allow a microleak for adjustment of air pressure inside the system.

The pressure of mercury vapour has been measured from standard tables (Hodgman, 1956) after calculating inside wall temperature T_W of the tube which is equal to the outside wall temperature increased by the temperature drop over the tube wall resulting from the impact of energy which is dissipated in the tube and carried away via the tube wall (Verweij, 1960). The outside wall temperature has been measured by a mercury in glass thermometer when the arc exists in a steady state condition. In the experiments the arcs have been cooled down by air coolers. Therefore, a steady outerwall temperature corresponds to a steady condition of the arc under investigation. After Verweij, (1960) the temperature drop has been estimated by considering the total energy dissipated $W = E\dot{i}$ per cm. along the tube length. Here E is the magnitude of electric field measured by noting the voltage drop across the arc minus standard cathode fall of 10 volts as measured by Lamar and Compton (1931), then divided by the entire arc length and i is the arc current. In fact, the amount of energy which escapes as radiation through the tube wall is comparatively small and the ultraviolet resonance radiation is absorbed within a very small penetrating depth in pyrex glass wall of the arc tube. Therefore the dissipated energy flux is carried away mainly by thermal conduction through the surface area of 1 cm. of the arc tube length, hence through $2\pi R$ sq.cm. (R is the inner tube radius).

The temperature drop ΔT_W is given by

$$W = 2\pi RK\frac{\Delta T_W}{d} \qquad \ldots(2.3)$$

where K is the thermal conductivity of the glass (K pyrex = 11×10^{-3} joul/cm/sec/°C) and d is the thickness of glass wall. For a typical operation of arc at a current of 2.5 A, ΔT_W has been estimated to be 7-8°C. A plot of saturated vapour pressure of mercury (P_{Hg}) with T_w has been shown in fig.2.3. As number density of ground state mercury atoms N_g is explicitly related with P_{Hg} by the relation

$$N_g = 3{\cdot}3 \times 10^{16} \frac{P_{Hg}}{T_W} \quad \ldots(2.4)$$

N_g has also been plotted against T_w in the fig.2.3.

2.6. Magnets and power supplies:

Magnetic field has been produced by an electromagnet. Depending upon the length and diameter of arc tube/glow tube, gap between the pole pieces of electromagnets has been adjusted. For accuracy in measurement, the pole-pieces have been so chosen that the magnetic field was uniform and without having any radial magnetic field component. For investigation in longitudinal magnetic fields, the total arc tube has been placed in between the pole pieces as shown in fig. 2.4, when a transverse magnetic field is utilized only certain portion of the positive column of

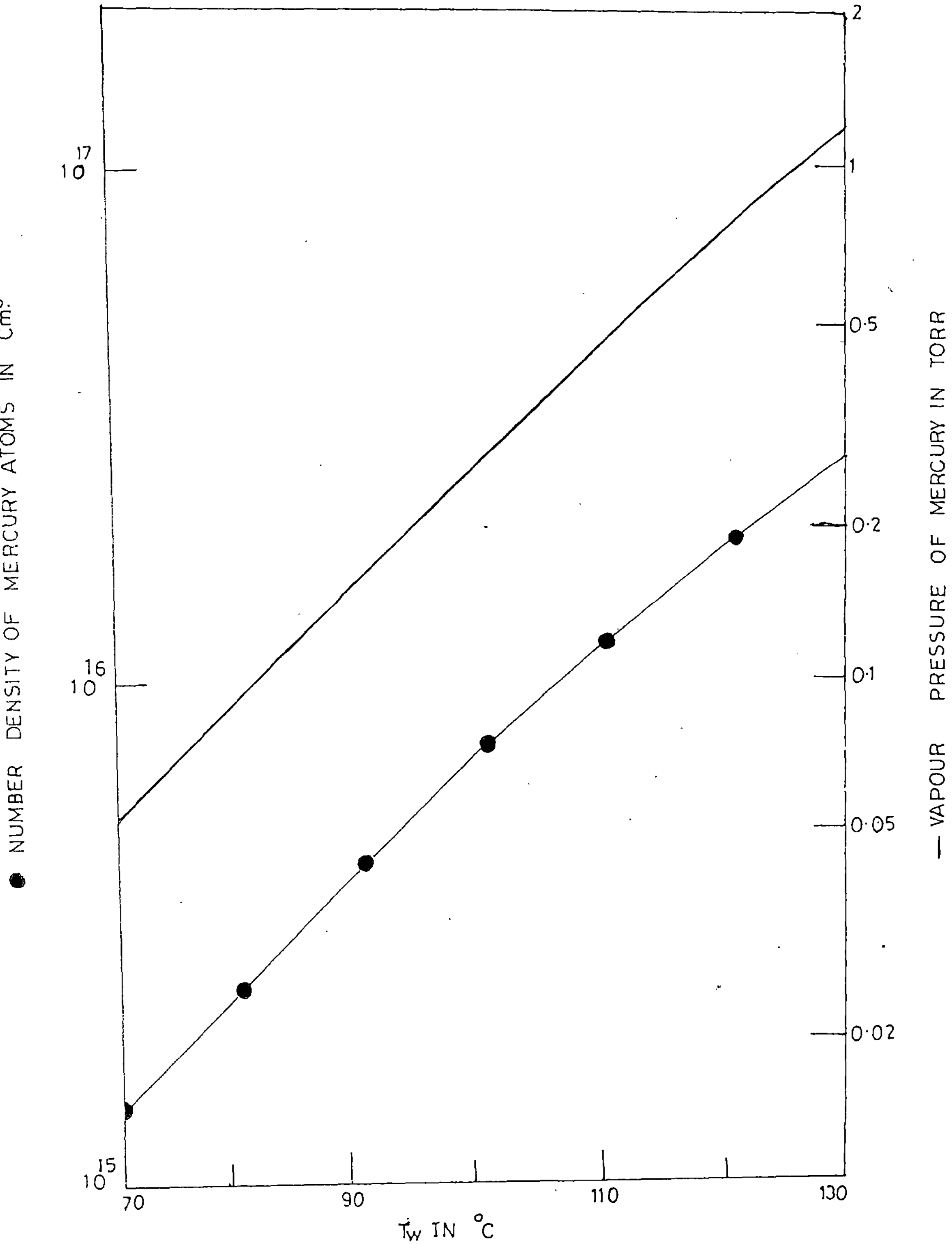

Fig. 2·**3**. Variation of vapour pressure and number density of mercury atoms with temperature of outer wall (T_W) of discharge tube.

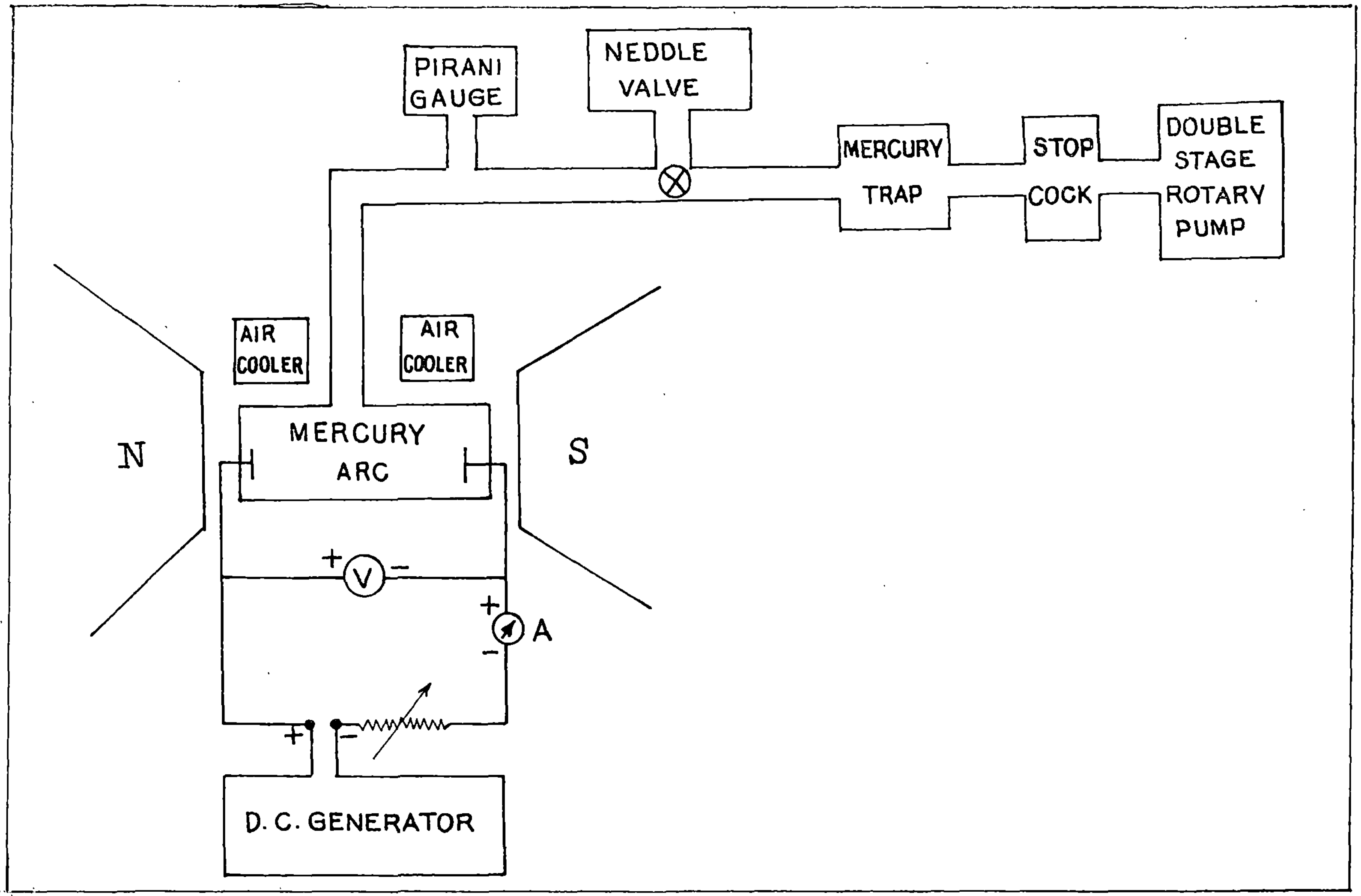

Fig. 2·4. Schematic diagram of experimental set-up in an axial magnetic field.

the arc tube, where investigations have been made, has been inserted between the pole pieces (fig. 2.5).

The magnetic field strength has been measured by gauss meter (Model G14). The electromagnets have been run by a stabilized dc power supply (Type EM20).

Both the mercury arc in the tube and some other metal arcs (in air) using Ag-Ag, Cu-Cu and Fe-Fe electrodes have been produced by a dc generator whose voltage may be adjusted by a rotary variable resistor fitted externally (in the front panel of a steel stand) and current can be adjusted with a rheostat inserted in series with the electrodes. The arc current has been varied upto 6-7 A. For photomultiplier tube, oscillator and dc amplifier the power supplies have been fabricated in the laboratory. The circuits for their fabrication have been taken from Radio Amature's Hand Book (1965).

The calibration curves for the magnetic field for different set-ups have been shown in fig. 2.6, 2.7 and 2.8.

2.7. Determination of electron density n_e and electron temperature T_e in a mercury arc utilizing tungsten probe:

A cylindrical tungsten probe of 0.014 cm. radius within a glass capsule with a bare tip of 0.1 cm. height has been placed into the plasma at a separation of

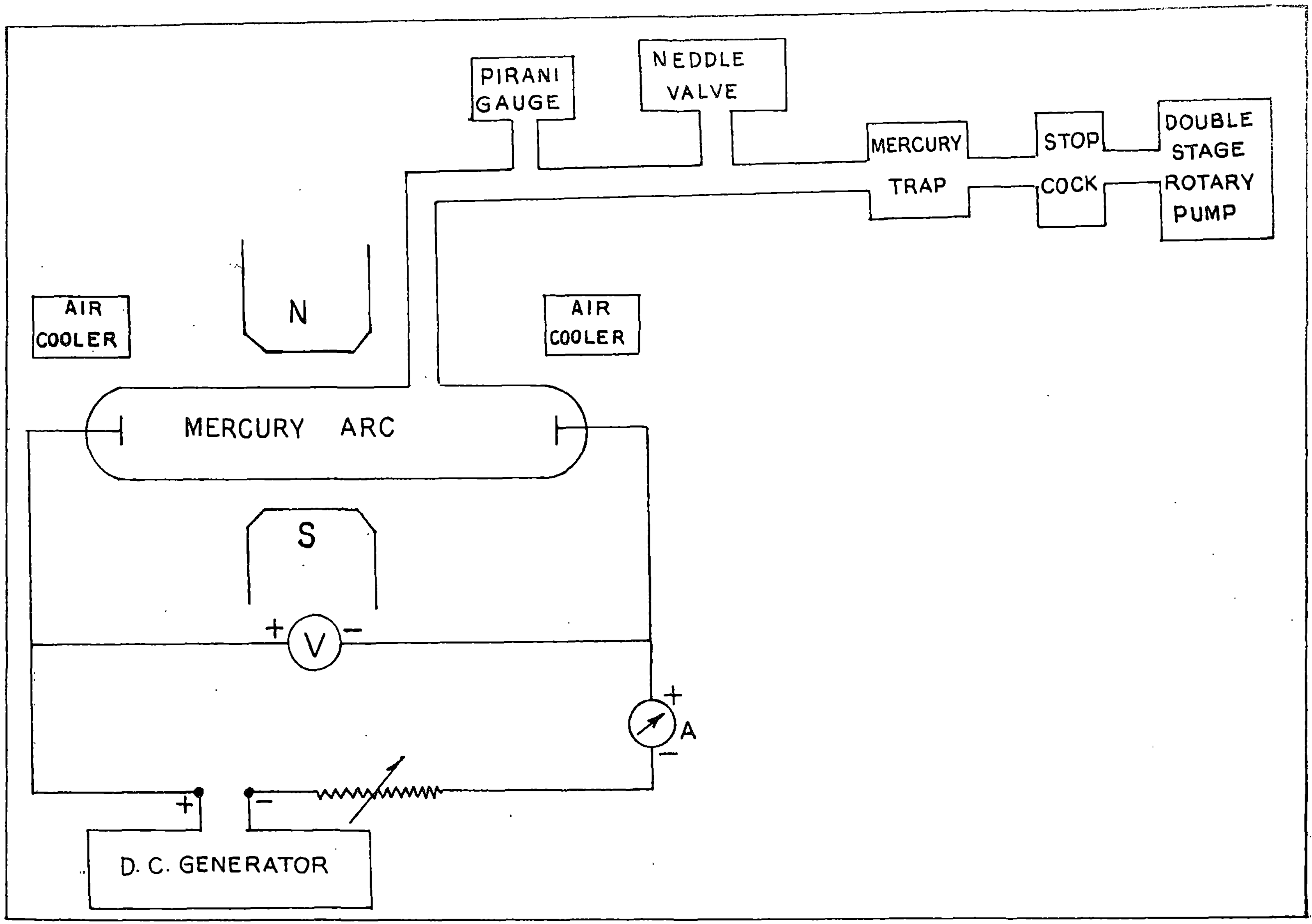

Fig. 2·5. Schematic diagram of experimental set-up in a transverse magnetic field.

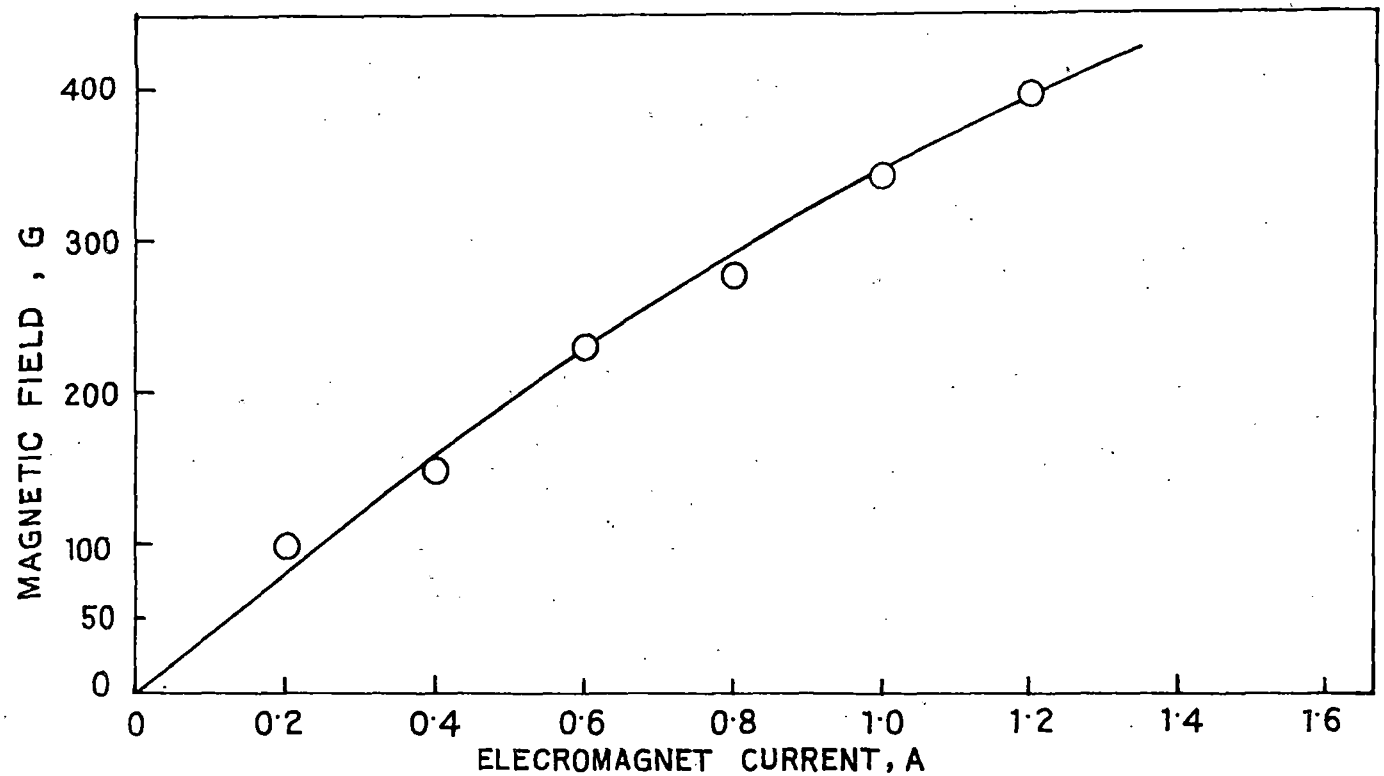

FIG. 2.6. MAGNETIC FIELD CALIBRATION CURVE, REF. CHAP. V.

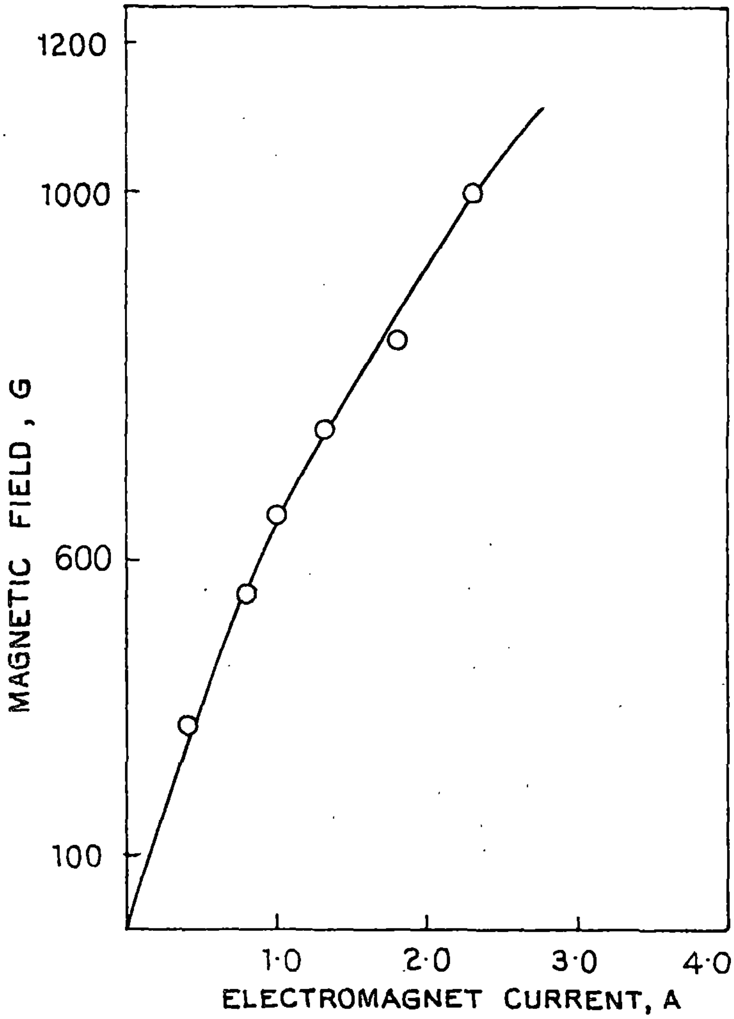

FIG. 2·7. MAGNETIC FIELD CALIBRATION CURVE
REF. CHAP. VI.

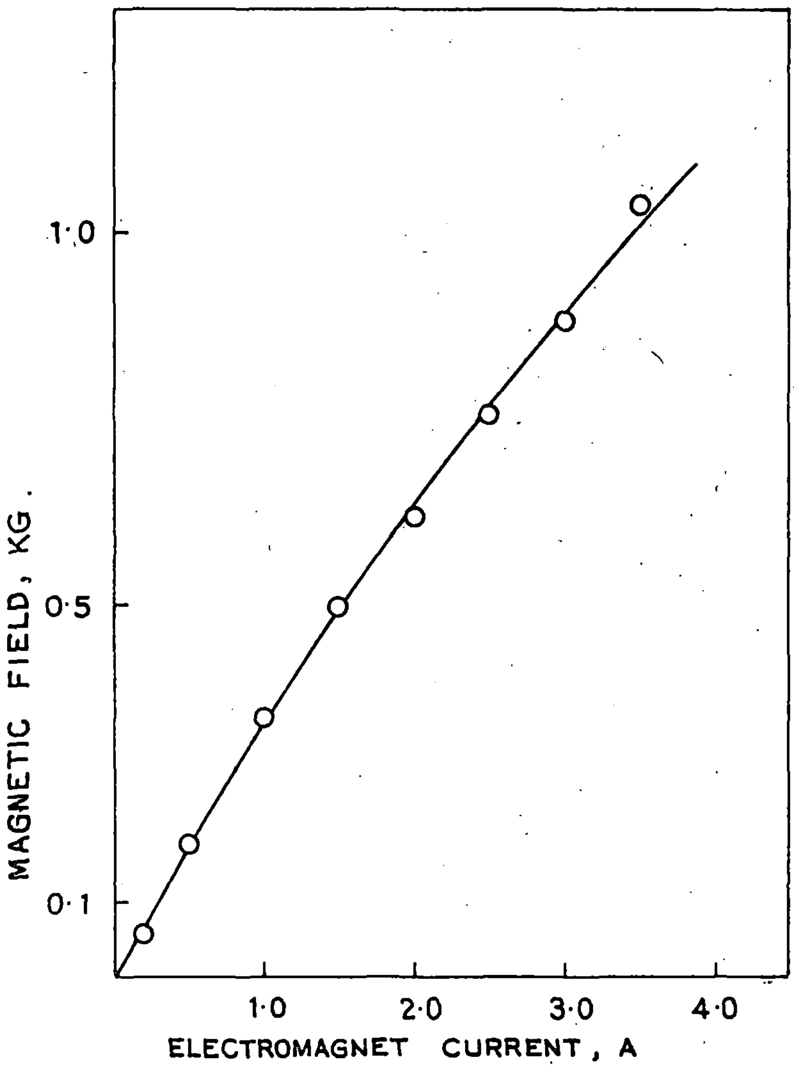

FIG. 2.8. MAGNETIC FIELD CALIBRATION CURVE, REF. CHAP. VI.

14 cm. from the anode of the tube as shown in fig.2.9(a) The tip of the probe is fixed accurately at the axis of the arc tube and the probe is perpendicular to the axis. In usual practice the height of probe (h) should be larger than radius (r_p) of the probe. But an upper limit of the ratio h/r_p may be calculated from the expression of electron saturation current to the probe

$$I_{e\langle sat\rangle} = - e n_e A_p \left(\frac{T_e}{2\pi m} \right)^{1/2} \qquad \ldots(2.5)$$

where e , n_e , m and T_e are the charge, density, mass and temperature of electrons and A_p is the probe collecting area ($A_p = 2\pi r_p h$). It is desirable that $I_{e\langle sat\rangle}$ should not be large enough so that probe would not become too hot or incandescent and get damaged. In this investigation h/r_p is nearly 7.14. Both h and r_p have been measured by a travelling microscope. It will be discussed in chapter III that the results for the probe of these characteristic dimensions in arc plasma can be interpreted in the light of orbital theory.

The whole circuit arrangement for probe current measurement has already been shown in fig. 2.9(a). The probe is provided with dc potential from a series of dry batteries through a potentiometer.

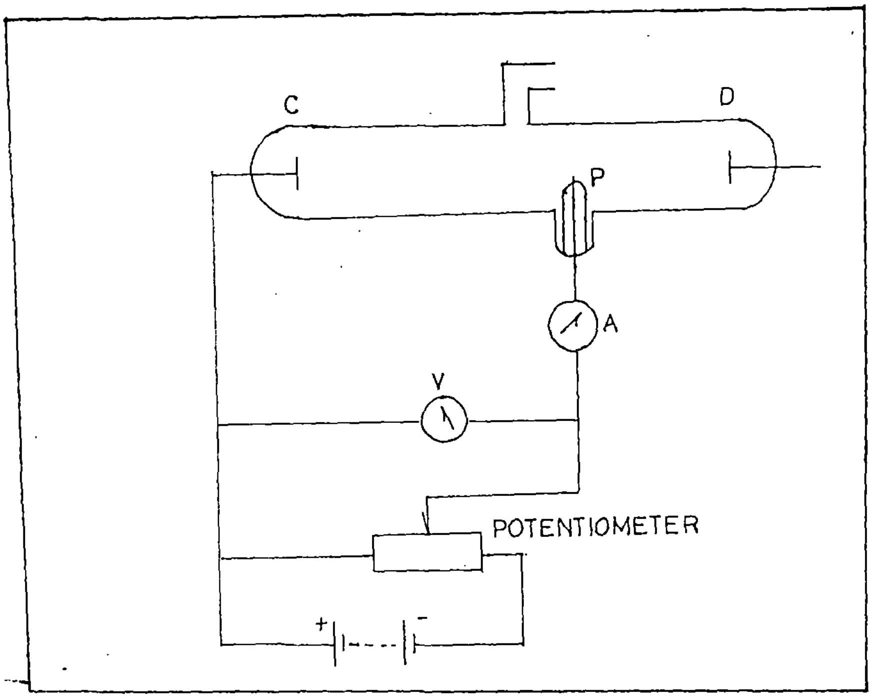

FIG. 2·9(a) SCHEMATIC EXPERIMENTAL ARRANGEMENT FOR MEASURING ELECTRON TEMPERATURE.

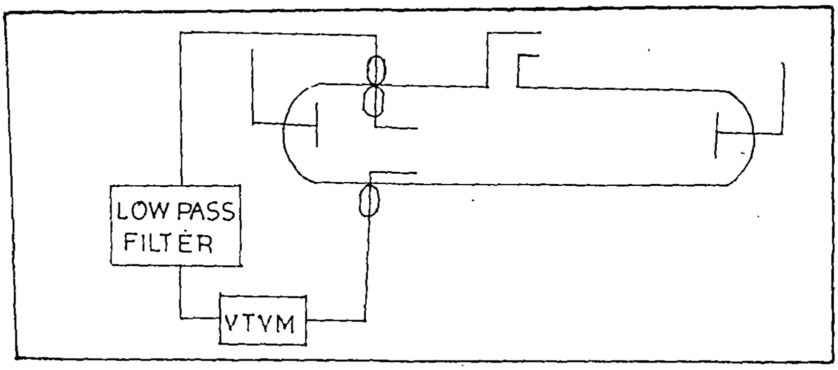

FIG. 2·9(b). SCHEMATIC EXPERIMENTAL ARRANGEMENT FOR MEASURING DIFFUSION VOLTAGE.

For changeover from ion current to electron current an external polarity reversal arrangement utilising manually operated band-switch is adopted to record the respective current. The probe circuit is connected to anode and the probe potential which is relatively negative with respect to anode has been varied in steps of 0.2 - 5 volts. The probe current which has been recorded, is the total current through the probe. Electron current I_e has been taken by sub.tracting ion current I_i from the total current

$$I_e = I_{tol} + |I_i| \qquad \text{...(2.6)}$$

In our present experiment I_i is observed to be smaller than I_{tol} by a factor of order 1000. So effectively I_e equal to I_{tol}.

2.8. Diffusion voltage measurement by probes:

Two cylindrical tungsten probes of radius 0.014 cm. and height 0.8 cm. are inserted parallel to one another, one along the axis $r = 0$ and the other at a separation of 0.6 cm. from the axis in the same cross sectional plane of the arc tube of 41 cm. length as shown in fig. 2.9 (b). The resultant voltage between the two probes has been recorded by a VTVM having an internal impedance of 100 MΩ. A low pass filter circuit is provided at the output of the probes to prevent oscillations generated in the arc from reaching the VTVM. The VTVM output gives the magnitude of the diffusion voltage. The diffusion voltage is recorded with variation of arc current from 2A to 5A for three background (buffer) air pressures (0.075 torr, 0.10 torr and 0.13 torr),

2.9. R.F. oscillator circuit:

The radiofrequency oscillator is of Hartley type; and the circuit diagram is shown in fig. 2.10(a). The range of frequency of this oscillator is from 3.3 MHz to 10.1 MHz. The inductance L of the tank circuit is divided into two parts L_1 and L_2 and their common point is connected to the cathode terminal of the vacuum tube 811. The end of L_1 is connected to the grid through the parallel combination of R_g and C_g, which provides the grid bias potential. The end of L_2 is connected to the plate of the oscillator valve 811 through the blocking capacitor C_c. Another variable gang condenser is inserted in parallel with the inductance (primary coil), thereby making a complete tank circuit. The current circulating in the resonant circuit passes through both parts of the inductance and developes a potential difference for the grid excitation. The direct component of the plate current is supplied from a stabilised high voltage power supply through a radio frequency choke.

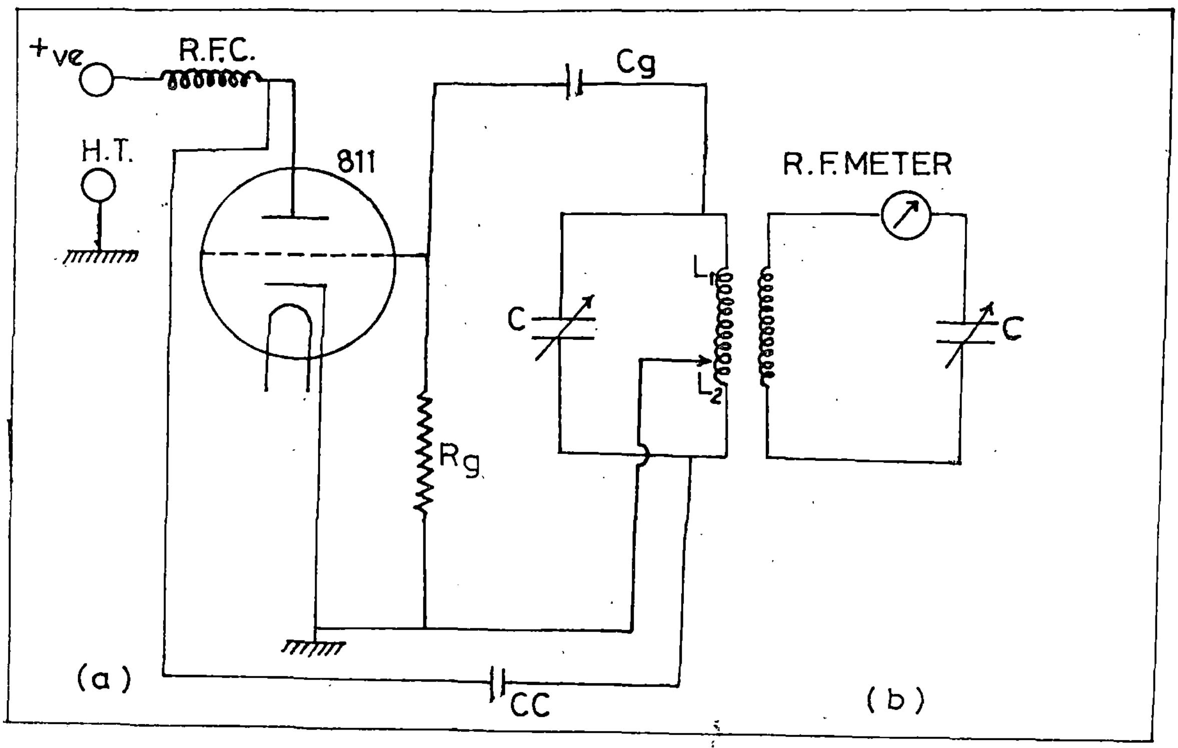

FIG.2·10. RADIO FREQUENCY OSCILLATOR CIRCUIT-(a); SECONDARY TUNING CIRCUIT-(b).

The blocking capacitor C_c, which has a small reactance compared with the load impedance, gives a path to the ac component, while the dc from the power supply is prevented. For a fixed gang condenser position, the oscillator frequency (3.69 MHz) has been measured in the experiment by an absorption wavemeter. The secondary receiving circuit consists of the coil wound around the arc tube, a variable tuning condenser and a radio frequency milliammeter (all connected in series, Fig. 2.10 (b)).

2.10. Measurement of electron atom collision frequency in an arc plasma by radiofrequency coil probe in conjunction with a longitudinal magnetic field:

In this diagnostic investigation a radio frequency coil probe technique has been employed to find electron - atom collision frequency in an arc plasma in presence of axial magnetic field. An arc tube made of pyrex glass of length 10.8 cms. and diameter 1.83 cm. is used. Besides the two tungsten mercury pool electrodes at the two ends, other two tungsten probes have been introduced upto the axis of the tube in the positive column with a separation of 4.6 cm.

as shown in fig. 2.11. A small coil of length 4.5 cm has been wrapped around the tube in the region of probe to probe separation. These coils supply radio frequency power induction from the externally applied high frequency oscillator. The arc tube was placed inside the two pole pieces of an electromagnet separated by 11.5 cm.

A radiofrequency milliammeter ranging from 0 to 120 mA (Thermocouple type) made by Weston Instruments, Inc. (USA Model No. 308) in series with a variable gang condenser has been connected at the two ends of the coil wound around the arc tube. These three elements connected in series act as a secondary tank circuit in the investigation.

The oscillator coil is placed near the work coil i.e. the coil wound surrounding the arc tube, and the induced rf potential is tuned with the variable condenser inserted in the secondary circuit in series with the rf milliammeter and the work coil. The arc is then produced by adopting the tilting process. Subsequently the rf meter indicator shifts from its previous position. The tuning condition is achieved by the variable gang condenser. A number of aircoolers and a water circulation system have been provided for controlling the arc temperature and to maintain a steady wall temperature. The rf meter reading is then recorded as far accurately

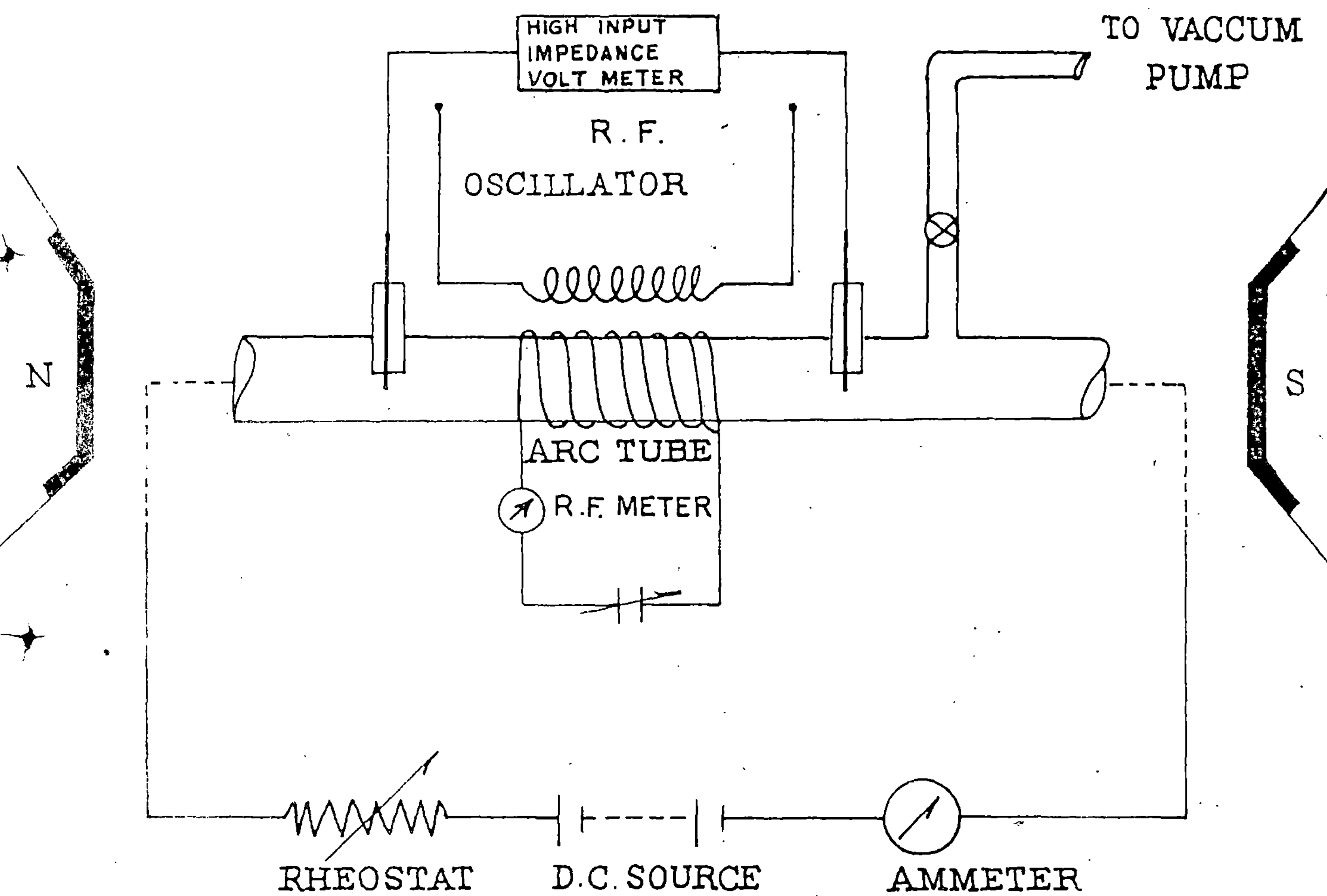

Fig.2·11. Schematic Experimental Arrangement for the study of Arc Plasma characteristics in Presence of Longitudinal Magnetic field.

as possible. This current reading is i_1. Then the voltage across the two probes inserted in the positive column has been measured by an electronic multimeter with high input impedance. Now without disturbing any arrangement of the circuit the arc is switched off. The meter recording pointer again shifts from its previous position. The tuning condition is again set by the condenser and the tuned current i_0 is recorded.

Before starting the experiment the magnetic field was first calibrated with current (Fig. 2.6).

The sequence of observations and measurements are given in the following paragraph :

The arc tube was placed in between the two pole pieces of electromagnet so that it may be tilted freely to strike it. The tube was placed along the magnetic field so that any radial magnetic field component should vanish. To maintain the desired discharge current rheostats were adjusted. The probe coil was tuned and the rf current i (i.e. the coil probe current in arc on condition and in absence of magnetic field) was noted. In this condition the probe to probe voltage E was noted. When the magnetic field was applied, the probe to probe voltage and discharge current decreased. In presence of the axial magnetic field the coil probe current i_B was noted. To avoid extinction of the arc for lower discharge current, the discharge current I_B was adjusted to its previous value I in presence of magnetic field and again E_B and I_B were noted simultaneously. Now both the magnet and the arc were turned off. The coil probe was retuned and the tuned current i_o i.e. the coil probe current in absence of plasma was noted. The whole procedure was repeated a number of times. The observation has been carried out for a fixed oscillator frequency 3.69 MHz.

The variation of the quantity $(\alpha - 1)$ where $\alpha = i_o/i_1$ is proportional to the arc current 'I', In this experiment each time the arc current was changed, sufficient time was allowed to pass to ensure equilibrium before any measurement [E or $(\alpha - 1)$] was made. $(\alpha - 1)$ and E varied linearly with the arc current. But due to application of axial magnetic field the value of E and $(\alpha - 1)$ decreased slowly with the increasing magnetic field. It was found that if the arc currents were in the lowerside, the reduction of current, due to the application of axial magnetic field some times caused extinction of the arc. To remove this difficulty, immediately after applying the magnetic field the arc current was adjusted to its original value when necessary. But it has been shown that the collision frequency was constant for various magnetic field at particular arc current.

2.11. <u>Evaluation of electron temperature in transverse and axial magnetic field in an arc plasma by measurement of diffusion voltage:</u>

For measurement of diffusion voltage in presence of 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 has been utilised and in presence of longitudinal 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. The arc is energised by a dc generator with a rheostat to change the current through the arc. The whole arc is cooled by air coolers and two mercury pool electrodes by water circulation. To maintain the background pressure fixed in the arc vessel, dehydrated air is introduced with an arrangement of needle valve which is suitably filled in the vacuum arrangement. For determination of plasma parameters in transverse magnetic field the positive column of the mercury arc is kept between the pole pieces of electromagnet while for that measurement in axial magnetic field the whole arc tube has been placed between the pole pieces.

As in previous articles, similarly two cylindrical tungsten wires of 0.014 cm. and 0.8 cm. height have been set parallel to one another one along the axis $r = 0$ and the other at a separation 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. height while other specifications remain same as in transverse magnetic field.

In both magnetic fields the output voltage at the two probes has been measured by a VTVM. It is actually the low pass filter output, as a low pass filter is connected at the output of the probes to prevent noise caused by oscillation in the arc from reaching in the VTVM. The diffusion voltage has been recorded as a function of the magnetic field with arc current as a parameter. For transverse magnetic field the diffusion voltage has been recorded upto the magnetic field 1000 G at three fixed 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.

2.12. Diagonostics by spectroscopic method:

To estimate the plasma parameters spectroscopic method has been utilized. Fig. 2.12 and Fig. 2.13 show a detailed schematic diagram of this experimental set up. The radiations from the axial regions of vertical discharge tube passing through a vertical slit is focussed by a double convex lens on the vertical slit of the collimator of the spectrograph. There is a Pellin-Broca prism for 90 degree deflection of the spectrum in the spectrograph. Such a mounting is essential as a monochromator is mounted with the fixed slit. The exit slit is perpendicular to the plasma source. The wavelength (arc and glow spectral lines) of the source is changed by rotating the prism with a mechanical arrangement fitted with an accurately calibrated drum. From Handbook of Chemistry and Physics Hodgman (1956), the wavelengths of the visible spectrum have been checked.

In general, this type of apparatus has a low resolving power which would be advantageous in the present investigations, because it is unable to resolve Zeeman splitting. The slit width ranging from 0.25 mm to 1 mm. can be varied with a micrometer arrangement, depending on the response of lines chosen to the photomultiplier. The slit width has been kept constant for a set of observation.

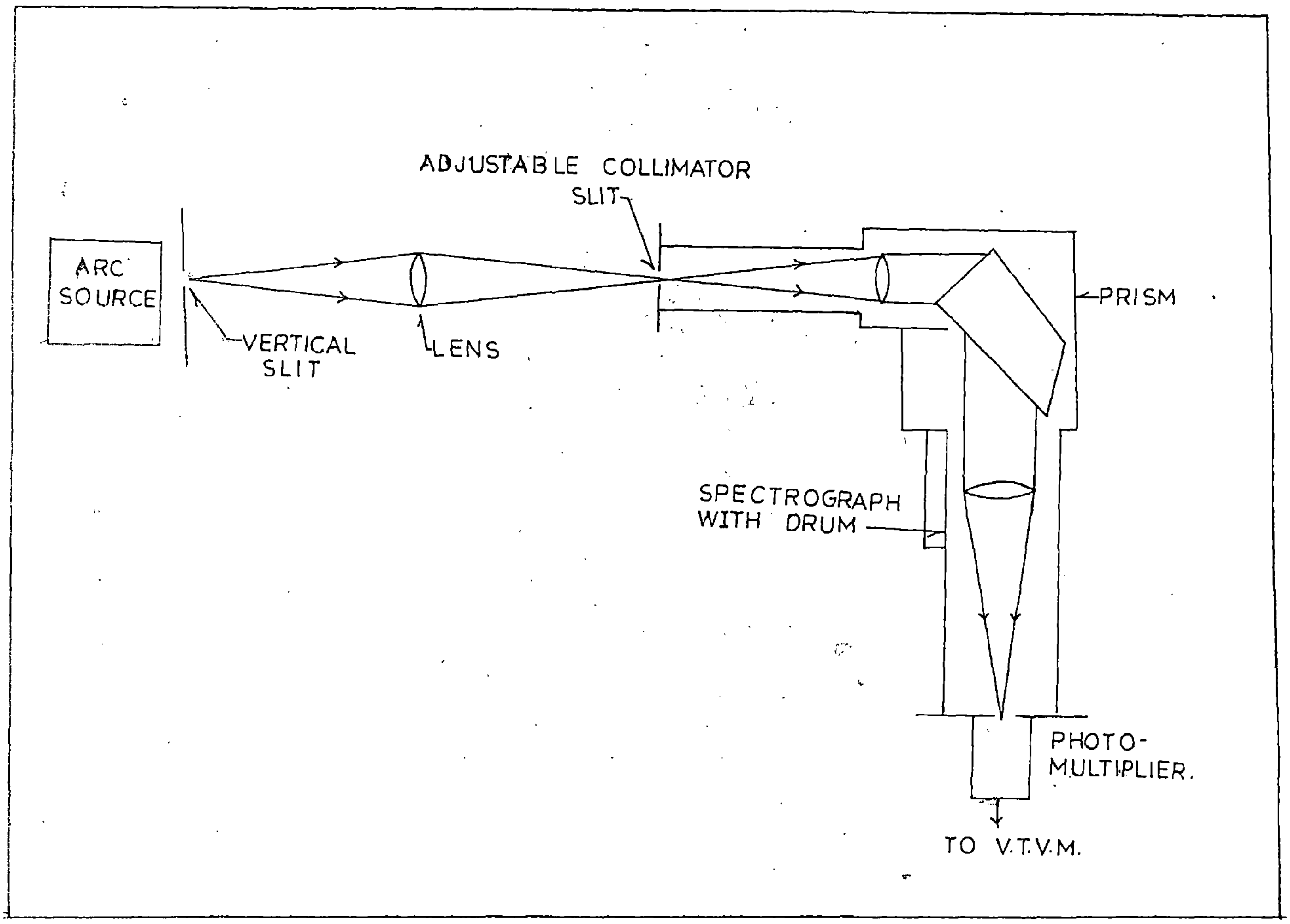

Fig. 2·12. Experimental set up for spectroscopic measurements.

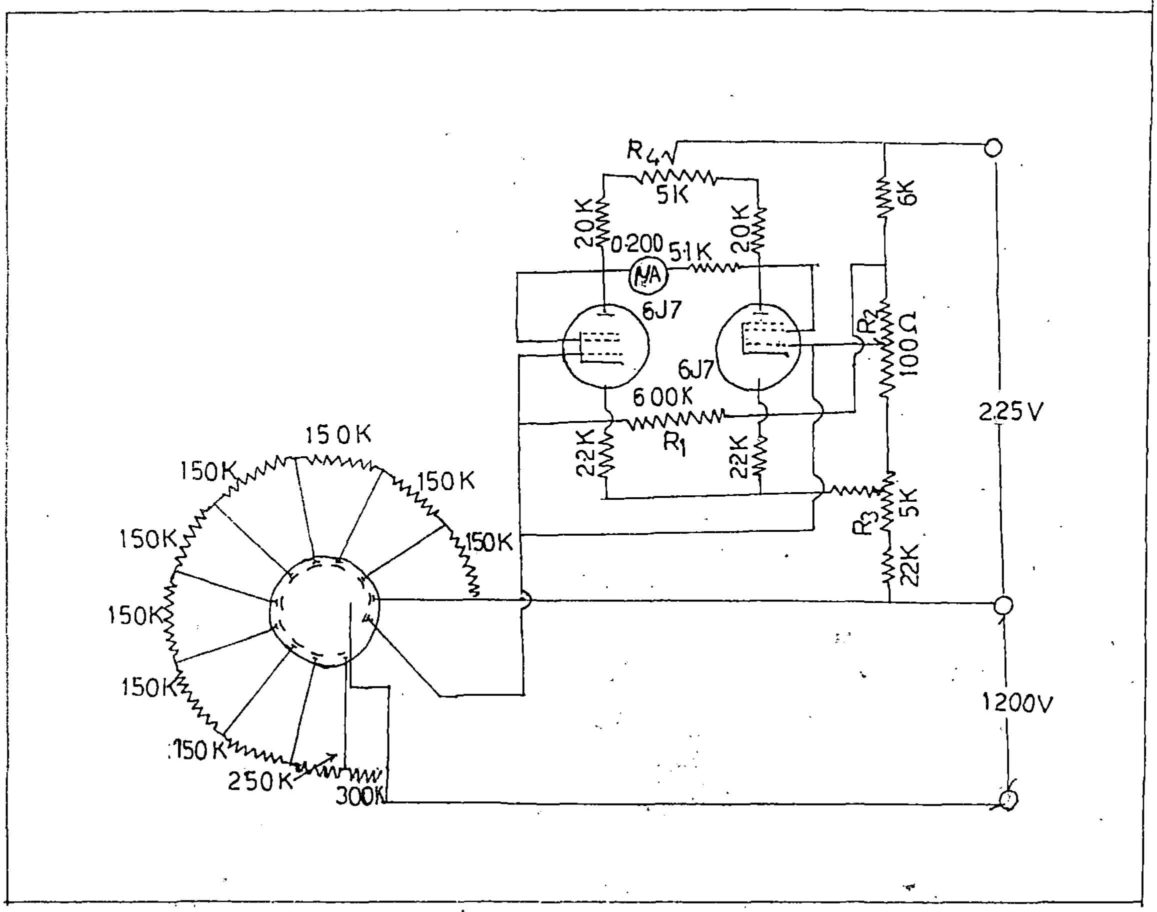

FIG. 2.13 PHOTOMULTIPLIER CIRCUIT.

For measuring T_e , two criteria for suitable line choice may be mentioned:-

(1) The energy of separation of the upper states of the two transitions chosen should be comparable to the value of T_e . But this is not possible always. In the visible region for two lines which have sufficient response to the detector the energy of separation of upper states becomes sometimes smaller than the value of T_e. One of the remedy that is suggested is to use one of the ionic lines and one atomic line.

(2) The lines should be such that in the near vicinity there would be no other line, so that $\int_0^\infty I_\nu \, d\nu$ is the measure of total intensity of a radiation with frequency ν and in our investigation slit widths are comparatively wide enough as to detect the total intensity of radiation.

The selected spectral line has been focussed on the cathode of the photomultiplier tube MI OFS29V$_\lambda$ operated at 1425 V, whereas the collimator is focussed by rock and pinion arrangements. Behind the eyepiece of the spectrograph the top cathode type photomultiplier which has low mean radiation equivalence of dark current is placed in a darkened ebonite housing. The power source of photomultiplier is provided in two sections : the first is 1200 v stabilized to supply the dynode voltage and the second is to provide 225 V between the final dynode and the anode as in Fig.2.13. To operate the VTVM the second voltage source is used. It consists of two 6J7 tubes operated at 32V on the plates and 1.3 V negative grid bias. The grids are connected to the two ends of a resistor R (600 KΩ) which is in series with the plate of the photomultiplier. A potential drop developed, when current flows through the resistor R_1 and one of the 6J7 tubes draws less current producing an imbalance in the plate circuit. A 0-200 μA meter is connected in between the plates of the 6J7 tubes to measure this unbalanced current. For this circuit arrangement for a signal 3V, the 6J7 tubes reached cut-off and beyond which there is no further increase in the meter deflection.

The microammeter is set to zero with R_2 and a coarse balance is made with R_4 with no radiation on the photomultiplier tube. In this way the effect of dark current in actual measurement of radiation is completely minimised. With 3V or a little more applied to resistor R_1, the meter is set to full scale deflection with the help of another resistor R_3. The radiation of the spectral line under investigation is recorded at the output by microammeter. The slit of the spectrograph is varied in such a way that meter deflection corresponding to the spectral line with strongest response to the photomultiplier is in the full scale range of the meter.

The sensitivity of a photomultiplier depends onwavelength of incident radiation and on quantum efficiency of the cathode material (including the effect of photomultiplier's window material). A characteristic of quantum efficiency of MIOFS29V_{λ} against wavelengths is plotted taking the values from Carl Zeiss brochure no. 40 - 637 - 2, in Fig.2.14. From this plot the cathode radiant sensitivity S in amperes per watt corresponding to a radiation of wavelength λ (Å) is calculated as

$$S = \frac{Q\,\lambda}{12395 \times 100} \qquad \ldots(2.7)$$

here Q is the percentage quantum efficiency. The relative spectral sensitivity for two lines are calculated and the microammeter reading for total intensities of lines are corrected for relative spectral response of the photomultiplier from the determined value of S . The emissive frequency ν is directly proportional to observed total intensity which can be separated into a continuous and discrete

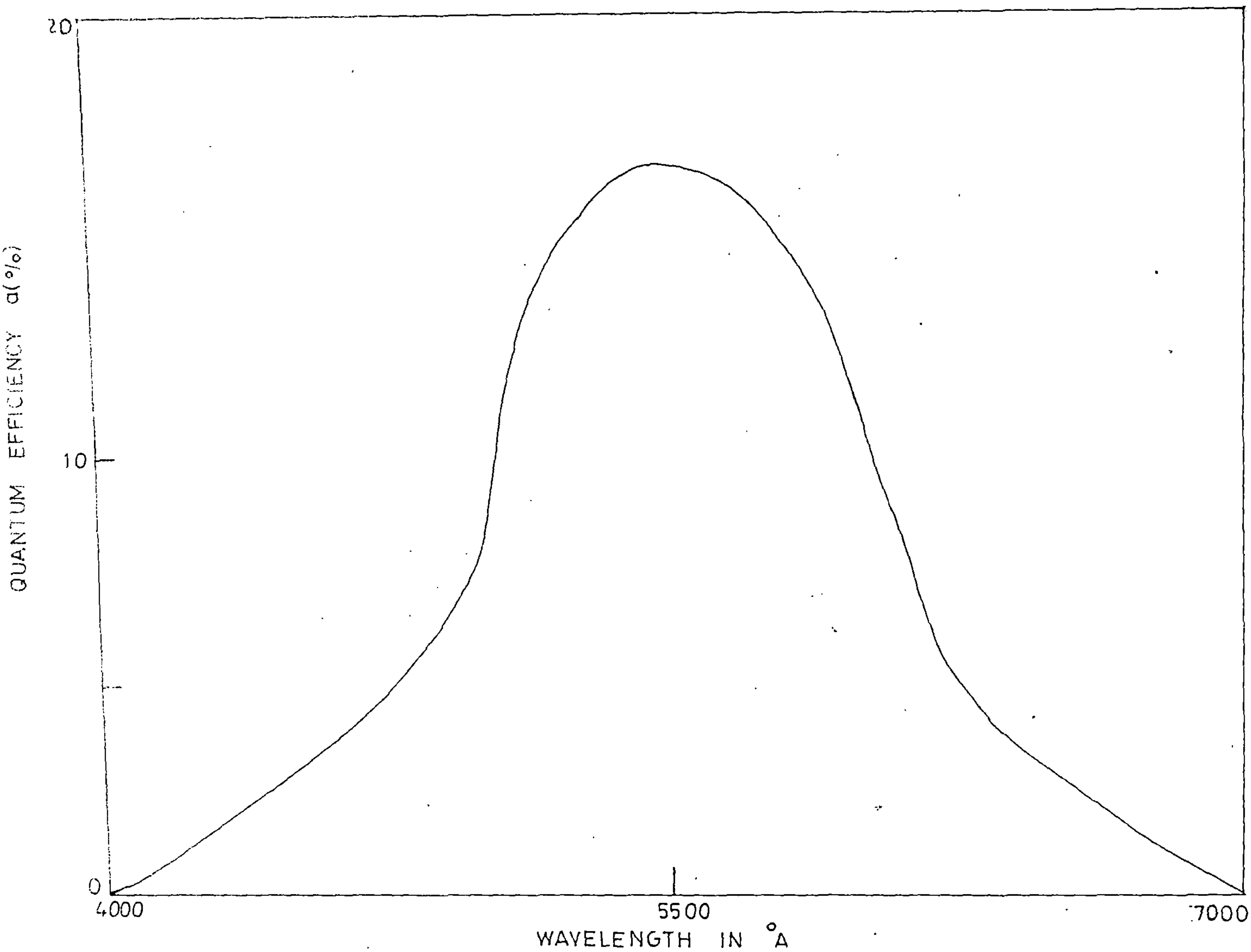

FIG. 2.14. QUANTUM EFFICIENCY IN % OF PHOTOMULTIPLIER M10F529V$_\lambda$
(VEB CARL ZEISS JENA BROCHURE NO. 40-637-2.)

part

$$\epsilon_{\nu} = \epsilon_{\nu,C} + \epsilon_{\nu,L} \qquad \ldots(2.8)$$

$\epsilon_{\nu,L}$ contains the ~~x~~ desired spontaneously emitted energy within the line, $\epsilon_{\nu,C}$ is eliminated by balancing the VTVM to the null of meter reading with resistors in the circuit when the continum radiation at the near vicinity at the line is focussed or the photomultiplier tube cathode and the contribution for $\epsilon_{\nu,C}$ is to be negligibly small.

2.13. Measurement of intensity enhancement of spectral lines with increasing arc current in arc plasma:

Two respective metal electrodes of a particular arc have been fixed with a vertical stand as shown in fig. 2.15, where upper metal electrode is attached to a vertically movable bench arrangement with the help of a screw. Initially the two electrodes are brought into contact by this screw. A dc source with an adjustable rheostat and an ammeter, is utilized to produce the arc namely for Ag-Ag, Cu-Cu and Fe-Fe in air. An accurately calibrated constant

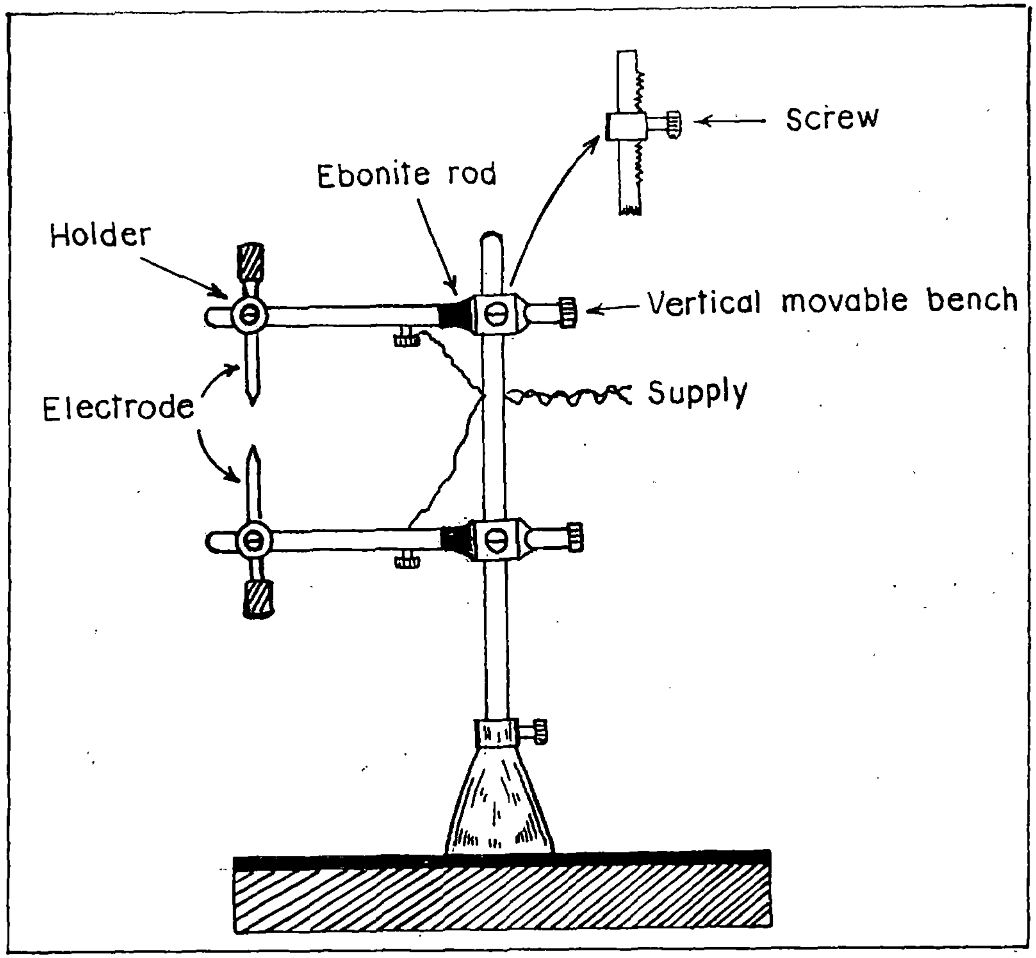

FIG. 2·15. METAL ARC ARRANGEMENT

deviation spectrograph has been used to measure the wavelength of the spectral lines of the arc sources. Each line is focussed on the cathode of the photomultiplier tube M10 FS29V $_{\lambda}$, and intensities are thus obtained by measuring the output of the photomultiplier which is measured by a difference amplifier. The whole arrangement of this spectroscopic part - its arrangement and its electronics circuit is given in the previous section.

The output microammeter current recorded in the difference amplifier is observed to be linearly proportional to the known spectral line intensities and the slit width of the spectrograph has been adjusted to obtain a large deflection in the microammeter, thereby enhancing the desired level of sensitivity in the measurement of the line intensity ratio. In case of silver electrodes the arc current is varied from 3A to 7A and in case of copper and iron electrode the variation is 2.5 A to 5 A.

2.14. Spectroscopic investigation in air and hydrogen discharges heated by repeated discharge of a bank of condensers:

A spectroscopic method is to be operated for measurements of electron temperature and electron density to which plasma can be raised by utilizing the bank condenser discharge. In this experimental arrangement a discharge tube of length 8 cm. having four electrodes is used. Electrodes are circular and parallel to each other. The discharge tube is connected to exhaust pump through glass tubes. Air and prepared hydrogen have been passed through dilute solution of caustic potash to remove traces of CO_2 and is then washed with water by passing through series of wash bottles containing cold water to remove traces of caustic potash, dust particles and organic matters. It has been dried by passing through a tower of fused $CaCl_2$ and finally through P_2O_5. The pressure inside the discharge tube has been kept constant by means of a needle valve and by utilizing Mcleod gauge pressure is measured. The separation between two electrodes is 2.95 cm. to which voltage (50 cycle ac) through variac is applied for breakdown of gases. By two electrodes separated by a distance 0.85 cm. a discharge from eight charged condensers (each of 24 μF) connected in parallel, has been passed. The whole spectroscopic method has been discussed in article 2.12. By utilizing this method, the enhancement of current before and after bank condenser discharge has been noted by a microammeter for a particular spectral line and hence repeated for the other lines. The enhancement of discharge current is also noted by milliammeter between two electrodes through which condenser discharge has been passed. The above procedure is repeated for 2250 volts, 2000 volts, 1750 volts and 1500 volts discharge voltages for 0.2 torr pressure in case of air glow and for 0.7 torr pressure in case of hydrogen glow. The whole experimental arrangement is as shown in Fig. 2.16.

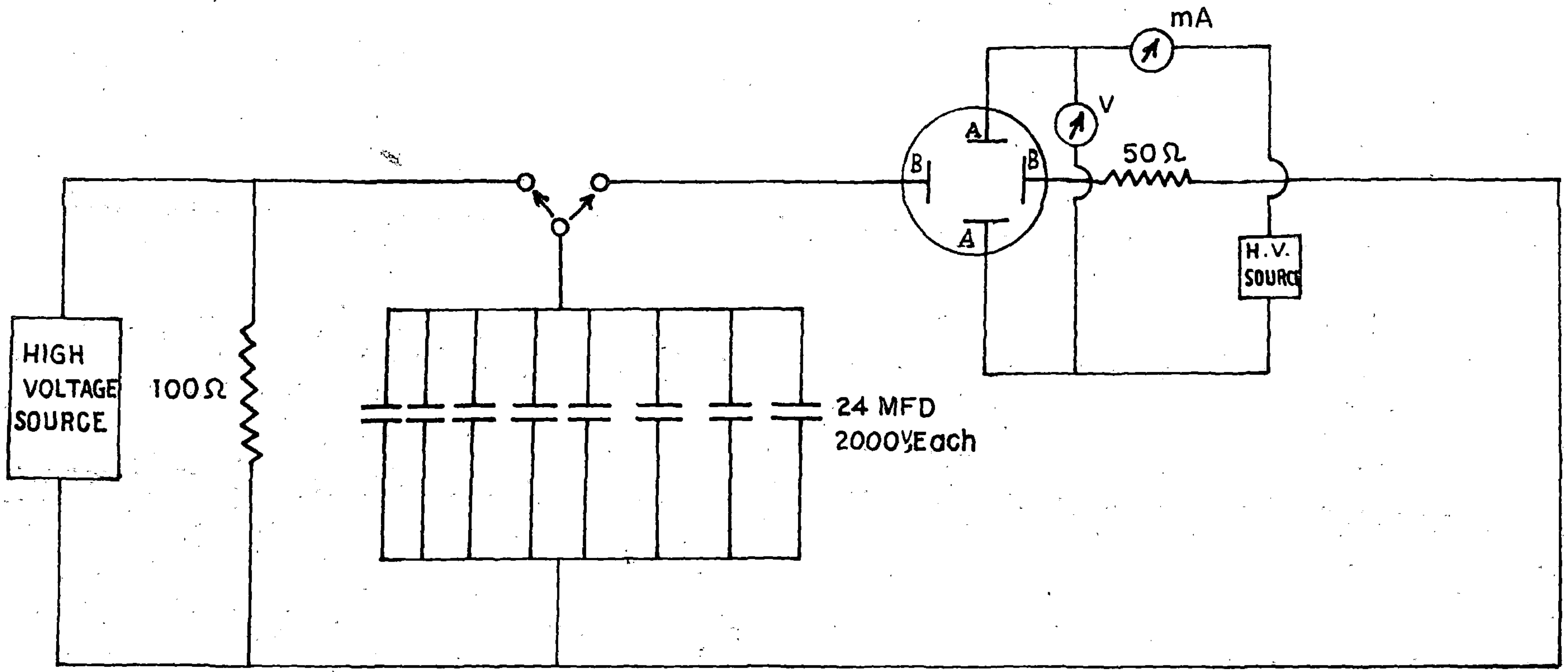

FIG. 2·16. ENHANCEMENT OF SPECTRAL INTENSITY BY BANK CONDENSER DISCHARGE .

References:

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2. Hodgman, C.D. (1956), Handbook of Chemistry and Physics, 38th. Edn. (Chemical Rubber Publishing Co., Ohio).

3. Lamar, E.S. and Compton, K.T. (1931), Phys. Rev. 37, 1069.

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CHAPTER III

MEASUREMENT OF PLASMA PARAMETERS IN AN ARC PLASMA BY PROBE METHOD

3.1. Introduction

A single probe method has been used to measure the electron temperature and electron density in an arc plasma in mercury vapour for arc current varying from 2 A to 5 A and for three background pressures namely 0.075, 0.10 and 0.13 torr. Langmuir's method for determination of electron density n_e and electron temperature T_e is well known and this is also a standard and simple method of measuring plasma parameters directly. In zero magnetic field the theory of the probe rests on the assumption that a parameter $\xi = r_p / \lambda_d$ introduced by Chen, Etievant and Mosher (1968) where r_p is the radius of the probe and λ_d is the Debye shielding length for repelled species should be greater than 5 (five). This should hold good in order that Langmuir's orbital theory for the determination of electron density and electron temperature by the single probe method can be regarded as valid. However, the limitations as well as the validity of these assumptions have been discussed by a large number of workers. In this regard a detailed discussion has been provided in the review article (Chapter I). In this laboratory Sadhya, Jana and Sen (1979) measured the electron density and electron temperature in a glow discharge in hydrogen, oxygen, nitrogen and air and investigated their variation in transverse and longitudinal magnetic fields by single probe method and the results were quantitatively explained by developing necessary mathematical formulation. It was further shown that the results obtained by probe method were in agreement with the results obtained by other methods, such as microwave and spectroscopic methods.

For the last few years Sen, S.N. and his research fellows, in this laboratory have taken up systematic investigation of the properties of arc plasma in order to develop a generalised theory as to the occurance of an arc plasma and bringing out the salient changes as regards the transition of glow discharge to arc plasma.

The measurement of electron temperature and its variation with an axial magnetic field in an arc plasma has been investigated by a spectroscopic method in detail [Sadhya and Sen (1980)] . Since a large collection of data regarding plasma parameters and their variation in a perturbing field is necessary to build up the theory for the occurance of arc plasma it is worthwhile to investigate whether the Langmuir single probe method can be utilized for measurement of arc plasma parameters. This will not only enable us to obtain the necessary data but will also extend the validity of Langmuir probe theory from the glow discharge to the arc plasma region. We report here the results of measurements of electron temperature and electron density in a mercury arc plasma for a range of arc current.

Another property that is of importance is the mechanism by which charged particles are lost by the ambipolar diffusion process . As experiment has been set up to measure the resultant diffusion voltage in an arc plasma for different arc currents. The method has been utilised by Sen, Ghosh and Ghosh (1983), in evaluation of electron temperature in glow discharge. The process of diffusion is basically connected with the radial distribution function of charged particles and an expression for the radial distribution function of the electrons in an arc plasma has been provided by Ghosal, Nandi and Sen (1978), the experimental results will be discussed in the light of the above theories.

3.2. Experimental Arrangement and Measurement

The method of measurement of electron temperature and electron density is the same as was used earlier and described in the paper by Sadhya, Jana and Sen (1979). In Chapter II the detailed experimental procedure for measurement of electron temperature and electron density has been given. Here, however, measurement has been carried out in a mercury arc plasma produced within a cylindrical glass tube of inner radius 1.31 cm with two mercury pool electrodes 38 cm apart. The schematic diagram of this experimental set up has been given in fig. 2.9 (a), (Chapt. II). The arc is produced by supplying power from a 250 V d.c. generator. The arc current has been varied from 2 A to 5 A by a regulated rheostat in series. Measurement has been taken for three background air pressures, namely 0.075 torr, 0.10 torr and 0.13 torr. A cylindrical tungsten wire of 0.014 cm radius within a glass capsule with a bare tip of 0.10 cm length is utilised as the probe which is placed at a distance of 14 cm from the anode. The probe current measurement circuit has been shown in Fig. 2.9 (a) (Chapt. II). The probe was supplied with d.c. bias voltage from dry battery through a potentiometer. For change over from ion current to electron current externally polarity reversal has been made with the help of band-switch. The circuit has been connected to the anode of the arc tube and the probe voltage which is relatively negative with respect to anode has been varied in steps from 0.2 - 5 volts. The probe current has been measured as a function of probe potential.

3.2.1. Measurement of T_e and n_e

According to Langmuir the relation between the probe current and probe voltage is given by

$$I_e = I_{re} \exp\left(-\frac{eV_p}{KT_e}\right) \quad \ldots(3.1)$$

and

$$I_{re} = \frac{1}{4} A n_e \left(\frac{8KT_e}{m\pi}\right)^{1/2} \ldots (3.2)$$

where the symbols have their usual significance. A is the effective electron collecting area of the probe and n_e is the unperturbed electron density. Assuming the distribution to be Maxwellian, T_e is calculated by taking the slope of the Boltzmann line in a semi-logarithmic plot of I_e versus V_p according to eqn. (3.1). Actually it is observed that the probe current never saturates. The rise of current with increasing positive potential is expected due to growth of effective collecting area of the probe as the sheath expands. Linear extrapolation of the curves has been made in such a way that the Boltzmann line is drawn through more points of less positive potential where the distribution is expected to be Maxwellian in accordance with the suggestion of Schott (1968). The other line is drawn in such a manner that it passes averaging the points deviated from being on the line of semilog plot points. The intersection of this line with the Boltzman line indicates the point of space potential (i.e. plasma potential) and the current corresponding to the space potential is taken as the saturation electron current which is utilised for calculating electron density from eqn. (3.2).

3.2.2. Method of measuring diffusion voltage in the arc plasma

An arc tube with internal radius 1.10 cm. was used for measurement of diffusion voltage. The separation between the two mercury pool electrodes was 4.0 cm. Two cylindrical probes of length 0.8 cm and radius 0.014 cm are placed parallel to one another one along the axis $r = 0$ and other at a distance of 0.6 cm from the axis. The output voltage at the probes was measured by a V.T.V.M. having an internal impedance of 100 $M\Omega$. A low pass filter circuit has been utilised at the output of the probes to prevent oscillations generated in the arc from reaching the V.T.V.M. The output voltage between the probes which measures the diffusion voltage has been measured for arc currents varying from 2.0 A to 5.0 A for three values of pressures namely 0.075 torr, 0.10 torr and 0.13 torr.

3.3. Results and discussion

The variation of probe current with probe potential has been plotted for arc currents 2.0, 2.5, 3.0, 4.0 and 4.5 A for pressure 0.075 torr in Fig. 3.1, for 2.0, 2.5, 3.0, 4.0 and 4.5 A for pressure 0.1 torr in Fig. 3.2 and for 2.0, 2.5, 3.0 and 4.0 A for pressure 0.13 torr in Fig. 3.3. From these results the variation of log I_e against the probe potential has been plotted for the three different pressures for the various values of the arc currents in Fig. 3.4, 3.5 and 3.6. As is expected the variation of log I_e against the probe potential is linear for a certain range of probe potential and from the slope of the curves the corresponding electron temperature has been calculated utilizing eqn. (3.1). From figs. 3.1, 3.2 and 3.3, it is seen that the probe current does not show saturation and the saturated electron current has been calculated by a method as suggested by Schott (1968). The electron density has been

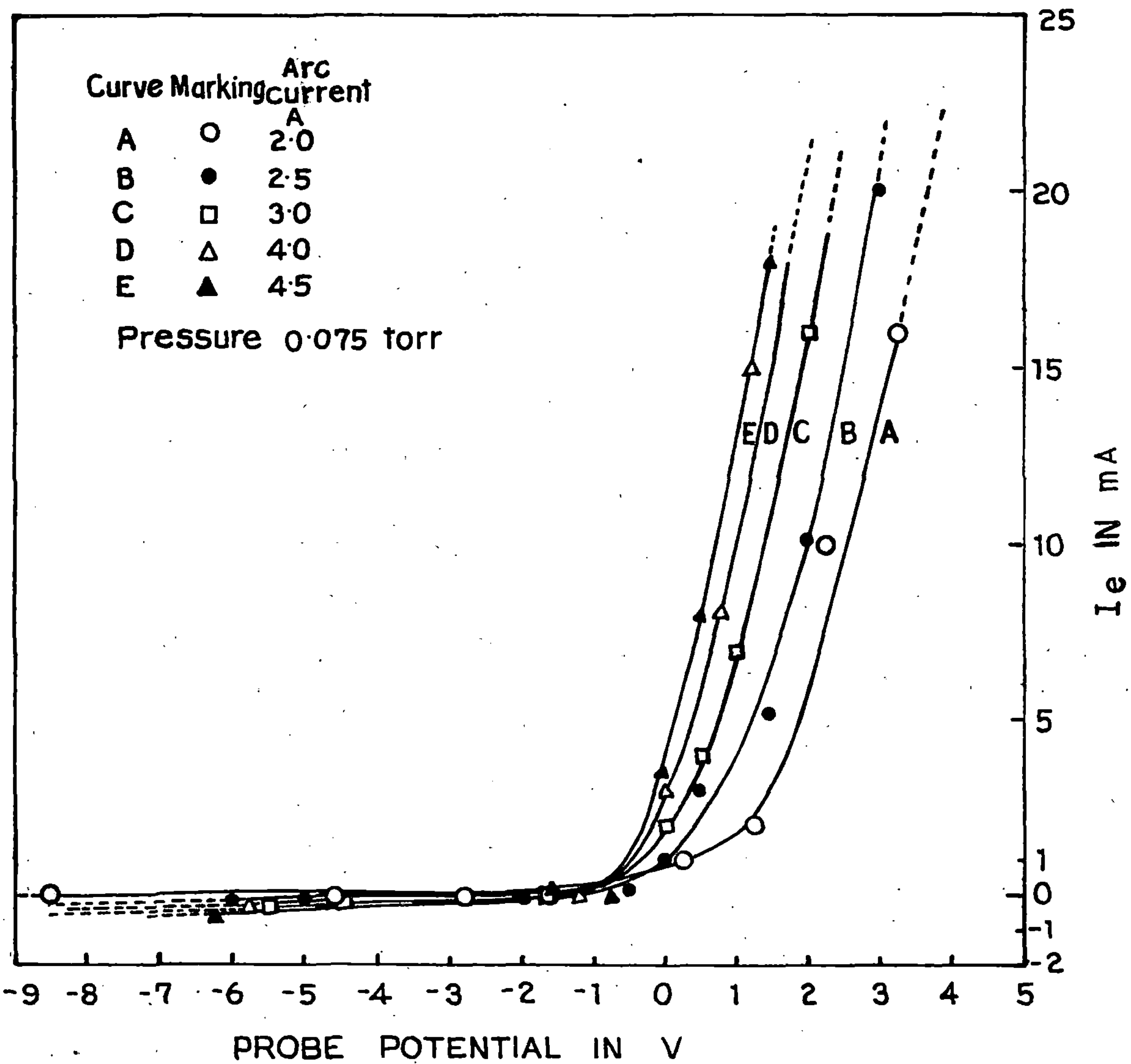
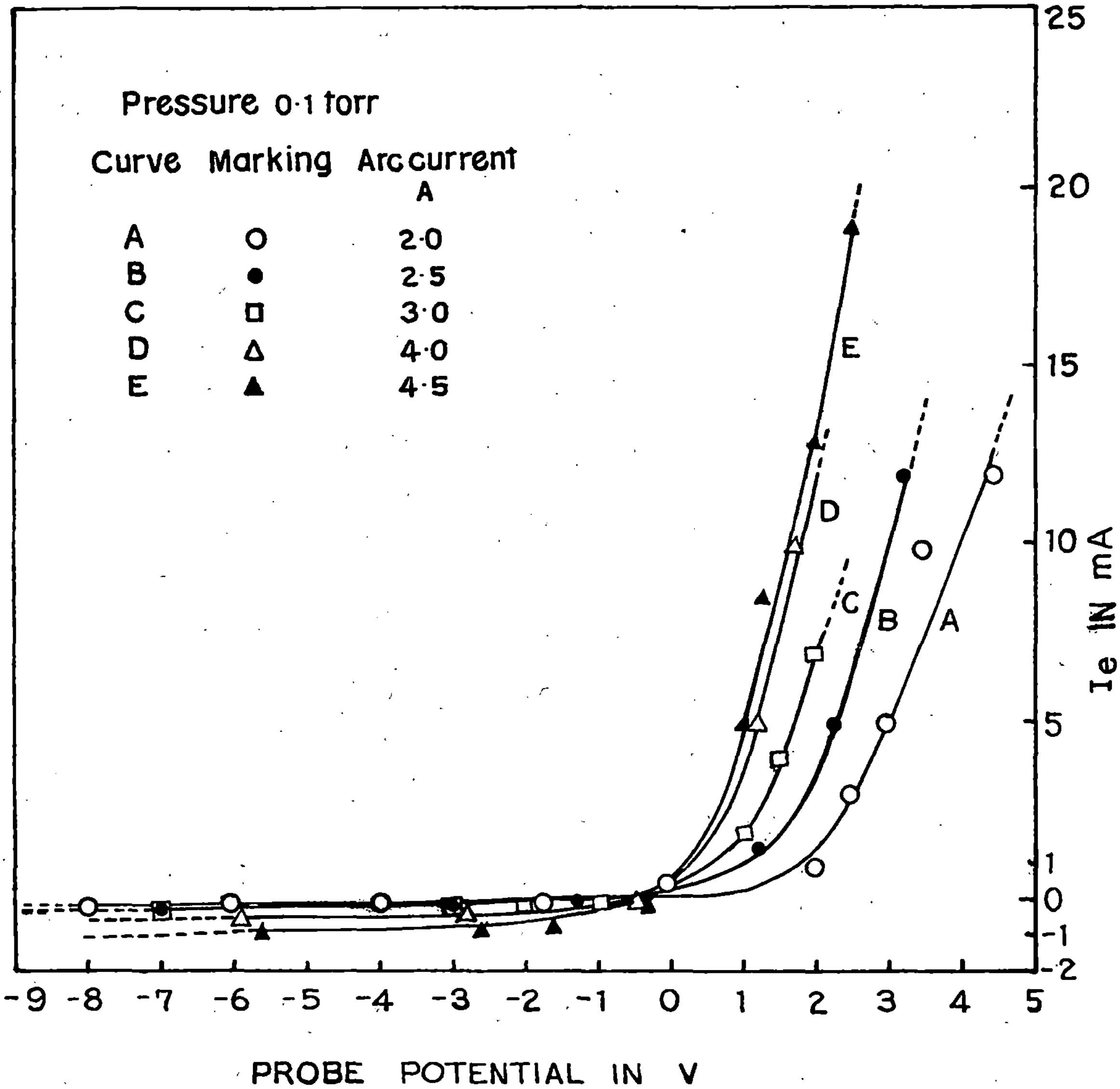

Curve Marking Arc current A
A 2·0
B 2·5
C 3·0
D 4·0
E 4·5
Pressure 0·075 torr
E D C B A
Ie IN mA
PROBE POTENTIAL IN V

FIG. 3·1



Pressure 0·1 torr
Curve Marking Arc current A
A ○ 2·0
B ● 2·5
C □ 3·0
D △ 4·0
E ▲ 4·5
A
B
C
D
E
25
20
15
10
5
1
0
-1
-2
Ie IN mA
-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5
PROBE POTENTIAL IN V

FIG 3·2.

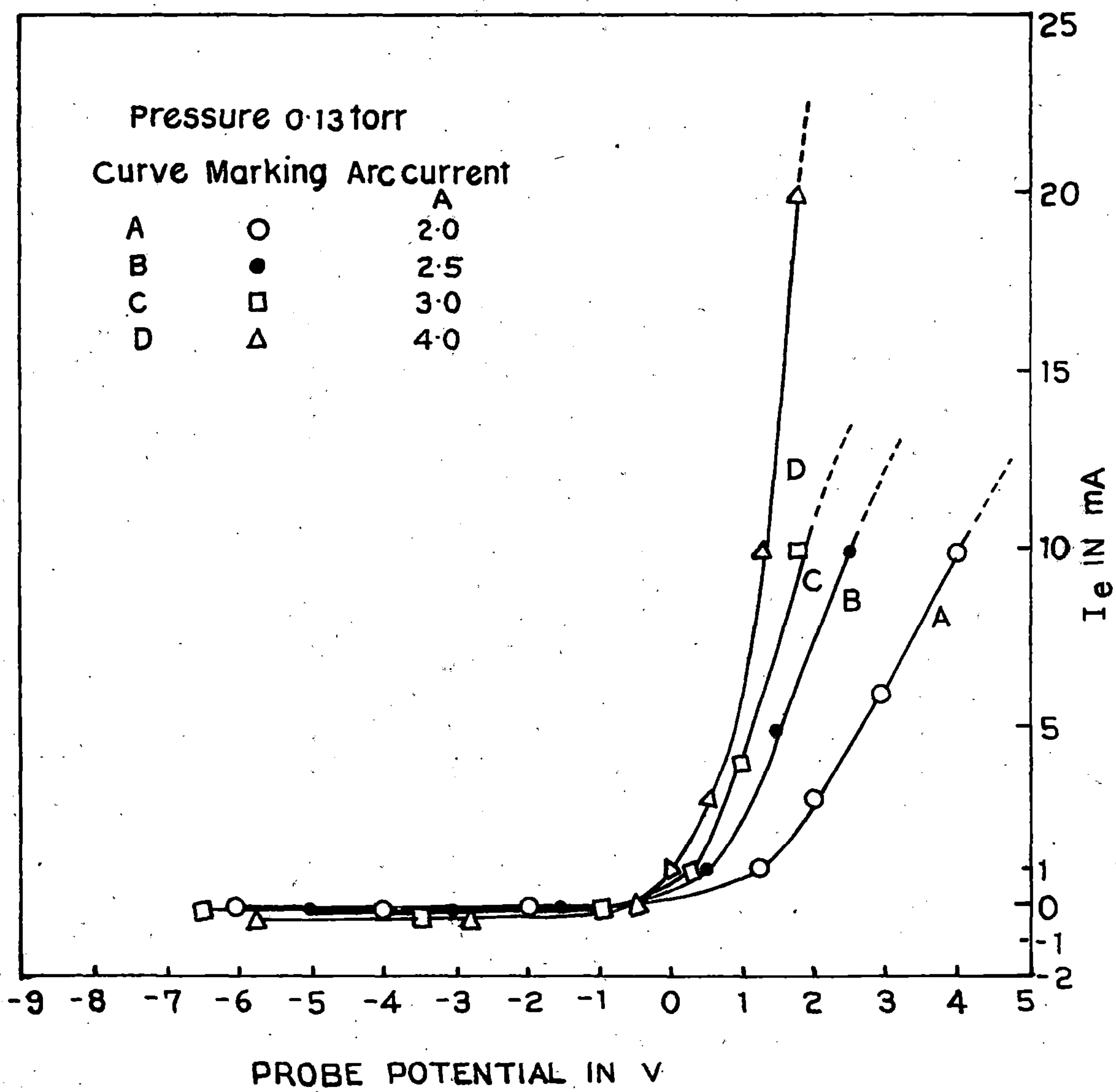
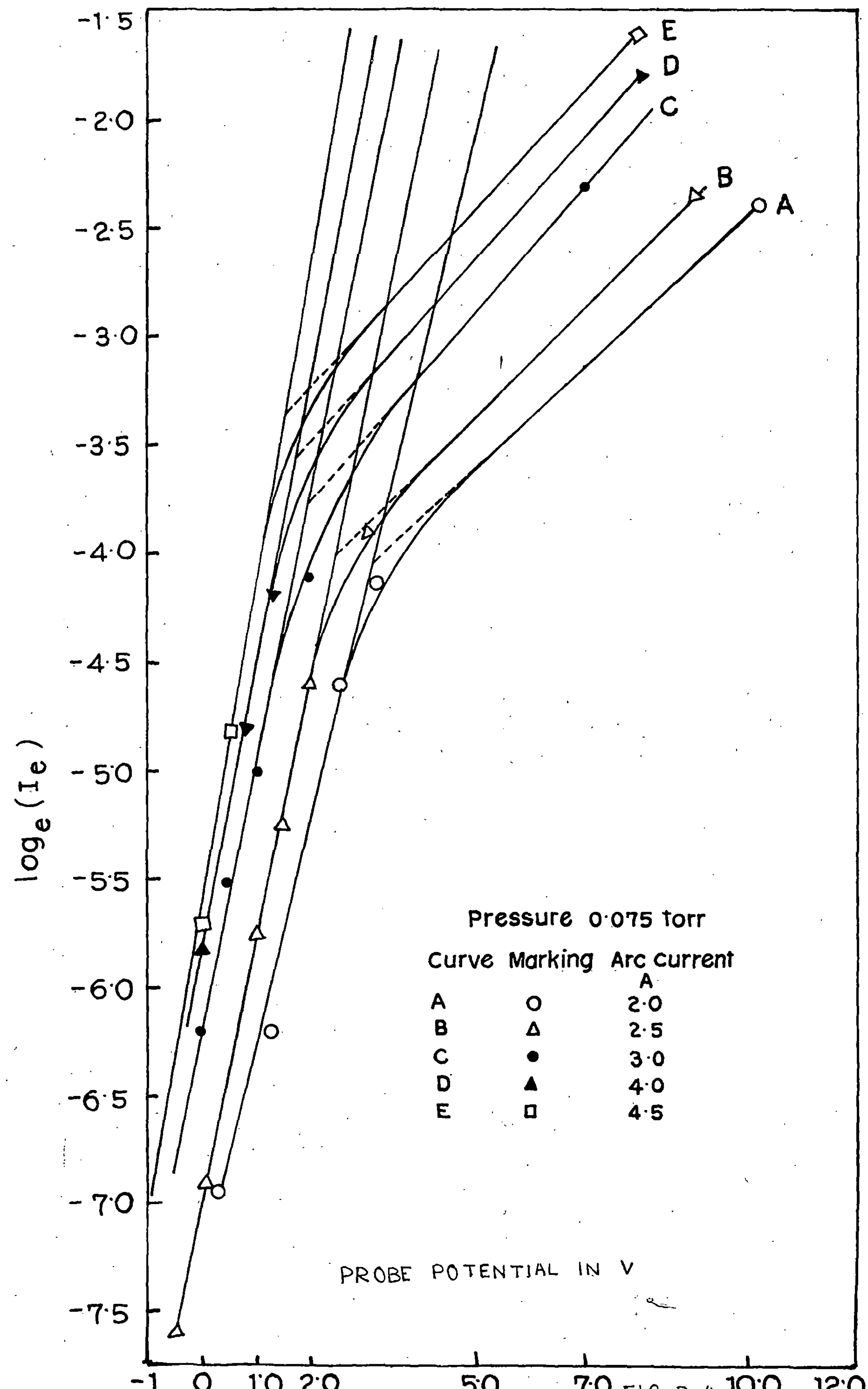

Pressure 0·13 torr
Curve Marking Arc current A
A O 2·0
B ● 2·5
C □ 3·0
D Δ 4·0
A
B
C
D
25
20
15
10
5
1
0
-1
-2
Ie IN mA
-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5
PROBE POTENTIAL IN V

FIG. 3·3



-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
-5.5
-6.0
-6.5
-7.0
-7.5
$\log_e(I_e)$
E
D
C
B
A
Pressure 0·075 torr
Curve Marking Arc current A
A O 2·0
B Δ 2·5
C ● 3·0
D ▲ 4·0
E □ 4·5
PROBE POTENTIAL IN V
-1
0
1·0
2·0
5·0
7·0
10·0
12·0

FIG. 3.4

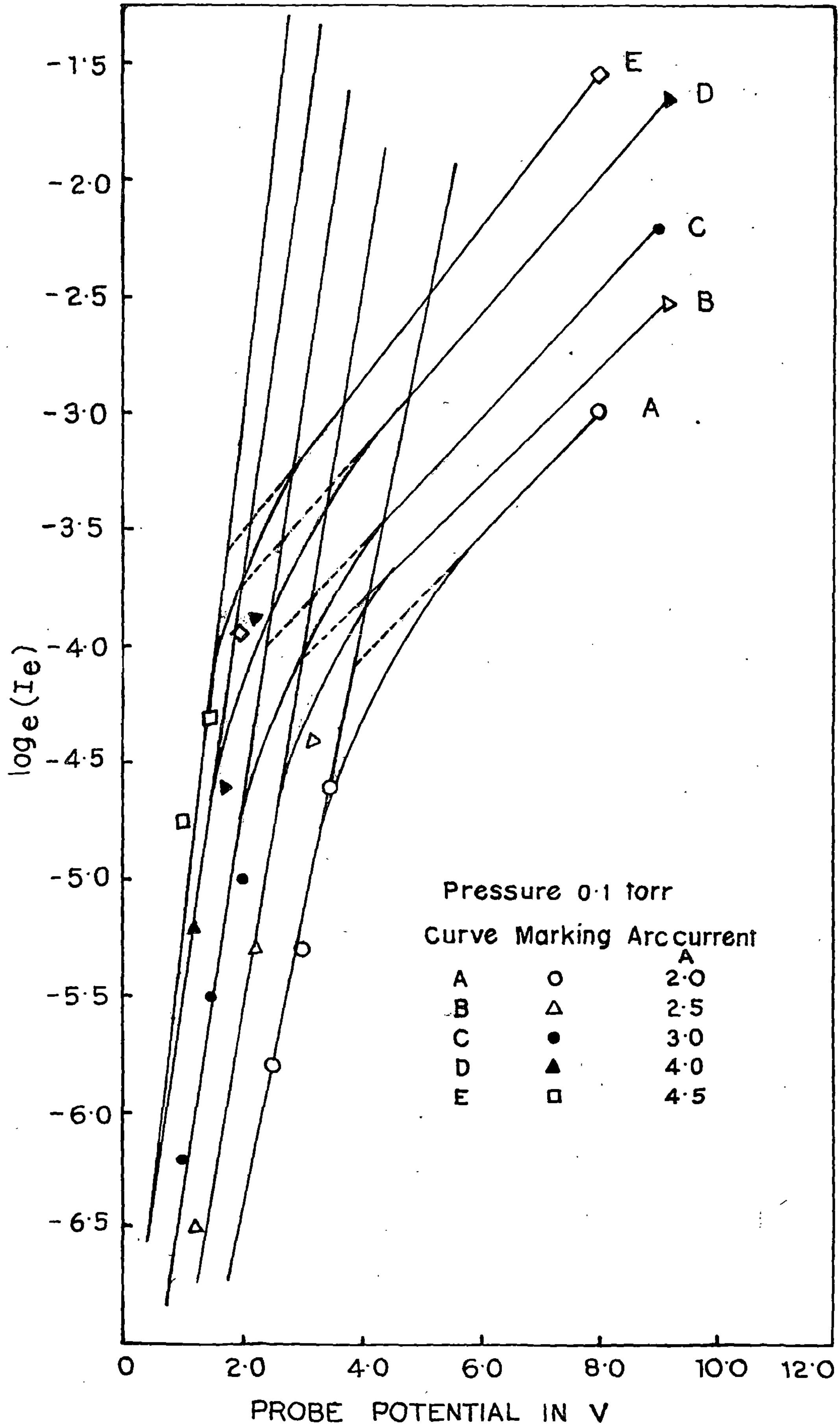
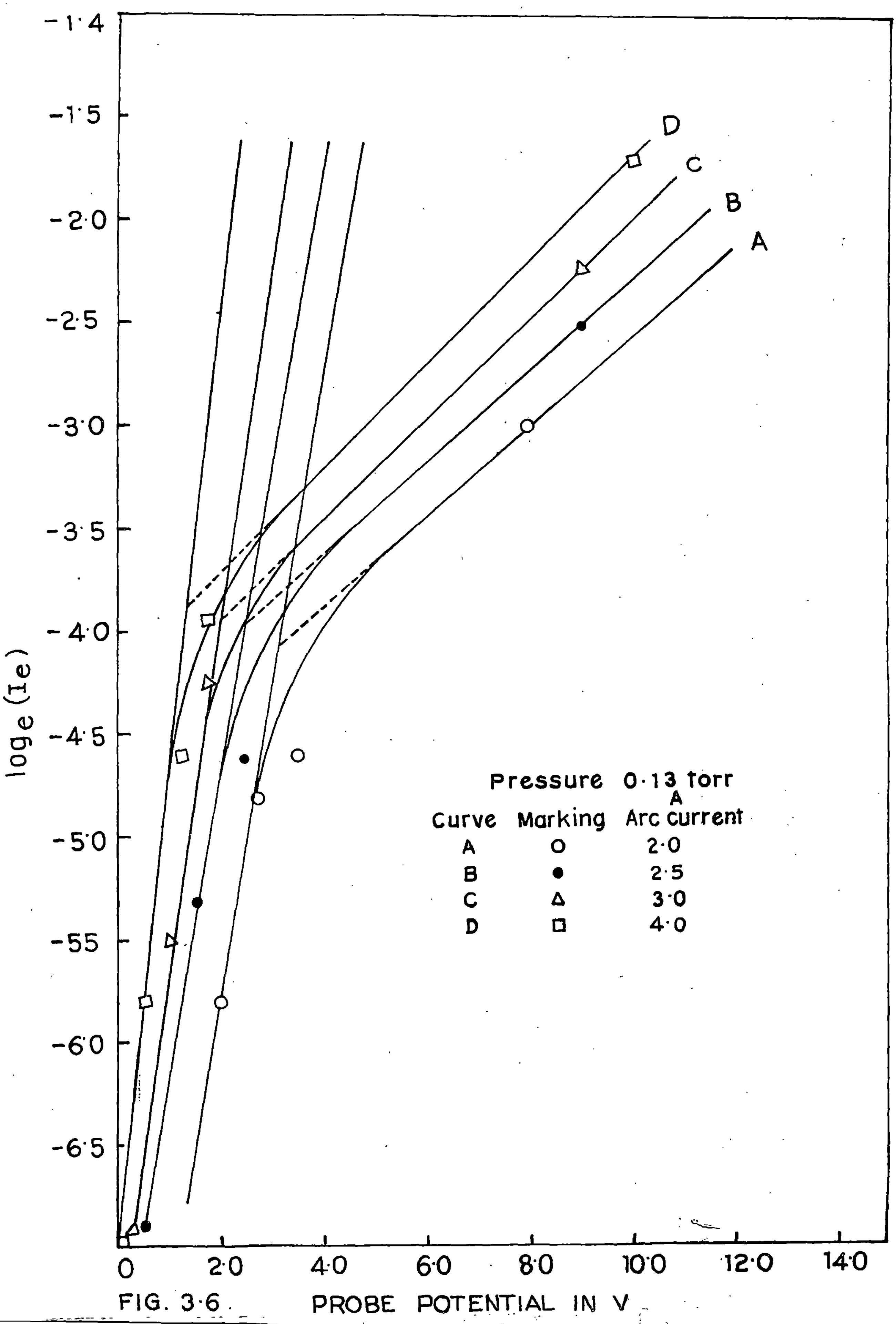

$\log_e(I_e)$
-1·5
-2·0
-2·5
-3·0
-3·5
-4·0
-4·5
-5·0
-5·5
-6·0
-6·5
E
D
C
B
A
Pressure 0·1 torr
Curve Marking Arc current A
A ○ 2·0
B △ 2·5
C ● 3·0
D ▲ 4·0
E □ 4·5
0
2·0
4·0
6·0
8·0
10·0
12·0
PROBE POTENTIAL IN V

FIG. 3·5.



-1·4
-1·5
-2·0
-2·5
-3·0
-3·5
-4·0
-4·5
-5·0
-55
-6·0
-6·5
$\log_e (I_e)$
0
2·0
4·0
6·0
8·0
10·0
12·0
14·0
D
C
B
A
Pressure 0·13 torr
Curve Marking Arc current A
A O 2·0
B ● 2·5
C Δ 3·0
D □ 4·0
PROBE POTENTIAL IN V

FIG. 3·6

calculated from eqn. (3.2). The results are entered in columns (4) and (5) of Table 3.1. Langmuir (1925) while studying the scattering of electrons in mercury arc discharge deduced an expression for the arc current density given by

$$I = 5{\cdot}76 \times 10^{-10} \frac{n_e \lambda E}{\sqrt{T_e}} \quad \ldots (3.3)$$

where n_e is the electron density, λ the mean free path of electron, T_e is the electron temperature and E is the axial electric field per cm. From this expression it is evident that at a particular pressure the quantity $IT_e^{1/2}/n_eE$ should be constant for different arc currents for different pressures. The results are entered in column 7 of table 3.1. It is evident that the values calculated for $IT_e^{1/2}/n_eE$ show a fair degree of consistency justifying the validity of eqn. (3.3) for the arc current.

From the eqn. (3.3) it is evident that the mean free path of the electron can be calculated for different values of pressures. Taking the mean value of $IT_e^{1/2}/n_eE$ as entered in column (8) of Table 3.1, the value of λ has been calculated and results entered in table 3.2, column (3). From col.(4)

it is evident that $P\lambda$ is almost a constant for three different pressures and we can calculate $L = .P\lambda$ the mean free path of the electron at a pressure of 1.0 torr in the mercury vapour. There is no direct method for measurement of mean free path of the electron in the gas. The mean free path of molecule from kinetic theory of gases is $1/\sqrt{2}N\pi\sigma^2$ where N is the number of molecules per unit volume and σ is the molecular diameter. In case of mercury this cames out to be 3×10^{-3} cm. at 1.0 torr.

The mean free path of an electron has been found by classical reasoning to be $4\sqrt{2}\,\lambda$ and this expression has the correct order of magnitude. However, the electronic mean free path becomes a function of the energy of electron due to Ramsauer and Townsend effect.

The variation of open circuited diffusion voltage with arc current as measured has been plotted in fig. 3.7 for three pressures namely 0.075 torr, 0.10 torr and 0.13 torr. It is observed 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. In a previous paper Sen, Ghosh and Ghosh (1983) have measured diffusion voltage in a glow discharge and have obtained the variation of electron temperature with a transverse magnetic field. In glow discharge the radial distribution of charged particles

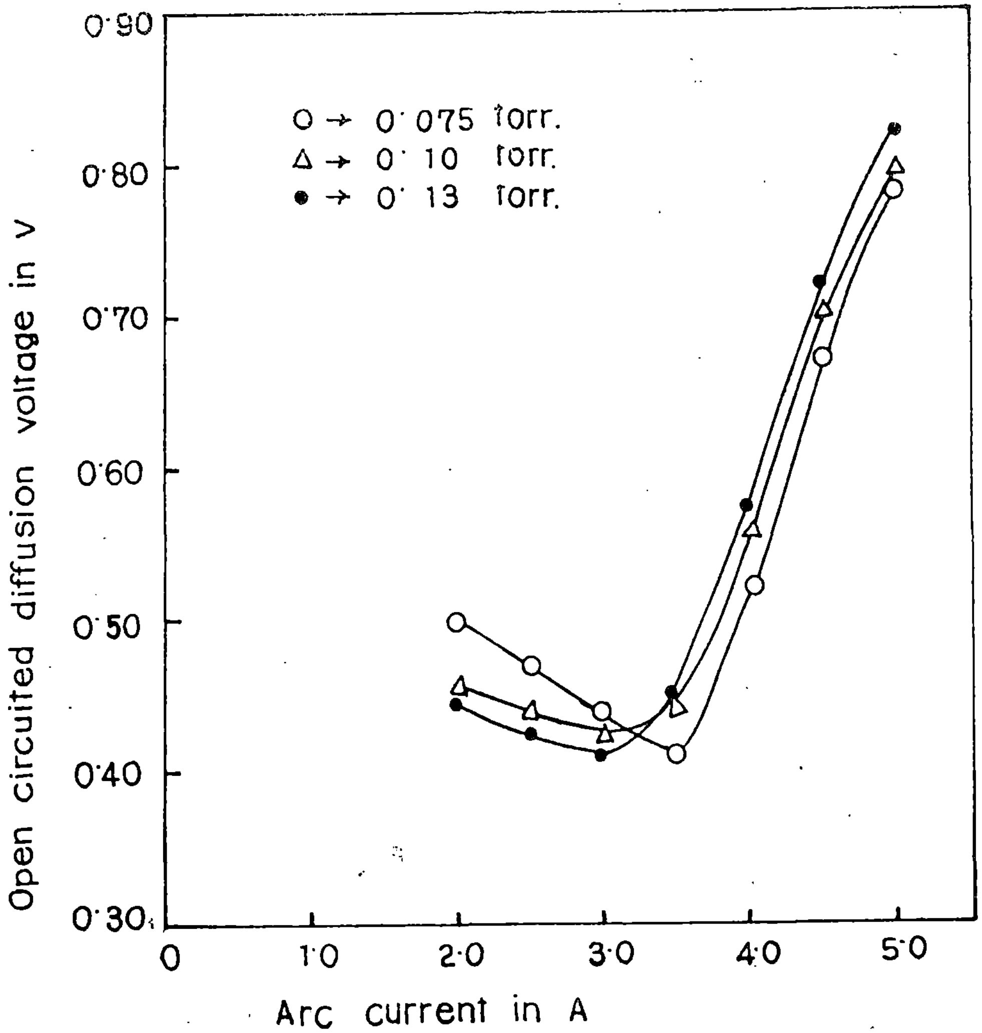

O → 0·075 torr.
Δ → 0·10 torr.
● → 0·13 torr.
Open circuited diffusion voltage in V
0·90
0·80
0·70
0·60
0·50
0·40
0·30
0
1·0
2·0
3·0
4·0
5·0
Arc current in A

FIG. 3·7.

Table 3.1

Background air pressure in Torr.	Arc current in amp.	Mercury vapour pressure in torr	Electron temperature in ^{o}K	Electron density x 10^{-12} cm^{-3}	Arc drop in volts	$\frac{I T_e^{1/2}}{n_e E}$ $x 10^{10}$	Average $\frac{I T_e^{1/2}}{n_e E}$ $x 10^{10}$
	2.0	0.2342	11487.3	0.6967	42	0.5159	
	2.5	0.2752	10131.0	0.7803	41	0.5534	
0.075	3.0	0.3032	9572.8	0.9812	39	0.5406	0.5352
	4.0	0.3342	9041.6	1.2964	38	0.5448	
	4.5	0.3658	8521.9	1.5608	36	0.5213	
	2.0	0.2343	8195.6	0.7856	44	0.3694	
	2.5	0.2752	7593.5	0.8580	43	0.4159	
0.1	3.0	0.3032	6066.9	1.0092	42	0.3890	0.3875
	4.0	0.3342	5839.4	1.3208	41	0.3980	
	4.5	0.3658	5532.1	1.5766	39	0.3655	
	2.0	0.2343	7785.8	0.8473	47	0.3124	
	2.5	0.2752	7079.2	0.9336	46	0.3453	0.3321
0.13	3.0	0.3032	5696.9	1.0948	44	0.3313	
	4.0	0.3342	4800.0	1.3704	42	0.3395	

Table 3.2.

Background pressure in torr	$\frac{I T_e^{1/2}}{n_e E}$ $\times 10^{10}$	λ cm	$P\lambda = L$ cm
0.075	0.5352	9.294×10^{-2}	6.971×10^{-3}
0.1	0.3875	6.728×10^{-2}	6.728×10^{-3}
0.13	0.3321	5.765×10^{-2}	7.494×10^{-3}

density has been assumed to be Besselian. It has however, been shown by Ghosal, Nandi and Sen (1978) that the radial distribution function for the azimuthal conductivity for an arc plasma is given by

$$\sigma(r) = \sigma(o)\left[1 - \left(\frac{r}{R}\right)^2\right]^n \quad \ldots(3.4)$$

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

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

where 'a' is an experimentally determined quantity which varies with arc current. This distribution function can very well represent the radial charged particle distribution in an arc plasma. It has been shown by Sen, Ghosh and Ghosh (1983) that the diffusion voltage V_R is

$$V_R = - \int \frac{dn_e}{n_e} \quad \frac{KT_e}{e} \quad \dots (3.5)$$

and since the electron density is proportional to the conductivity we get from equation (3.4)

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

and from eqn. (3.5)

$$V_R = - \frac{nKT_e}{e} \int \frac{\left(-\frac{2r}{R^2}\right)}{\left(1 - \frac{r^2}{R^2}\right)} dr$$

Let $Z = \left(1 - \frac{r^2}{R^2}\right)$

then $$V_R = - \frac{nKT_e}{e} \int \frac{dZ}{Z}$$

$$= - \frac{nKT_e}{e} \log Z + C$$

eqn. at

$$r = 0, \ V_R = 0 \text{ and } C = 0$$

Hence

$$V_R = -\frac{nKT_e}{e}\log\frac{R^2-r^2}{R^2}$$

$$= \frac{2nKT_e}{e}\log\frac{R}{\sqrt{R^2-r^2}} \qquad \cdots (3.6)$$

The values of electron temperature for the arc current for which diffusion voltage has been measured can be obtained from the first part of the present paper. Some values for n were obtained by Ghosal, Nandi and Sen (1978), but a measurement of n for a wider range of current has been carried out in this laboratory by the present author and variation in the value of n with arc current is plotted in fig. 3.8. Hence it is numerically possible to calculate the values of V_R for different arc currents at different pressures from eqn. (3.6). The results are entered in Table 3.3. It is observed that though the theoretically calculated values are higher than the corresponding experimental results, the minimum voltage occurs at the same value of arc 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.

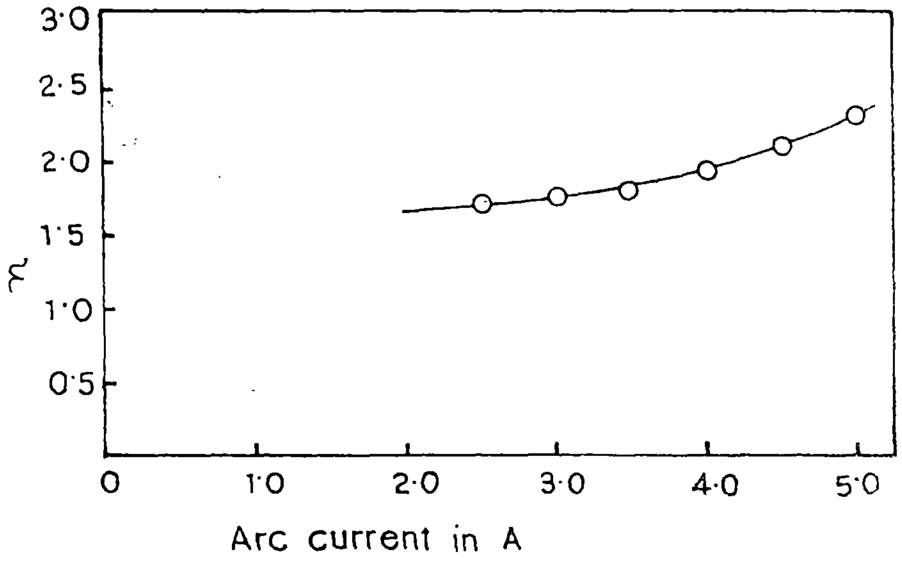


FIG. 3·8.

Table 3.3

Pressure in Torr	Arc current in Amps.	Diffusion voltage in volts	
		Experimental	Theoretical
	2.0	0.498	0.575
	2.5	0.470	0.527
	3.0	0.438	0.506
0.075	4.0	0.518	0.539
	4.5	0.670	0.544
	5.0	0.78	0.588*
	2.0	0.458	0.410
	2.5	0.438	0.374
	3.0	0.435	0.349
0.10	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	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 values

The results are presented in table 3.4.

Table 3.4

Pressure in Torr	Arc current in Amp at which diffusion voltage is minimum
0.075	3.50
0.10	3.25
0.13	3.00

We can thus conclude that the distribution formula for azimuthal conductivity as proposed by Ghosal, Nandi and Sen (1978) gives results in quantitative agreement with experimental results. We have thus seen that the Langmuir probe method can also be utilised for the measurement of electron temperature and electron density just as in the case of glow discharge and the results are consistent with the values obtained by spectroscopic method (Sadhya and Sen, 1980). Langmuir's expression for arc current (eqn. 3.3) is verified and the results provide a means of calculating the electronic mean free path in the gas.

The not too satisfactory agreement between the diffusion voltage calculated and experimentally observed results may be attributed to some uncertainty in the value of n but the occurance of minima as observed experimentally at the same calculated value of the arc current at three pressures lends support to the validity of distribution function as proposed by Ghosal, Nandi and Sen (1979). The importance of the experiment is that the electron temperature can be measured accurately without perturbing the plasma by only measuring the open circuited diffusion voltage.

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Measurement of plasma parameters in an arc plasma by a single probe method

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A single probe method has been used to measure the electron temperature and electron density in an arc plasma in mercury vapour for arc current varying from 2 to 5 A and for three background pressures of 0.075, 0.1 and 0.13 torr. Langmuir's expression [*Phys Rev* (*USA*), 26 (1925) 585] for arc current has been found to be valid within the range of arc current investigated and the results have been utilized to calculate the mean free-path of the electron in mercury vapour. The open circuited diffusion voltage in the arc plasma has also been measured for the same range of current and voltage. Utilizing the radial distribution function of conductivity as introduced by S K Ghosal, G P Nandi and S N Sen [*Int J Electron* (*GB*), 44 (1978) 409] an analytical expression for the diffusion voltage has been calculated which can satisfactorily explain the observed results. The validity of the probe method for measurement of plasma parameters in an arc plasma has been discussed.

1 Introduction

The measurement of plasma parameters such as electron density and electron temperature by single probe Langmuir method is well known. In zero magnetic field, the theory of the probe rests on the assumption that the parameter $\xi = r_p/\lambda_d$ introduced by Chen *et al.*[1], where r_p is the radius of the probe and λ_d is the Debye shielding length, for repelled species, should have a value greater than 5. This should hold good in order that Langmuir's orbital theory for the determination of electron density and electron temperature by the single probe method can be regarded as valid. Sadhya *et al.*[2] measured the electron density and electron temperature in a glow discharge in hydrogen, oxygen, nitrogen and air and investigated their variation in transverse magnetic fields by the single probe method and the results were quantitatively explained by developing necessary mathematical formulation. It was further shown that the results obtained by the probe method were in agreement with the results obtained by other methods, such as microwave and spectroscopic methods.

For the last few years we have taken up a systematic investigation of the properties of arc plasma in order to develop a generalized theory as to the occurrence of an arc plasma and bringing out the salient changes as regards the transition of glow discharge to arc plasma. The measurement of electron temperature and its variation with an axial magnetic field in an arc plasma has been investigated by a spectroscopic method in detail by Sadhya and Sen[3]. Since a large collection of data regarding plasma parameters and their variation in a perturbing field is necessary to build up the theory for the occurrence of arc plasma, it is worthwhile to investigate whether the Langmuir single probe method can be utilized for measurement of arc plasma parameters. This will not only enable us to obtain the necessary data but will also indicate whether Langmuir's oribital theory can be extended for measurement in case of arc plasma as well. We report here the results of measurement of electron temperature and electron density in a mercury arc plasma for different background air pressures and the corresponding mercury vapour pressures for different arc currents.

Another important property that is of importance is the mechanism by which charged particles are lost from a plasma. One of the main factors is the loss by the ambipolar diffusion process. When the process of diffusion becomes ambipolar, a steady radial voltage develops due to charge separation which is defined as diffusion voltage. An experiment has been set up to measure the resultant diffusion voltage in an arc plasma for different arc currents. The method has been utilized by Sen *et al.*[4] in evaluation of electron temperature in glow discharge. The process of diffusion is basically connected with the radial distribution function of charged particles and an expression for the radial distribution function of the electrons in an arc plasma has been provided by Ghosal *et al.*[5] The experimental results will be analyzed in the light of the above theories.

2 Experimental Arrangement and Measurement

The method of measurement of electron temperature and electron density is the same as was used earlier and described in the paper by Sadhya *et al.*[2] Here however, measurement has been carried out in a mercury arc plasma produced within a cylindrical glass tube of inner radius 1.31 cm with two mercury pool electrodes 38 cm apart. The arc is excited by supplying power from a 250 V dc generator where the arc current has been varied from 2 to 5 A by a regulated rheostat in series. Measurement has been taken for three background air pressures (0.075, 0.1 and 0.13 torr). The corresponding values of mercury vapour pressure for different arc currents are entered in Table 1. A cylindrical tungsten wire of 0.014 cm radius within a glass capsule with a bare tip of 0.1 cm length is utilized as the probe which is placed at a distance of 14 cm from the anode.

2.1 Measurement of T_e and n_e

In order to justify the validity of Langmuir's probe theory in the present experimental set-up, the vapour pressure of mercury was determined as in an earlier paper by Sadhya and Sen[3] by noting the temperature of the wall for different arc currents. The results are entered in the third column in Table 1. The Debye shielding length λ_d is of the order of 10^{-3} cm for these pressures and since the radius of the probe is 0.014 cm, the criteria (Chen *et al.*[1]) that $\xi = r_p/\lambda_d$ should be greater than 5 is satisfied. Further the electronic mean free-path of mercury vapour at an average pressure of 0.3 torr is 7.6×10^{-2} cm and the radius of the probe is 1.4×10^{-2} cm and hence $r_p < \lambda_e$, which also satisfies the criteria for Langmuir's probe theory. According to Langmuir, the relation between the probe current and probe voltage is given by:

$$I_e = I_{re} \exp\left(-\frac{eV_p}{kT_e}\right) \qquad \ldots (1)$$

and

$$I_{re} = \frac{1}{4} A n_e \left(\frac{8kT_e}{m\pi}\right)^{1/2} \qquad \ldots (2)$$

where the symbols have their usual significance. A is the effective electron collecting area of the probe and n_e is the unperturbed electron density. Assuming the distribution to be Maxwellian, T_e is calculated by taking the slope of the Boltzmann line in a semilogarithmic plot of I_e versus V_p according to Eq. (1). Actually it is observed that the probe current never saturates. The rise of current with increasing positive potential is expected due to growth of effective collecting area of the probe as the sheath expands. Linear extrapolation of the curves has been made in such a way that the Boltzmann line is drawn through more points of less positive potential where the distribution is expected to be Maxwellian in accordance with the suggestion of Schott[6]. The other line is drawn in

Table 1—Variation of electron temperature and electron density at different arc currents for different pressures

Background air pressure torr	Arc current A	Mercury vapour pressure in torr	Electron temp. K	Electron density $\times 10^{-12}$ cm^{-3}	Arc drop V	$IT_e^{1/2}/n_eE$ $\times 10^{10}$	Average $IT_e^{1/2}/n_e$ $\times 10^{10}$
0.075	2.0	0.2343	11487.3	0.6967	42	0.5159	0.5352
	2.5	0.2752	10131.0	0.7803	41	0.5534	
	3.0	0.3032	9572.8	0.9812	39	0.5406	
	4.0	0.3342	9041.6	1.2964	38	0.5448	
	4.5	0.3658	8521.9	1.5608	36	0.5213	
0.1	2.0	0.2343	8195.6	0.7856	44	0.3694	0.3875
	2.5	0.2752	7593.3	0.8580	43	0.4159	
	3.0	0.3032	6066.9	1.0092	42	0.3890	
	4.0	0.3342	5839.4	1.3208	41	0.3980	
	4.5	0.3658	5532.1	1.5766	39	0.3653	
0.13	2.0	0.2343	7785.8	0.8473	47	0.3124	0.3321
	2.5	0.2752	7079.2	0.9336	46	0.3453	
	3.0	0.3032	5696.9	1.0948	44	0.3313	
	4.0	0.3342	4800.0	1.3704	42	0.3395	

such a manner that it passes averaging the points deviated from being on the line of semilog plot points. The intersection of this line when extrapolated backwards with the Boltzmann v line indicates the point of space potential and the current corresponding to this space potential is taken as the saturation electron current which is utilized for calculating electron density from Eq. (2).

2.2 Method of Measuring Diffusion Voltage in the Arc Plasma

A mercury arc with internal radius 1.1 cm was used for measurement of diffusion voltage. The separation between the two mercury pool electrodes was 41 cm. Two identical cylindrical probes of length 0.8 cm and diameter 0.01 cm are placed parallel to each other, one along the axis $r=0$ and the other at a radial distance 0.6 cm from the axis. The output voltage at the probes was measured by a VTVM having an internal impedance of 100 MΩ. The voltage across the two probes is the diffusion voltage and has been measured for arc currents varying from 2 to 5 A for three values of background air pressure namely 0.075, 0.10 and 0.13 torr.

3 Results and Discussion

The variation of probe current with probe potential has been plotted for arc currents 2, 2.5, 3, 4 and 4.5 A for a background pressure 0.075 torr in Fig. 1; for arc currents 2.0, 2.5, 3, 4 and 4.5 A for a pressure 0.1 torr in Fig. 2 and for arc currents 2.0, 2.5, 3.0 and 4.0 A for a pressure 0.13 torr in Fig. 3. From these results the variation of log I_e against the probe potential has been plotted for

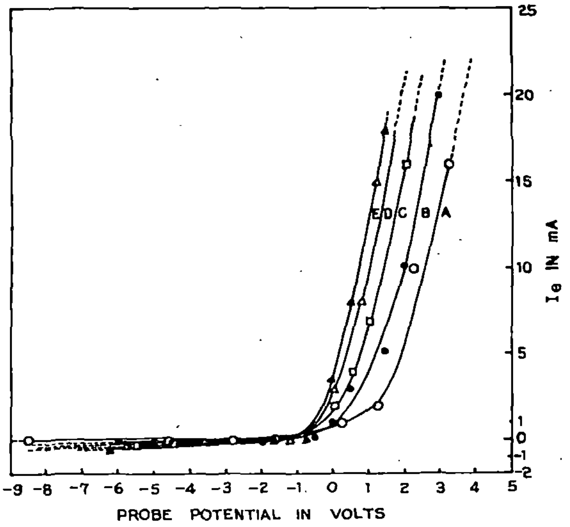

Fig. 1—Variation of probe current with probe voltage [pressure 0.075 torr]

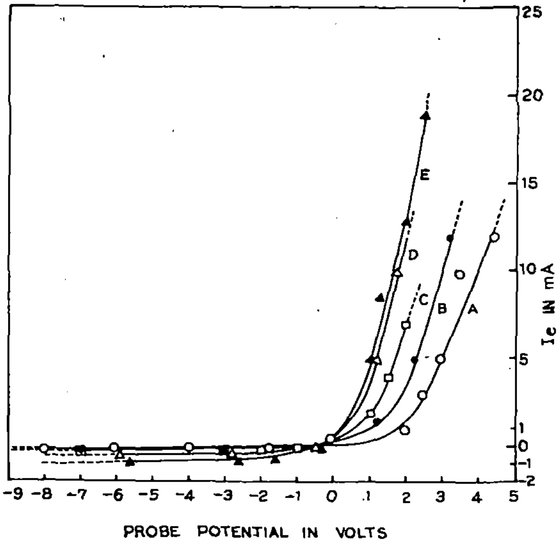

Fig. 2—Variation of probe current with probe voltage [pressure 0.1 torr]

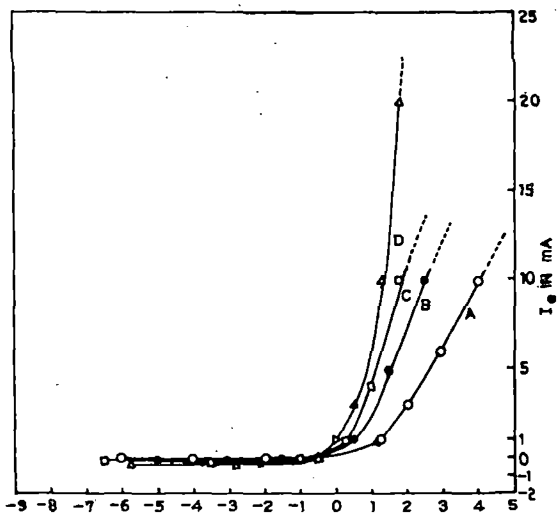

Fig. 3—Variation of probe current with probe voltage [pressure 0.13 torr]

the three different pressures for the various values of the arc currents in Figs 4-6. As is expected, the variation of $\log I_e$ against the probe potential is linear for a certain range of probe potential and from the slope of the curves the corresponding electron temperature has been calculated utilizing Eq. (1). From Figs 1-3 it is seen that the probe current does not show saturation and as mentioned earlier the saturated electron current has been calculated by a method as suggested by Schott[6]. The electron density has been calculated from Eq. (2). The results are prsented in Table 1. Langmuir[7] while studying the scattering of electrons in a mercury arc discharge deduced an ex-

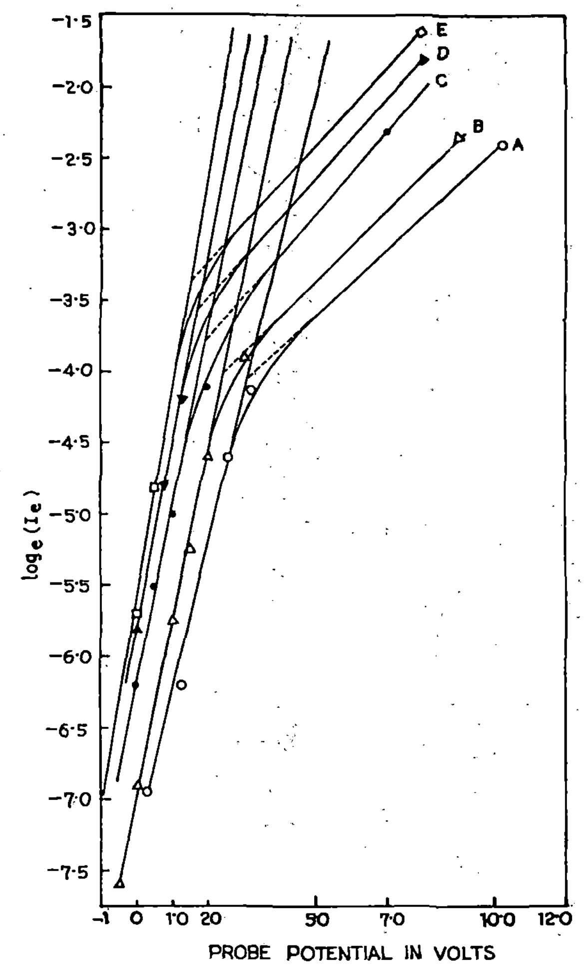

Fig. 4—Variation of log T_e with probe voltage [pressure 0.075 torr]

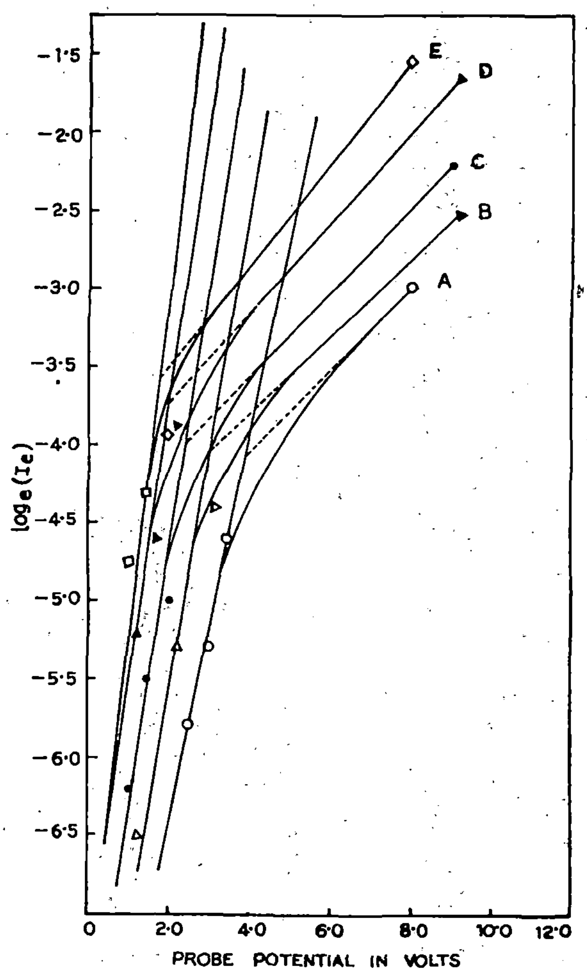

Fig. 5—Variation of log I_e with probe voltage [pressure 0.1 torr]

pression for the arc current density given by:

$$I = 5.76 \times 10^{-10} \frac{n_e \lambda_e}{T_e^{1/2}} \qquad \ldots (3)$$

where n_e is the electron density, λ_e, the mean free-path of the electron, T_e, the electron temperature and E the axial electric field per cm. From this expression it is evident that at a particular pressure, the quantity $IT_e^{1/2}/n_eE$ should be a constant for different arc currents. Since both the electron temperature and electron density have been measured for different arc currents and corresponding voltage drop across the arc has been measured, the quantity $IT_e^{1/2}/n_eE$ can be calculated for different arc currents for different pressures. The results are entered in column 7 of Table 1. It is evident that the values calculated for $IT_e^{1/2}/n_eE$ show a fair degree of consistency justifying the validity of Eq. (3) for the arc current.

From Eq. (3) it is evident that λ_e the mean free-path of the electron can be calculated for different values of background air pressure. Taking the mean value of $IT_e^{1/2}/n_eE$ as entered in column 8 of Table 1, the value of λ_e has been calculated and results entered in Table 2, column 3. From column 4 it is evident that $P\lambda_e$ is almost a constant for three different pressures and we can calculate $L = P\lambda_e$ the mean free-path of the electron at a pressure of 1 torr. The result is entered in the fourth column in Table 2. There is no direct method for measurement of mean free-path of the electron in the gas. The mean free-path of a molecule from kinetic theory of gases is $1/\sqrt{2}n\pi\sigma^2$ where N is the number of molecules per unit volume and σ is the molecular diameter. In case of mercury, this comes out to be 3×10^{-3} cm at 1 torr. The mean free-path of an electron has been found by classical reasoning to be $4\sqrt{2}\lambda$ and this expression gives the correct order of magnitude as obtained experi-

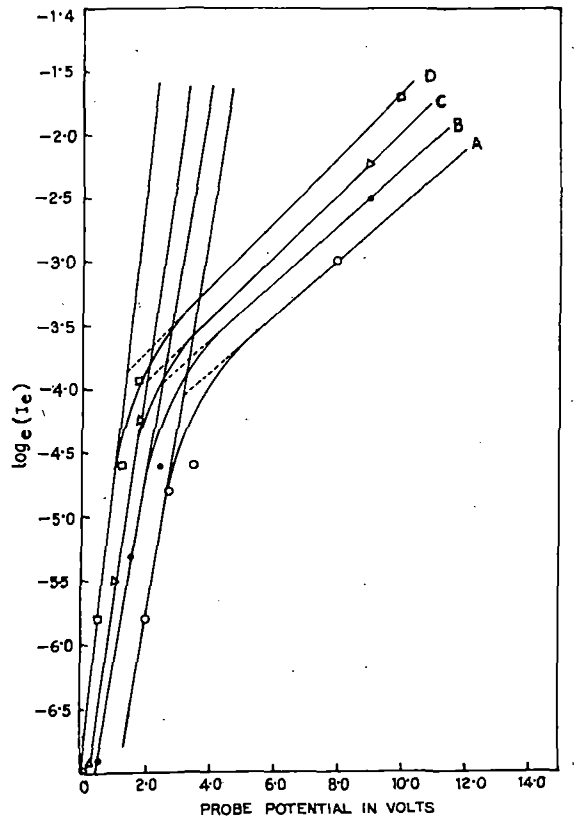

Fig. 6—Variation of log I_e with probe voltage [pressure 0.13 torr]

Table 2—Calculation of electronic mean free-path at different pressures

Background pressure torr	$IT_e^{1/2}/n_eE$ $\times 10^{10}$	$\lambda_e \times 10^{-2}$ cm	$P\lambda_e = L \times 10^{-3}$ cm
0.075	0.5352	9.294	6.971
0.1	0.3875	6.728	6.728
0.13	0.3321	5.765	7.494

mentally for mean free-path of the electron at a pressure of 1 torr. However, the electronic mean free-path becomes a function of the energy of electron due to Ramsauer and Townsend effect.

The variation of open circuited diffusion voltage with arc current as measured has been plotted in Fig. 7 for three background pressures namely 0.075, 0.1 and 0.13 torr. It is observed 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 (Table 3). In a previous paper (Sen *et al.*[4]) diffusion voltage has been measured in a glow discharge and the variation of electron temperature with a transverse magnetic field determined. In glow discharge, the radial distribution of charged

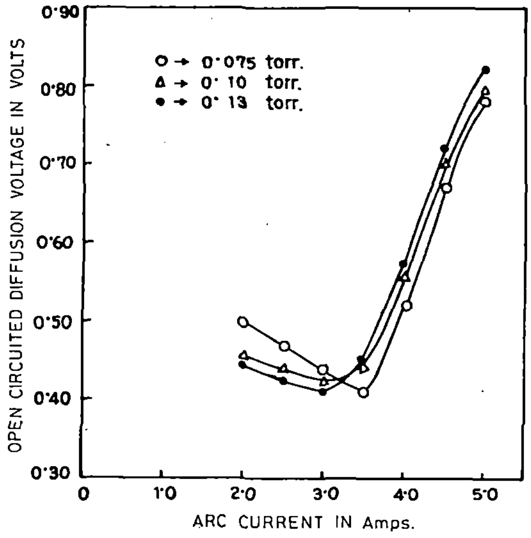

Fig. 7—Variation of diffusion voltage with arc current

Table 3—Experimental values of arc current at which diffusion voltage is minimum for different pressures

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

particle density has been assumed to be Besselian. It has, however, been shown by Ghosal *et al.*[5] that the radial distribution function for the azimuthal conductivity for an arc plasma is given by:

$$\sigma(r) = \sigma_0 \left[1 - \left(\frac{r}{R}\right)^2\right]^n \qquad \ldots (4)$$

where σ_0 is the axial conductivity, σ the conductivity at a distance r from the axis, R the radius of the arc and n a constant[5] given by:

$$n = \left[\frac{R^2}{a} - 1\right]$$

where a is an experimentally determined quantity which varies with arc current. This distribution function can very well represent the radial charged particle distribution in an arc plasma. It has been shown by Sen *et al.*[4] that the diffusion voltage V_R is:

$$V_R = -\int \frac{dn_e}{n_e} \frac{kT_e}{e} \qquad \ldots (5)$$

and since the electron density is proportional to σ, we get from Eq. (4):

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

and from Eq. (5)

$$V_R = -\frac{nkT_e}{e}\int\frac{-\frac{2r}{R^2}}{\left(1-\frac{r^2}{R^2}\right)}\,dr$$

Let

$$Z=\left[1-\frac{r^2}{R^2}\right]$$

then

$$V_R = -\frac{nkT_e}{e}\int\frac{dZ}{Z} = -\frac{nkT_e}{e}\log Z$$

$$V_R = -\frac{nkT_e}{e}\log\frac{R^2-r^2}{R^2}$$

$$=\frac{2nkT_e}{e}\log\frac{R}{\sqrt{R^2-r^2}} \qquad \ldots (6)$$

The values of the electron temperature corresponding to the arc currents for which diffusion voltage has been measured are reported in the earlier part of the present paper. Some values of n were obtained by Ghosal *et al.*[5], but a measurement of n for a wider range of current has been recently carried out in this laboratory and variation in the value of n with arc current is plotted in Fig. 8. Hence it is numerically possible to calculate the values of V_R for different arc currents at different pressures from Eq. (6). The results are presented in Table 4. It is observed that though the theoretically calculated values are higher than the corresponding experimental results, 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 increase of pressure as is observed experimentally. The discrepancy between the theoretically calculated and experimentally observed values of V_R may be due to the fact that both n and, T_e are functions of the radius of the arc tube. We can thus conclude that the distribution formula for azimuthal conductivity as proposed by Ghosal *et al.*[5] gives results in quantitative agreement with experimental results. We have thus seen that the Langmuir probe method can also be utilized for the measurement of electron temperature and electron density in an arc plasma just as in the case of glow discharge. It is not possible to calculate the percentage accuracy in these measurements but the results are consistent quantitatively with the values obtained by the spectroscopic method (Sadhya and Sen[3]). Langmuir's expression for arc current [Eq. (3)] is verified and the results provide

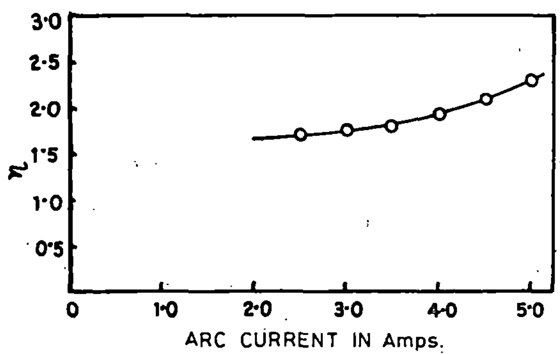

Fig. 8—Variation of n with arc current

Table 4—Experimental and calculated values of diffusion voltage at different arc currents for three different pressures

Pressure torr	Arc current A	Diffusion voltage in V Exptl	Diffusion voltage in V Theor.
0.075	2.0	0.498	0.575
	2.5	0.470	0.527
	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	0.588*
0.10	2.0	0.458	0.410
	2.5	0.438	0.374
	3.0	0.435	0.349
	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*
0.13	2.0	0.446	0.390
	2.5	0.425	0.348
	3.0	0.410	0.307
	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

a means of calculating the electronic mean free-path in the gas.

The not too satisfactory agreement between the diffusion voltages calculated and experimentally observed results may be attributed to some uncertainty in the value of n but the occurrence of minima as observed experimentally at the same calculated value of the arc current at three pressures lends support to the validity of distribution function as proposed by Ghosal *et al.*[5]

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CHAPTER IV

EVALUATION OF DIFFUSION COEFFICIENT OF ELECTRONS IN A MERCURY ARC PLASMA BY MEASUREMENT OF DIFFUSION CURRENT

4.1. Introduction

In literature there are extensive references regarding the measurement of drift velocity of electrons in ionized gases for a wide range of (E/P) values but corresponding measurements of diffusion coefficient of electrons and ions have not been reported to such a large extent. The earlier methods used for evaluation of diffusion constant of electrons and ions were based on the well known expression $\mu_e / D_e = e / KT_e$ where μ_e the mobility of the electrons was obtained from the experimental measurement of drift velocity and T_e the electron temperature was also obtained from an independent measurement. A systematic investigation regarding the diffusion of slow electrons in nitrogen and hydrogen was carried on by Crompton and Sutton (1952) using a modification of the well-known method of Townsend as suggested by Huxley and Zaazou (1949). They measured the ratio V_d / D_e for (E/P) values varying from .05 to 20 volts/cm torr for both nitrogen and hydrogen and taking the values of V_d from previous measurements of Nielson (1936) evaluated the values of D_e. It was observed that D_e increases with the increase of (E/P). Most of the work reported in the literature regarding measurement of diffusion coefficient refers to measurement of temporal variation of charge density in a decaying plasma and assuming the validity of equation of continuity the value of the diffusion coefficient has been evaluated. Mass spectrometeric measurements have yielded information regarding the nature of ions in case of ionic diffusion. Some measurements have also been reported regarding the variation of diffusion coefficient in either a transverse or a longitudinal magnetic field. Almost all the results reported regarding measurement of diffusion coefficient relate to glow discharge or to a decaying plasma and practically little work on the diffusion process in an arc plasma has been reported. In a recent communication (Sen, Gantait and Acharyya, 1989) the open circulated diffusion voltage in an arc plasma has been measured over a range of arc current and utilizing the radial distribution function of conductivity as introduced by Ghosal, Nandi and Sen (1978) the results have been analysed. Further from the measurement of diffusion voltage in an arc plasma in a transverse as well as in an axial magnetic field (Sen, Acharyya, Gantait and Bhattacharjee, 1989) variation of electron temperature has been investigated. It has been presumed that if the closed circuit diffusion current in an arc plasma can be measured then from the relation

$$I_D = en_{av}\mu E - eD_e \frac{dn_e}{dr} \quad \ldots(4.1)$$

the diffusion coefficient D_e could be evaluated provided that other quantities such as n_{av} the average electron density and μ_e the mobility coefficient are obtained from an independent observation. Hence in the present investigation it is proposed to measure the diffusion current in an arc plasma for a range of arc cufrent and also at different pressures so as to evaluate the diffusion coefficient of electrons in an arc plasma and study its variation with increasing arc current and pressure.

4.2. Experimental set up

The method of measurement of diffusion voltage in an arc plasma has been discussed in detail in chapter (III). A mercury arc with internal radius 1.1 cm. was used for measurement of diffusion voltage and diffusion current. Separation between the two mercury pool electrodes was 41 cm. Two identical cylindrical probes of length 0.8 cm. and diameter .01 cm are placed parallel to one another one along the axis and the other at a distance of 0.6 cm. from the axis. The output voltage between the two probes which is the diffusion voltage is measured with a VTVM having an internal impedance of 10 MΩ . A milliammeter connected between the two probes measures the diffusion current. Results are reported for arc current varying from 2 to 5 amp. and for three pressures namely 0.075 0.1 and 0.13 torr.

4.3. Results and discussion

The variation of diffusion voltage and diffusion current in the mercury arc plasma against the variation of arc current from 2 A to 5 A has been plotted for a background air pressure of 0.075 torr in fig. (4.1) for 0.1 torr in fig. (4.2) and for a pressure of 0.13 torr in fig. (4.3). It is evident that the variation of a diffusion voltage is the same as observed earlier (Chapter III), but the diffusion current increases slowly for small arc current but shows an almost exponential rise with the further increase of arc current. The nature of variation of

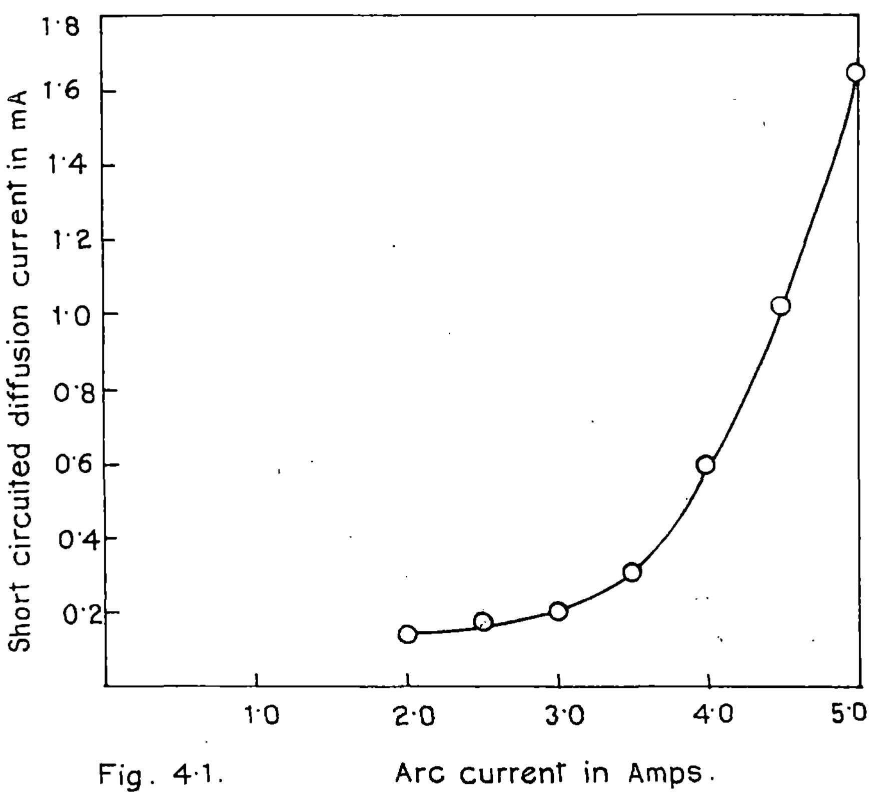
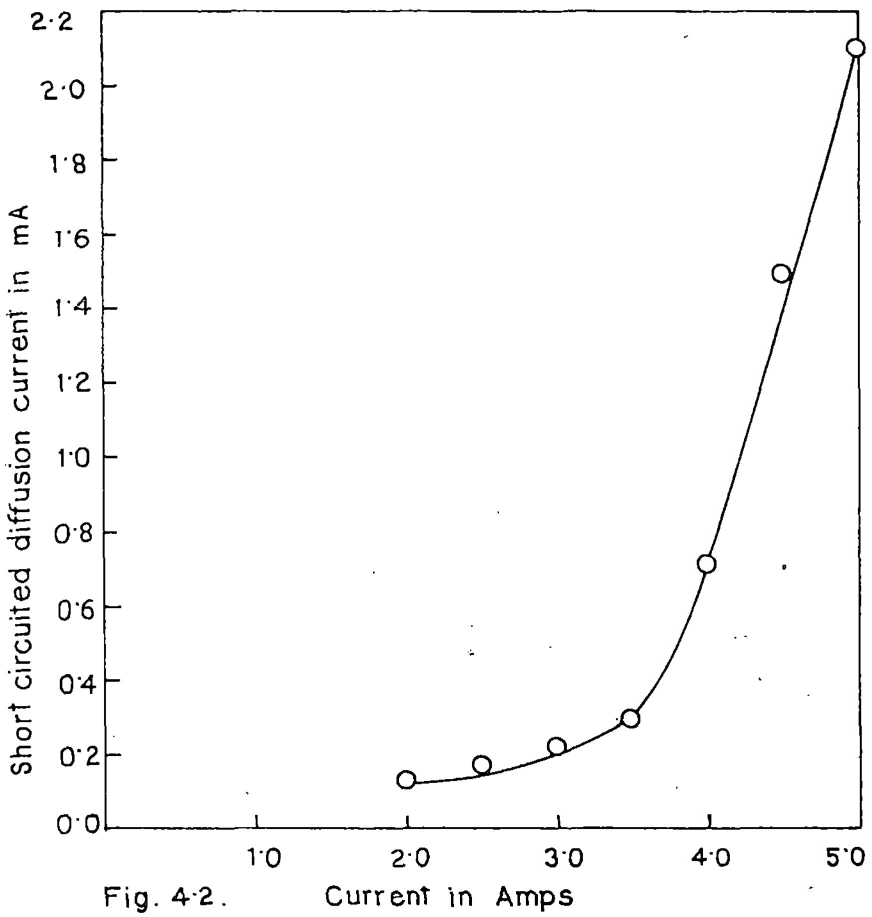

Short circuited diffusion current in mA
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
1·0
2·0
3·0
4·0
5·0
Arc current in Amps.

Fig. 4·1.



2·2
2·0
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0·0
1·0
2·0
3·0
4·0
5·0
Short circuited diffusion current in mA
Current in Amps

Fig. 4·2.

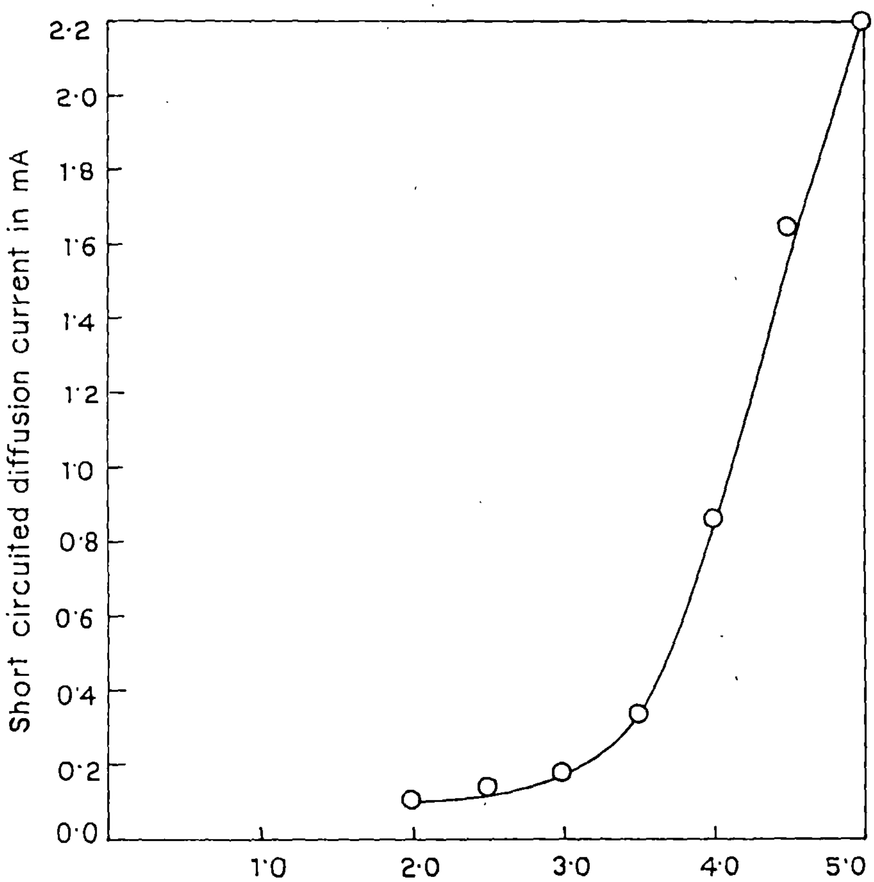


Fig. 4·3 Arc current in Amps.

diffusion current with arc current is of similar nature for all the three pressures. The current which is measured is due to both drift and diffusion and the current density can be written as

$$I_D = \frac{n_o e^2 E}{m \nu_c} - eD_e \frac{\partial n_e}{\partial r} \qquad \cdots (4{\cdot}2)$$

where n_o is the average electron density and ν_c the collision frequency. In case of an arc plasma it has been postulated by Ghosal, Nandi and Sen (1978) that

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

where n is a factor which depends upon arc current (Chapter III).

Hence

$$I_D = \frac{n_o e^2 E}{m \nu_c} + \frac{2eDn_o n}{R^2} \left\{ 1 - \frac{r^2}{R^2} \right\}^{n-1} \qquad \cdots (4.3)$$

The values of n_o for different arc currents have been obtained in chapter (III) for all the three pressures by independent probe measurements, E as the diffusion voltage drop per cm. which has been evaluated from the measured diffusion voltage drop and ν_c for mercury vapour for the three pressures have been calculated from the relation $\nu_c = v_r / \lambda_e$ where the values of λ_e the mean free path have been obtained in chapter (III) and the value of v_r the random velocity has been collected from McDaniel (1964). Regarding the values of n it is to be noted that some values of n were obtained by Ghosal, Nandi and Sen (1978) but a measurement of n for a wider range of current has been recently carried out in this laboratory and the variation in the value of n with arc current has been plotted in fig. (3.1, 3.2, 3.3) chapter (III). Thus the values of n_e , E, ν_c and n are entered in Table (4.1), (4.2), (4.3) for three different pressures. The corresponding values of D_e are entered in the last column in each table.

From the tabulated results, it is observed that the diffusion coefficient of electrons in mercury vapour in an arc varies from 673 cm^2/sec to 1717 cm^2/sec at a pressure of 0.075 torr, from 512 cm^2/sec to 2500 cm^2/sec for a pressure of 0.1 torr and from 395 cm^2/sec to 1765 cm^2/sec at a pressure of 0.13 torr for arc current varying from 2 to 4.5 amps. in each case. We have not come across any experimental

Table 4.1.

P = 0.075 torr

Arc current in Amp.	Diffusion current in mA	Diffusion voltage drop/cm.	Value of n_e x 10^{-12}	δ_c x 10^{-9}	n	$(1-\frac{r^2}{R^2})^{n-1}$	D_e x 10^{-4} $cm^2 sec^{-1}$
2.0	0.14	0.83	1.2476		1.65	0.7949	0.06739
2.5	0.17	0.783	1.4297		1.7149	0.7769	0.070305
3.0	0.22	0.73	1.8167	6.38	1.7446	0.7688	0.071125
4.0	0.60	0.863	2.5962		1.9667	0.7108	0.13023
4.5	1.02	1.1167	3.2832		2.1059	0.6767	0.1717

values for electron diffusion in mercury vapour in literature and consequently the accuracy of the results obtained by this method could not be verified. However, it is noted that the diffusion coefficient of mercury as obtained in this investigation is approximately one order of magnitude smaller than the corresponding values for hydrogen and nitrogen as reported by Crompton

Table 4.2

P = 0.1 torr.

Arc current in Amp.	Diffussion current in mA.	Diffusion voltage drop/cm.	Value of $n_e \times 10^{-12}$	$\delta_c \times 10^{-9}$	n	$(1-\frac{r^2}{R^2})^{n-1}$	$D_e \times 10^{-4}$ $cm^2 sec^{-1}$
2.0	0.12	0.7633	1.4068		1.65	0.7949	0.05123
2.5	0.16	0.73	1.5721	8.814	1.7149	0.7769	0.0601
3.0	0.20	0.725	1.8686		1.7446	0.7688	0.06286
4.0	0.72	0.927	2.6451		1.9667	0.7108	0.1534
4.5	1.50	1.167	3.3164		2.1059	0.6767	0.25000

and Sutton (1952). From the theory which assumes that collision is the main factor responsible for diffusion it can be deduced that the diffusion coefficient of electrons D_e in an ionised gas is given by $D_e = 1/3\,\lambda_e v_e$ where λ_e is the mean free path of electron and V_e is the random velocity of electrons in the gas. In general it may be assumed that $v_e = 10^8$ cm/sec and λ_e is of the order of

Table 4.3

P = 0.13 torr.

Arc current in Amps	Diffusion current in mA	Diffusion voltage drop/cm.	Value of n_e $\times 10^{-12}$	ν_c $\times 10^{-9}$	n	$(1-\frac{r^2}{R^2})^{n-1}$	$D_e \times 10^{-4}$ $cm^2 sec^{-1}$
2.0	0.10	0.7433	1.5173		1.65	0.7949	0.03958
2.5	0.14	0.7083	1.7106		1.7149	0.7769	0.04839
3.0	0.18	0.6833	2.0271	10.286	1.7446	0.7688	0.05215
4.0	0.86	0.95	2.7444		1.9667	0.7108	0.17658

10^{-2} cm, so that D_e comes out to be of the order of 10^6 $cm^2 sec^{-1}$, but actually electrons in their motion through the gases induce dipoles and as a result the effective mean free path is reduced due to polarization, consequently the actual diffusion coefficient is reduced by at least one order of magnitude or may be more. The order of magnitude for the diffusion coefficient for the electrons in mercury vapour thus seems to be of the right order of magnitude. Further the mean free path of electrons in an ionised gas depends upon the energy of the electrons according to Townsend, Ramsauer effect and hence will depend upon the arc current which is a function of the velocity and so of the energy of the electrons. Consequently the diffusion coefficient of the electrons will be a function of the arc current as is observed in the present investigation and also observed by Crompton and Sutton (1952) for increasing values of (E/P). Further it is observed from the present experimental results that the diffusion coefficient decreases with the increase of pressure which is consistent with the theoretical expression that diffusion coefficient is directly proportional to mean free path. It is further noted that the diffusion coefficient increases with the increase of arc current for the three pressures investigated here which may be due to the fact with the increase of arc current, temperature of the mercury vapour increases as has been measured by Sadhya and Sen (1980) and as v_e is proportional to $T^{1/2}$ for the same pressure D_e should increase with the increase of temperature and hence with arc current.

In an earlier paper by Sadhya and Sen (1980) the detailed physical processes occuring in an arc plasma have been investigated and 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 but the number of free electrons is much greater than those of atomic and molecular ions and so it can be assumed that the diffusion coefficient measured here represents diffusion by electrons mainly. A mass spectrometric analysis would have provided the relative number of atomic and molecular ions present. Further the physical processes occuring in an arc plasma are different from those occuring in a glow discharge and no consistent theory has been developed regarding diffusion process in an arc plasma. It is expected that the values obtained here for electron diffusion in the mercury vapour may be useful in developing a theory for diffusion process in an arc discharge.

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CHAPTER V

MEASUREMENT OF ELECTRON ATOM COLLISION FREQUENCY IN AN ARC PLASMA BY RADIOFREQUENCY COIL PROBE IN CONJUNCTION WITH A LONGITUDINAL MAGNETIC FIELD.

5.1. Introduction

Ghosal, Nandi and Sen (1976, 1978) utilized the coil probe diagnostic technique for the measurement of azimuthal conductivity and its radial distribution. Experiments were performed for low pressure arc discharge where the change of coil impedance due to the insertion of plasma medium was only resistive and the measurements were insensitive to small change of coil reactance. For glow discharges where the conductivity is comparatively low both the resistive and reactive parts of the change of the coil impedance is significant and by measuring

those two coil impedance parameters, several authors, viz. Basu and Maiti (1973); Basu and Hore (1977); Tanaca and Hogi (1964) were able to determine the plasma conductivity as well as the electron - atom collision frequency in the plasma. It has been noted

however, that for determining collision frequencies for an arc plasma the coil probe alone is inadequate.

However, it is conjectured that if a small steady longitudinal magnetic field is used in conjunction with the coil probe, the expected tensorial behaviour of plasma conductivity might be utilized to measure the collision frequency. In our laboratory a number of experiments were performed by Gupta and Mandal (1967), Sen and Gupta (1969), Sen and Jana (1978) on the radio frequency conductivity of a transversely magnetized plasma by a capacitor probe method. They were able to determine momentum transfer collision frequency/cross-section for electrons and also other parameters. In the capacitor probe method the plasma is inserted within a parallel plate condenser which forms a part of the tank circuit, which is inductively excited by a r.f. oscillator. The plasma acts thereby as a lossy dielectric within the parallel plate capacitor. The parameters were determined from the measurements of real and imaginary parts of the impedance of the glow discharge plasma in a number of gases. But all those measurements suffered from the disadvantage that the radial distribution of electron density could not be taken into account and all those measurements were some kind of gross average of the plasma parameters over the dimension of the capacitors.

Actually the purpose of the present study is to explore 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 can be determined. The relevant theory has been developed taking the effect of radial distribution of conductivity into account.

5.2. Theory:-

If the plasma is embedded in a static magnetic field, the relation between current density $\vec{J}$ and electric field $\vec{E}$ cannot be expressed in terms of a scalar conductivity as

$$\vec{J} = \sigma_0 \vec{E} \quad \ldots \quad (5.1)$$

where σ_0 is the isotropic scalar conductivity which has no directional property. We talked about azimuthal and axial electrical average conductivities, where directional property had been attributed, which was due to the radial non-uniformity of plasma density. The situation is expected to be quite different if the plasma is assumed to be embedded in a static magnetic field. The relation between current density $\vec{J}$ and electric field $\vec{E}$ in this case cannot be expressed in terms of a scalar conductivity as in eqn. (5.1). Either by solving the fluid equations given by Uman (1964) or by solving the transport equation and using small perturbation approximation given by Krall and Trivelpiece (1973) it can be shown that for a uniform axial steady magnetic field, along Z direction eqn, (5.1) is to be replaced by,

$$\begin{pmatrix} J_x \\ J_y \\ J_z \end{pmatrix} = \begin{pmatrix} \sigma_1 & \sigma_2 & 0 \\ -\sigma_2 & \sigma_1 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} \quad \cdots (5.2)$$

where σ_1 , σ_2 and σ_3 are the components of the conductivity tensor in cartesian coordinate system.

For radiofrequency electric fields where the radiofrequency is much smaller than electron atom collision frequency and in presence of a superimposed magnetic field the quantities σ_1 , σ_2 , σ_3 are given by

$$\sigma_1 = \frac{e^2 n_e}{m_e} \frac{\nu_{ce}}{\nu_{ce}^2 + \omega_{eB}^2} \quad \cdots (5.3)$$

$$\sigma_2 = \frac{e^2 n_e}{m_e} \quad \frac{\omega_{eB}}{\nu_{ce}^2 + \omega_{eB}^2} \qquad \ldots(5.4)$$

$$\sigma_3 = \frac{e^2 n_e}{m_e \nu_c} \qquad \ldots(5.5)$$

where the ionic contribution to conductivity has been neglected and ν_{ce} and ω_{eB} are the electron atom collision frequency and electron cyclotron frequency respectively.

For the sake of cylindrical symmetry of the present experimental arrangement the conductivity tensor defined by eqn. (5.2) may be transformed into cylindrical coordinate system (r , ϕ , z) for convenience to yield,

$$\begin{pmatrix} J_r \\ J_\phi \\ J_z \end{pmatrix} = \begin{pmatrix} \sigma_1 & r\sigma_2 & 0 \\ -r\sigma_2 & r^2\sigma_1 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix} \begin{pmatrix} E^R \\ E^\phi \\ E^Z \end{pmatrix} \qquad \cdots(5\cdot6)$$

where it is assumed that the magnetic field is applied in the z-direction and where the subscripts and superscripts (R, ϕ , Z) differentiate the covariant and contravarient components of the relevant vectors respectively; eqn. (5.6) may be rewritten in terms of the radial, azimuthal and axial components of the current density and electric field vectors as

$$\begin{pmatrix} J_r \\ rJ_\phi \\ J_z \end{pmatrix} = \begin{pmatrix} \sigma_1 & r\sigma_2 & 0 \\ -r\sigma_2 & r^2\sigma_1 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix} \begin{pmatrix} E_r \\ E_\phi/r \\ E_z \end{pmatrix} \quad \ldots (5.7)$$

If now it is assumed that the electric field is purely azimuthal i.e. $E_r = E_z = 0$, the azimuthal component of current density may be obtained from eqn.(5.7) as

$$J_\phi = \sigma_1 E_\phi \quad \ldots (5.8)$$

Eqn. (5.8) clearly defines the azimuthal conductivity which is equal to σ_1 which in presence of magnetic field is different from the axial conductivity σ_z defined by

$$J_z = \sigma_z E_z \quad \ldots (5.9)$$

It may be noted here from eqn. (5.3) and (5.5) that the relation between the azimuthal and axial conductivity may be written as

$$\sigma_\phi = \frac{\sigma_z}{1 + \omega_{eB}{}^2/\nu_{ce}{}^2} \quad \ldots (5.10)$$

5.2.1. Working formulae:-

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

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

and

$$\sigma(r) = \sigma_o \left[1 - \left(\frac{r}{R}\right)^2\right]^n \qquad \ldots(5.11)$$

where α denotes the ratio of the radiofrequency current without and with the plasma, R_o radiofrequency resistance of the coil and K is the constant depending upon the number of the turnsof the primary coil.

Theyintroduced a term 'a' defined to be the construction parameters and is given by

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

$$= \frac{E}{I}(\alpha - 1)\ \frac{R_o}{f^2\ K^2\ \ell}$$

$$= \frac{\int_0^R r^3\ f(r)\ dr}{\int_0^R r\ f\ (r)\ dr} \qquad \cdots (5.12)$$

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. (5.12)) is not valid. This is evident because

$$\frac{\int_0^R r^3 \sigma_\phi(r)\,dr}{\int_0^R r\sigma_z(r)\,dr} = \frac{\int_0^R r^3 \sigma_{o\phi} f_B(r)\,dr}{\int_0^R r\sigma_{oz} f_B(r)\,dr} = \frac{\sigma_{o\phi}\int_0^R r^3 f_B(r)\,dr}{\sigma_{oz}\int_0^R r f_B(r)\,dr} \quad \ldots(5.13)$$

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

$$\frac{\int_0^R r^3 f_B(r)\,dr}{\int_0^R r f_B(r)\,dr} = a_B \quad \ldots(5.14)$$

a_B may till be said to be the constriction parameters in presence of magnetic field since it is only dependent on the form of the conductivity distribution function $f_B(r)$. Thus in analogy with eqn. (5.12) we get

$$\frac{\sigma_{o\phi}}{\sigma_{oz}} \; a_B \doteq \frac{E_B}{I_B}\left(\alpha_B - 1\right)\frac{R_o}{f^2 K^2 \ell} \quad \ldots(5.15)$$

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

Writing

$$\frac{E_B}{I_B}(\alpha_B - 1) = a_B' \qquad \ldots(5.16)$$

$$\frac{E}{I}(\alpha - 1) = a' \qquad \ldots(5.17)$$

We get from eqn. (5.15) and (5.16)

$$\frac{\sigma_{0\phi}}{\sigma_{0z}} a_B = a_B' \frac{R_0}{f^2 K^2 \ell} \qquad \ldots(5.18)$$

and from (5.12) and (5.17)

$$a = a' \frac{R_0}{f^2 K^2 \ell} \qquad \ldots(5.19)$$

So from eqns. (5.18) and (5.19)

$$\frac{\sigma_{0\phi}}{\sigma_{0z}} \cdot \frac{a_B}{a} = \frac{a_B'}{a'} \qquad \ldots(5.20)$$

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

$$\frac{\sigma_{0\phi}}{\sigma_{0z}} = \frac{a'_B}{a'} \qquad \ldots(5.21)$$

The quantities α'_B and α' may be experimentally determined and their ratio if found different from unity will indicate the tensorial behaviour of conductivity in the magnetic field, from eqn. (5.10) and (5.21) we then get

$$\nu_{ce} = \frac{\omega_{eB}}{\left[\frac{\alpha'}{\alpha'_B} - 1\right]^{1/2}}$$

$$= \frac{1\cdot 76 \times 10^7 \times B}{\left[\frac{\alpha'}{\alpha'_B} - 1\right]^{1/2}} \qquad \ldots(5.22)$$

where B is expressed in gauss.

5.3. Experimental arrangement:-

A schematic diagram for experimental arrangement has been described in chapter II of article 2.10. A mercury arc has been utilised, the arc tube of which is cylindrical (length 10.8 cm and diameter 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 cooled by the external circulation of air. The pressure inside the arc tube at desired value is maintained by a variable microleak of a needle valve fitted to the pump line of the discharge tube. 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/s).

The oscillator coil was placed near the working coil and the induced radiofrequency voltage was tuned with a variable condenser. The tuned current was measured with a radiofrequency milliammeter and a magnetic field was then superimposed adjusting the rheostat to make the arc current the same as without magnetic field, tuned current was recorded again. Simultaneously probe to probe voltage with and without magnetic field was measured with a high impedance voltmeter. The whole sequence of measurement of tuned radiofrequency current and probe to probe voltage were performed at different magnetic fields viz. 100G, 150G, 230G, 280G, 345G discretely to study the above parameters at the same arc conditions. Each set of observation was taken at three different pressures namely 0.052 torr, 0.075 torr and 0.17 torr.

Tube specification and associated data:

Electrode to electrode separation of the arc tube = 10.82 cm .Outer diameter of the tube = 1.83 cm. Inner diameter of the tube = 1.56 cm.

Coil length = 4.5 cm.

Wire diameter = 0.1 cm.

Probe to probe separation = 4.6 cm.

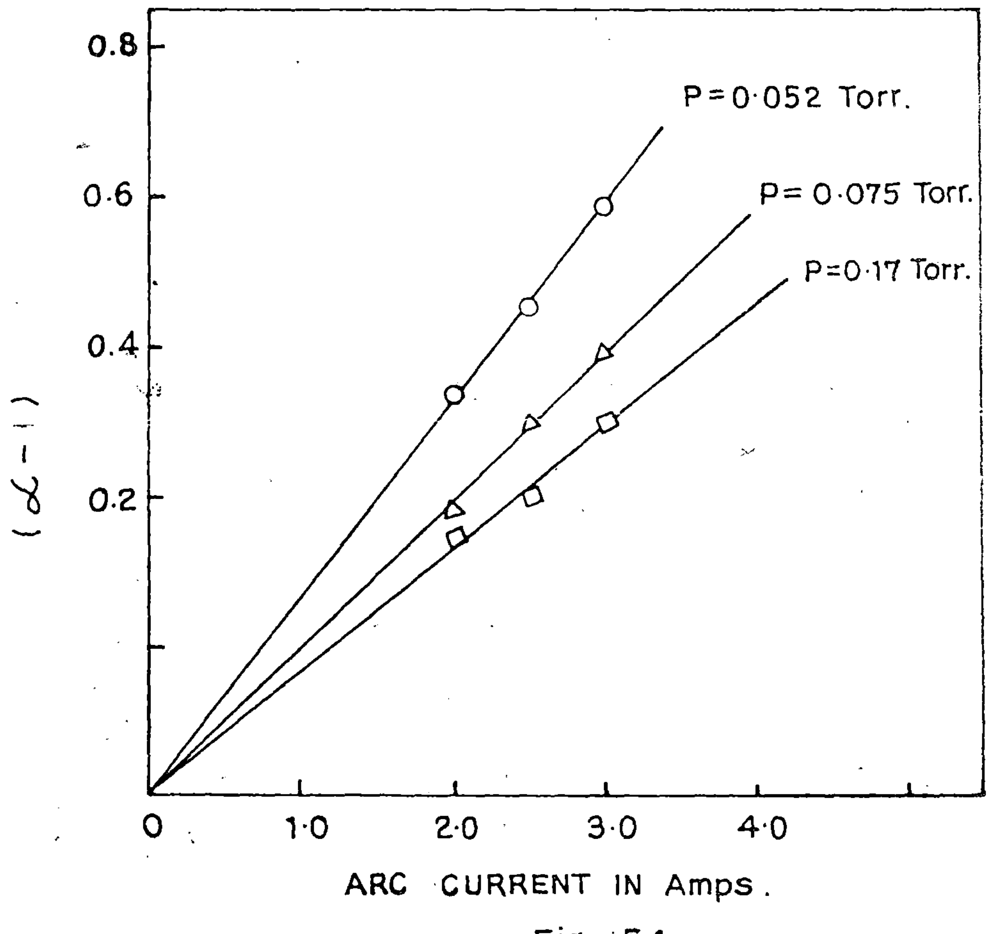
Number of turns = 41

Inductance of the coil = 8.5 MH

Mutual inductance = 0.2073 Henry

5.4. Results and discussion:-

The tunned coil probe current i_o without the arc being excited and the current i when the arc is excited were taken for different arc current 2.0 A, 2.5 A, and 3.0 A for three different pressures 0.052 torr, 0.075 torr and 0.17 torr. The values of $(\alpha - 1)$ where $\alpha = i_o/i$ thus obtained have been plotted against arc current for three differrent pressures in Fig. 5.1. The probe to probe voltage for three different arc currents for three different pressures have been measured and the values of E and $a = E/I(\alpha - 1)$ for zero magnetic field have been entered in table 5.1. The corresponding quantities E_B and α_B have been measured in presence of different magnetic fields 100G, 150G, 230G, 280G and 345G for arc current 2A and 100G, 150G, 230G, 280G, 345 G and 400G in case of arc currents 2.5 A and 3.0A. The corresponding values of $a'_B = \frac{E_B}{I_B}(\alpha_B - 1)$



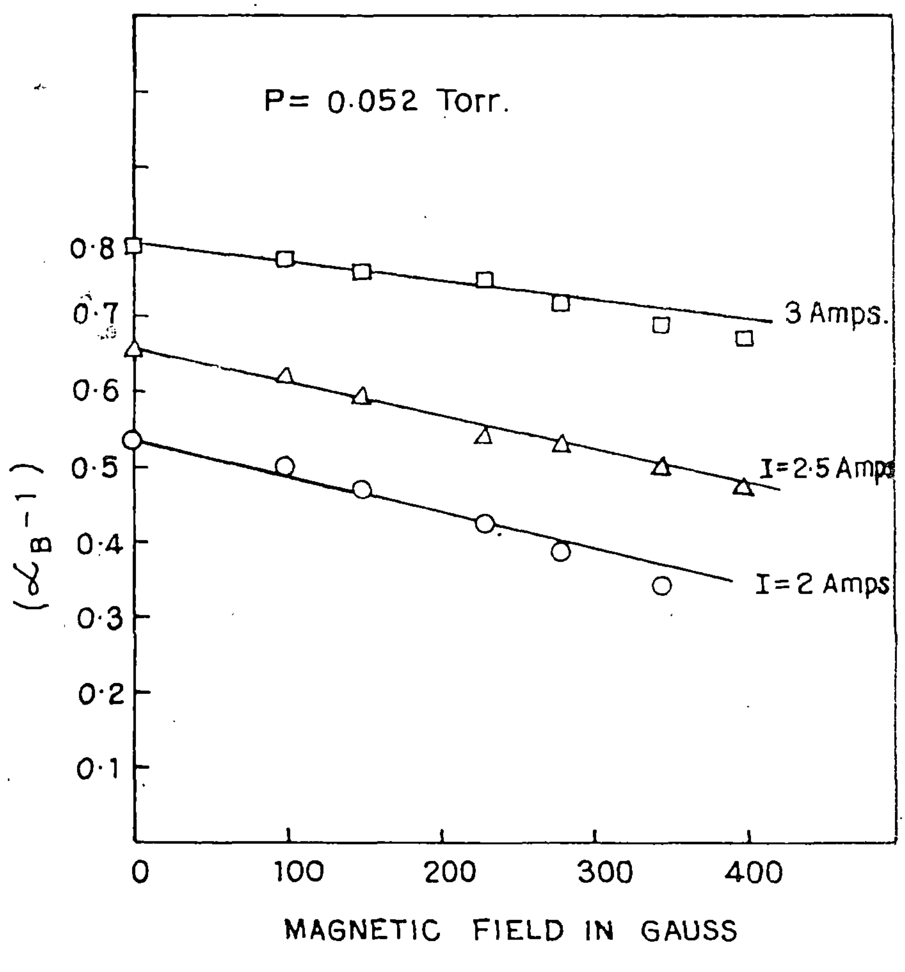
0.8
0.6
0.4
0.2
(γ − 1)
P = 0·052 Torr.
P = 0·075 Torr.
P = 0·17 Torr.
0
1·0
2·0
3·0
4·0
ARC CURRENT IN Amps.

Fig. 5·1.

have been calculated. In table 5.1 all the above values are entered. It has been noted that there is a slight fall in the main arc current when the magnetic field is increased. The value of the exciting voltage of the arc has been slightly adjusted to restore the current to its original value. The values of $\sqrt{a'/a'_B - 1}$ have been entered in table 5.1. The values of (α_B - 1) have been plotted against the corresponding values of magnetic field for three arc currents at three different pressures in figures 5.2, 5.3 and 5.4. The values of $\sqrt{a'/a'_B - 1}$ have been plotted against the corresponding values of magnetic field for three arc currents for pressure 0.052 torr, 0.075 torr and 0.17 torr in figures 5.5, 5.6 and 5.7 respectively. As may be observed they are found to be straight lines passing through the origin. The proportionality between $\sqrt{a'/a'_B - 1}$ and B confirms the theoretical assumption made earlier. Thus assuming the validity of the equation

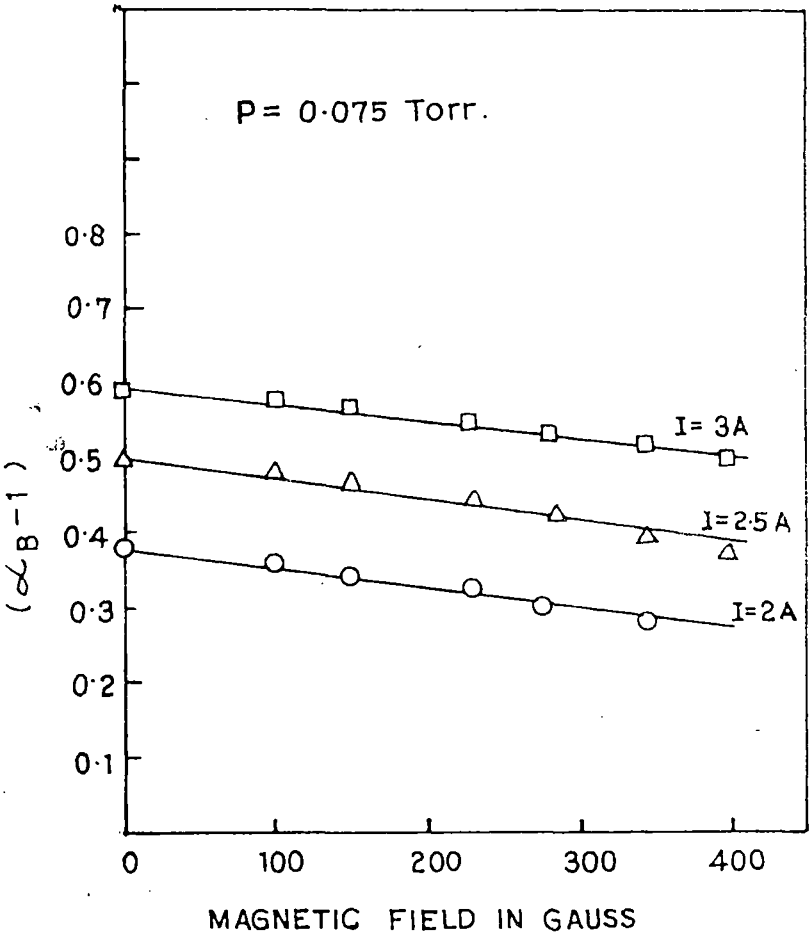
$$\nu_{ce} = \frac{1 \cdot 76 \times 10^7 \times B}{\sqrt{a'/a'_B - 1}}$$

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 5.1.



P= 0·052 Torr.
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
$(\alpha_B{}^{-1})$
3 Amps.
I=2·5 Amps
I=2 Amps
0
100
200
300
400
MAGNETIC FIELD IN GAUSS

FIG. 5·2.



P= 0·075 Torr.
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
$(\alpha_B - 1)$
I= 3A
I=2·5 A
I=2A
0
100
200
300
400
MAGNETIC FIELD IN GAUSS

Fig. 5·3

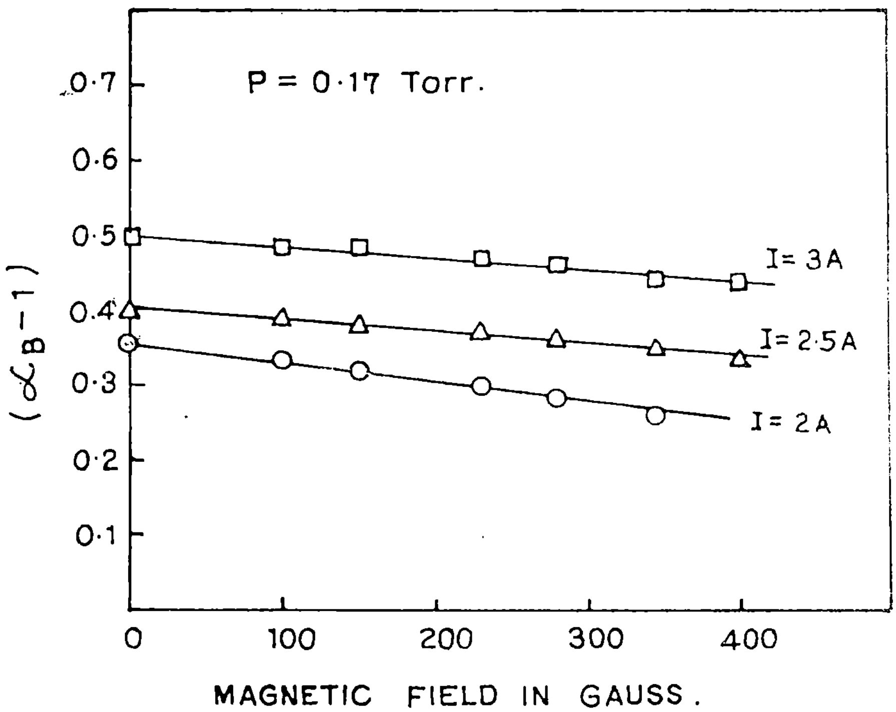

P = 0·17 Torr.
0·7
0·6
0·5
0·4
0·3
0·2
0·1
$(\alpha_B - 1)$
I= 3A
I= 2·5A
I= 2A
0
100
200
300
400
MAGNETIC FIELD IN GAUSS.

Fig.5·4

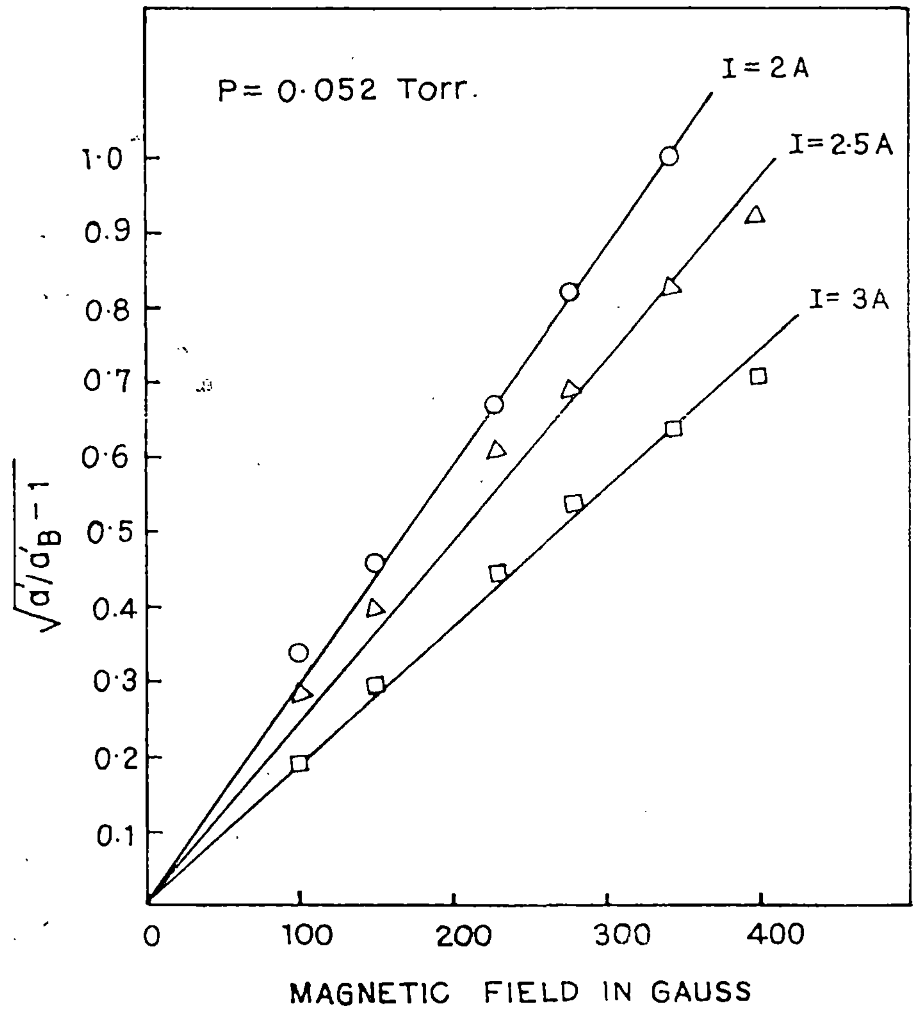
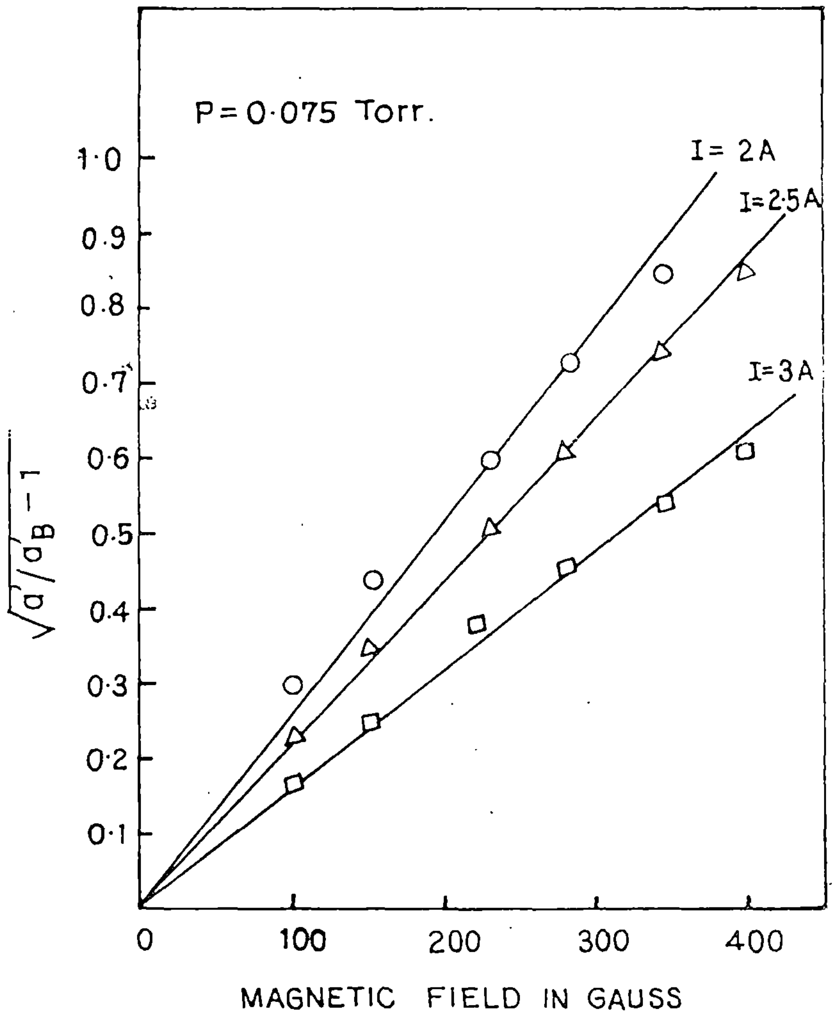
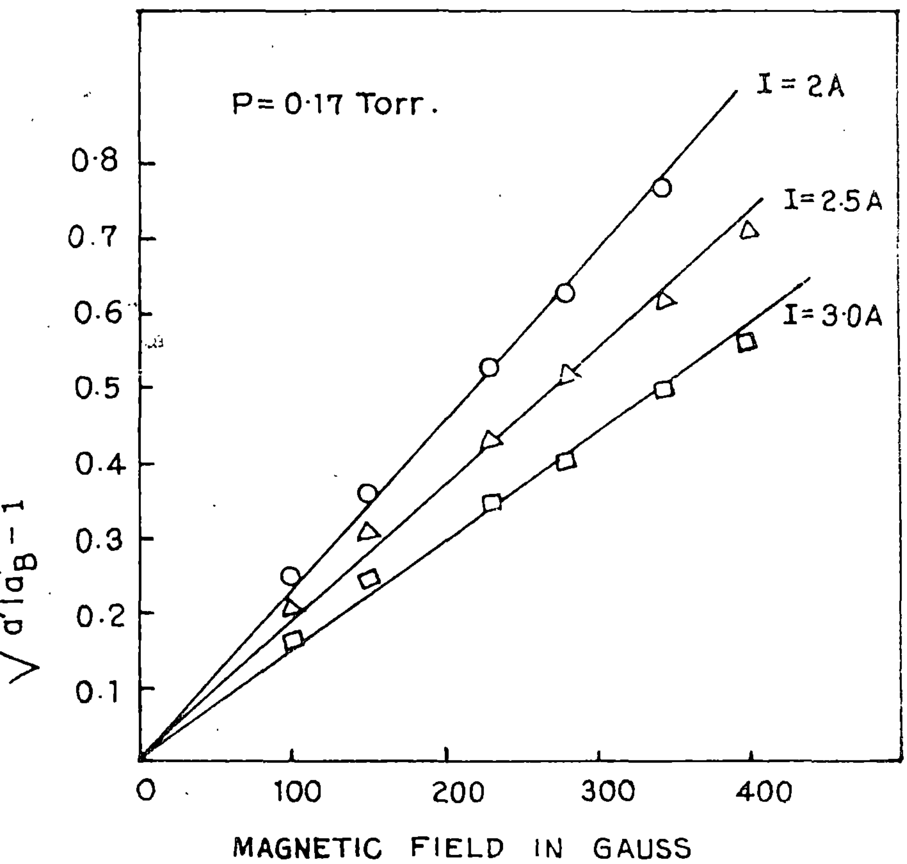

P= 0·052 Torr.
I = 2 A
I= 2·5 A
I= 3 A
$\sqrt{a'/a'_B} - 1$
1·0
0.9
0·8
0·7
0·6
0·5
0.4
0·3
0·2
0.1
0
100
200
300
400
MAGNETIC FIELD IN GAUSS

Fig. 5·5.



P=0·075 Torr.
I= 2A
I=2·5A
I=3A
$\sqrt{a'/a'_B - 1}$
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
100
200
300
400
MAGNETIC FIELD IN GAUSS

Fig 5·6



P= 0·17 Torr.
I = 2A
I=2·5A
I=3·0A
0·8
0.7
0·6
0·5
0.4
0·3
0·2
0·1
$\sqrt{a'/a'_B - 1}$
0
100
200
300
400
MAGNETIC FIELD IN GAUSS

Fig. 5·7.

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. It is evident from the results 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 increases the collision frequency. But 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 cooling arrangement. For this reason we have not tried to correlate momentum transfer collision frequency ν_{ce} with arc current.

It is to be noted 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. In this theory the magnetic field has been used as a probe. If higher magnetic fields are used the simple theory pastulated 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 5.1

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	0.300		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	5.964 x	0.576	0.340	0.0979	0.395	6.714 x	0.598	0.320	0.0957	0.350	7.612
230	0.511	0.425	0.1086	0.675	10^9	0.533	0.325	0.0865	0.600	10^9	0.565	0.300	0.0848	0.530	$\times 10^9$
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	0.500	0.4706	0.0941	0.330	8.042 x	0.522	0.380	0.0793	0.285	9.36
230	0.457	0.5429	0.0991	0.5600	10^9	0.467	0.4478	0.0837	0.505	10^9	0.496	0.370	0.0733	0.430	$\times 10^9$
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	0.0579	0.740	
Arc current 3 amp.															
0	0.348	0.7925	0.0919			0.446	0.5902	0.0877			0.500	0.500	0.0833		
100	0.337	0.7857	0.0882	0.1950		0.439	0.5806	0.0850	0.165		0.496	0.490	0.0810	0.150	
150	0.330	0.7650	0.0843	0.2850	9.308 x	0.430	0.5737	0.0823	0.240	10.98 x	0.489	0.480	0.0783	0.225	11.79
230	0.304	0.7544	0.0765	0.435	10^9	0.413	0.5555	0.0765	0.350	10^9	0.478	0.468	0.0747	0.345	$\times 10^9$
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		0.391	0.5230	0.0682	0.550		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	

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Measurement of the electron–atom collision frequency in an arc plasma by a radiofrequency coil probe in conjunction with a longitudinal magnetic field

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and B. BHATTACHARJEE†

The theory developed by Ghosal, Nandi and Sen (1976, 1978) regarding the radial distribution of conductivity of an arc plasma has been modified to allow for the tensorial behaviour of the plasma when the arc is placed in a longitudinal magnetic field. A working formula has been developed to measure the electron–atom collision frequency where the magnetic field has been used as a probe. This paper reports the results of measurement in an arc plasma (arc current 2, 2·5 and 3 A) and pressure (0·052, 0·075, 0·17 Torr). The values of electron–atom collision frequencies (ν_{ce}) obtained are consistent with standard literature values and the method can be regarded as an alternative one for determining ν_{ce}.

1. Introduction

A considerable number of investigations of low-pressure positive columns in arc and glow discharges have been made in our laboratory, using coil probe and other techniques, aimed at measuring, amongst other things, the azimuthal conductivity and its radial distribution and the electron–atom collision frequency (ν_{ce}) (Ghosal *et al.* 1976 1978, Sen and Jana 1978). All have suffered from the disadvantage that the radial distribution of electron density could not be taken into account, so that measurements represented some kind of gross average. However, it was conjectured that if a small steady longitudinal magnetic field were used in conjunction with the coil probe, then the expected tensorial behaviour of plasma conductivity might be used to explore the values of ν_{ce}.

The purpose of the present study has been to explore the tensorial behaviour of plasma conductivity in the presence of a longitudinal magnetic field, and hence from the measured impedance parameters, in the presence and absence of the magnetic field, to determine ν_{ce}. The relevant theory has been developed, taking the effect of the radial distribution of conductivity into account.

2. Theoretical considerations

If a steady magnetic field B is applied along the Z axis of a cylindrical plasma column (radius R) and the ion contribution to the conductivity is neglected, the current density J and the electric field E will be given by the tensor

$$\begin{bmatrix} J_r \\ J_\phi \\ J_z \end{bmatrix} = \begin{bmatrix} \sigma_1 & r\sigma_2 & 0 \\ -r\sigma_2 & r^2\sigma_1 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix} \begin{bmatrix} E_r \\ E_\phi \\ E_z \end{bmatrix} \tag{1}$$

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where

$$\left.\begin{aligned} \sigma_1 &= \frac{e^2 n_e}{m_e} \frac{\nu_{ce}}{\nu_{ce}^2 + \omega_{eB}^2} \\ \sigma_2 &= \frac{e^2 n_e}{m_e} \frac{\omega_{eB}}{\nu_{ce}^2 + \omega_{eB}^2} \\ \sigma_3 &= \frac{e^2 n_e}{m_e \nu_e} \end{aligned}\right\} \tag{2}$$

and, ν_{ce} and ω_{eB} are the electron–atom collision frequency and electron cyclotron frequency, respectively. It is assumed that the frequency of the applied radio-frequency field is $\ll \nu_{ce}$ and when there is no magnetic field $\omega_{eB} = 0$.

The azimuthal conductivity σ_ϕ aand the axial conductivity σ_z are different, but it may be noted that

$$\sigma_\phi = \frac{\sigma_z}{1 + (\omega_{eB}^2/\nu_{ce}^2)} \tag{3}$$

3. Working formulae

Ghosal *et al.* (1978) introduced a quantity defined by

$$\alpha - 1 = \frac{\omega^2 K^2 l}{2\pi R_0} \int_0^R r^2 \sigma(r)\, dr \tag{4}$$

with

$$\sigma_r = \sigma_0[1 - (r/R)^2]^n \tag{5}$$

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

They also introduced a term a (the constriction parameter) defined by

$$a = \frac{\int_0^R r^3 \sigma(r)\, dr}{\int_0^R r\sigma(r)\, dr} = \frac{E}{I}(\alpha - 1)\frac{R_0}{f^2 K^2 l} = \frac{\int_0^R r^3 f(r)\, dr}{\int_0^R r f(r)\, dr} \tag{6}$$

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.

However, in the presence of a magnetic field in the Z direction, (6) is not valid. This is evident because

$$\frac{\int_0^R r^3 \sigma_\phi(r)\, dr}{\int_0^R r\sigma_z(r)\, dr} = \frac{\int_0^R r^3 \sigma_{0\phi} f_B(r)\, dr}{\int_0^R r\sigma_{0z} f_B(r)\, dr} = \frac{\sigma_{0\phi} \int_0^R r^3 f_B(r)\, dr}{\sigma_{0z} \int_0^R r f_B(r)\, dr} \tag{7}$$

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

If we write

$$\frac{\int_0^R r^3 f_B(r)\, dr}{\int_0^R r f_B(r)\, dr} = a_B \tag{8}$$

then a_B may be said to be the constriction parameter in the presence of the magnetic field since it is only dependent on the form of the conductivity distribution function $f_B(r)$. Thus, by analogy with (6), we get

$$\frac{\sigma_{0\phi}}{\sigma_{0z}}\, a_B = \frac{E_B}{I_B}(\alpha_B - 1)\frac{R_0}{f^2 K^2 l} \tag{9}$$

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

Writing

$$\frac{E_B}{I_B}(\alpha_B - 1) = a'_B \tag{10}$$

$$\frac{E}{I}(\alpha - 1) = a' \tag{11}$$

we get, from (9) and (10),

$$\frac{\sigma_{0\phi}}{\sigma_{0z}}\, a_B = a'_B \frac{R_0}{f^2 K^2 l} \tag{12}$$

and, from (6) and (11),

$$a = a' \frac{R_0}{f^2 K^2 l} \tag{13}$$

So, from (12) and (13),

$$\frac{\sigma_{0\phi}}{\sigma_{0z}} \frac{a_B}{a} = \frac{a'_B}{a'} \tag{14}$$

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

$$\frac{\sigma_{0\phi}}{\sigma_{0z}} = \frac{a'_B}{a'} \tag{15}$$

The quantities a'_B and a' may be experimentally determined and their ratio will indicate the tensorial behaviour of the conductivity in the magnetic field. From (3) and (15), we then get

$$\nu_{ce} = \frac{\omega_{eB}}{\left(\dfrac{a'}{a'_B} - 1\right)^{1/2}} = \frac{1{\cdot}76 \times 10^7 B}{\left(\dfrac{a'}{a'_B} - 1\right)^{1/2}} \tag{16}$$

where B is expressed in gauss.

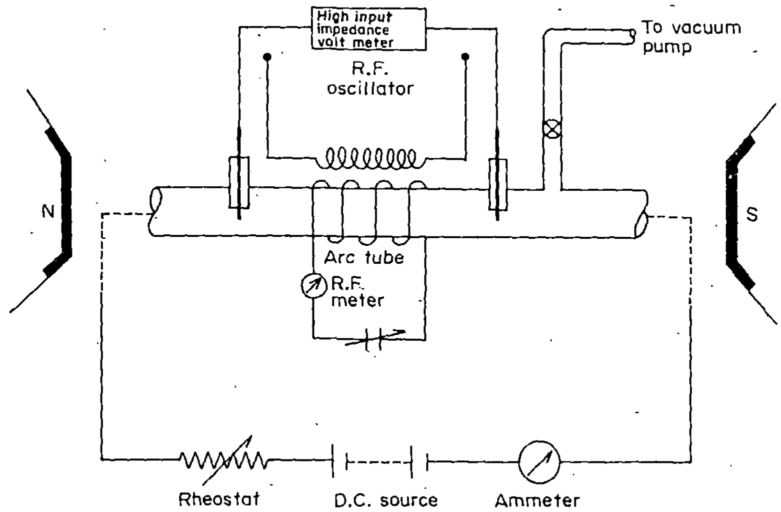

Figure 1. Schematic experimental arrangement for study of arc plasma characteristics in presence of a longitudinal magnetic field. Electrode separation = 10·82 cm. Outer diameter of the arc tube = 1·83 cm. Inner diameter = 1·56 cm. Coil length = 4·5 cm. Wire diameter = 0·1 cm. Probe-to-probe separation = 4·6 cm. Number of turns = 41. Inductance of the coil = 8·5 mH. Mutual inductance = 0·2073 μH.

4. Experimental arrangement

A schematic diagram of the experimental arrangement is shown in Figure 1. It has been described in detail by Ghosal *et al.* (1976). A mercury arc has been used, the arc tube of which is cylindrical (length 10·8 cm and diameter 1·83 cm) and is energized by a stabilized d.c. source with a rheostat to control the current, which is measured by an ammeter. The mercury arc is cooled by the external circulation of air. The pressure inside the arc tube is maintained at the desired value by a variable microleak needle valve fitted to the pump line of the discharge tube. The mercury arc is placed between the pole pieces of an electromagnet energized by a stabilized d.c. source. The lines of force are parallel to the direction of the flow of arc current.

The oscillator coil was placed near the working coil and the induced radiofrequency voltage was tuned with a variable condenser. The tuned current was measured with a radiofrequency milliammeter and a magnetic field was then superimposed. Adjusting the rheostat to make the arc current the same as without the magnetic field, the tuned current was recorded again. The probe-to-probe voltage with and without magnetic field was measured simultaneously, by a high-impedance voltmeter. The whole sequence of measurement of tuned radiofrequency current and probe-to-probe voltage was performed at different magnetic fields (100 G, 150 G, 230 G, 280 G and 345 G), to study the above parameters under the same arc conditions. Each set of observations was taken at three different pressures, namely 0·052, 0·075 and 0·17 Torr.

5. Results and discussion

Measurements of i_0, the tuned coil probe current without the arc being excited, and i, the current when the arc is excited without a magnetic field, were taken for

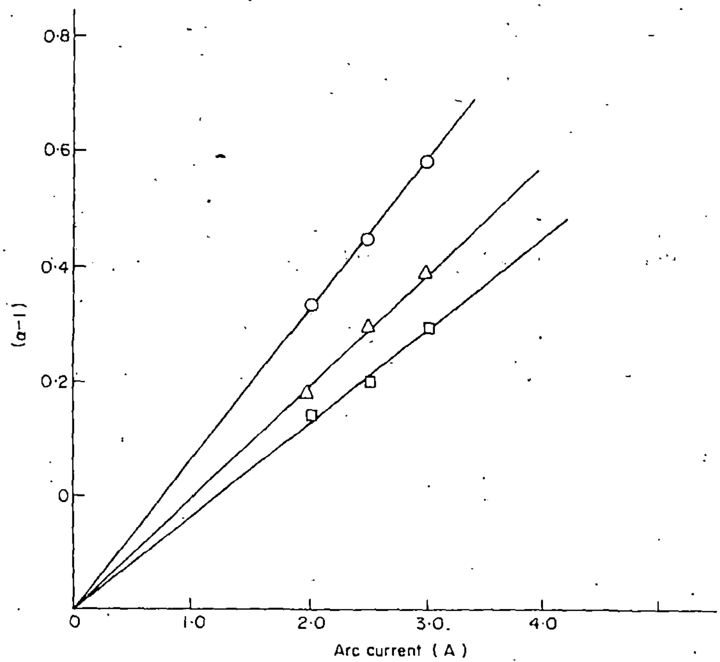

Figure 2. Variation of $(\alpha - 1)$ with arc current for three different pressures: $P = 0{\cdot}052$ Torr (○); $P = 0{\cdot}075$ Torr (△); and $P = 0{\cdot}17$ Torr (□).

different arc currents (2·0, 2·5 and 3·0 A) for three different pressures (0·052, 0·075 and 0·17 Torr). The values of $(\alpha - 1)$, where $\alpha = i/i_0$ thus obtained have been plotted against arc current for three different pressures in Fig. 2. The probe-to-probe voltages for three different arc currents for three different pressures have been measured and the values of E and $a = (E/I)(\alpha - 1)$ for zero magnetic field are given in the Table. The corresponding quantities, E_B and α_B in the presence of different magnetic fields, 100 G, 150 G, 230 G, 280 G and 345 G in the case of arc current 2 A, and 100 G, 150 G, 230 G, 280 G, 345 G and 430 G for arc currents of 2·5 and 3 A) have been measured, and the details have been entered in the Table in columns 2, 3, 7, 8, 12 and 13, for three different pressures. The corresponding values of $a'_B = (E_B/I_B)(\alpha_B - 1)$ have been entered in the Table in columns 4, 9, and 14. The values of $[(a'/a'_B) - 1]^{1/2}$ are given in the Table (columns 5, 10 and 15). The values of $(\alpha_B - 1)$ are plotted against the corresponding values of magnetic field for the three arc currents at different pressures in Figs. 3, 4 and 5. The values of $[(a'/a'_B) - 1]^{1/2}$ have been plotted against the corresponding values of magnetic field for three arc currents for pressures 0·052, 0·075 and 0·017 Torr in Figs. 6, 7 and 8. As may be observed, they are found to be straight lines passing through the origin. The proportionality between $[(a'/a'_B) - 1]^{1/2}$ and B confirms the validity of the assumptions made in deriving (16) and allows it to be used with some confidence to determine ν_{ce}; the values of this parameter for three different discharge currents and three different pressures are given in the Table, in columns 6, 11 and 16.

The results for ν_{ce} are consistent with those obtained by the microwave transmission method in our laboratory and also with literature values. From the results

Current	Magnetic field (G)	P = 0·052 Torr: E_B (V cm^{-1})	$(\alpha'_B - 1)$	a'_B	$[(a'/a'_B) - 1]^{1/2}$	ν_{cc}	P = 0·075 Torr: E_B (V cm^{-1})	$(\alpha'_B - 1)$	a'_B	$[(a'/a'_B) - 1]^{1/2}$	ν_{cc}	P = 0·17 Torr: E_B (V cm^{-1})	$(\alpha'_B - 1)$	a'_B	$[(a'/a'_B) - 1]^{1/2}$	ν_{cc}
	0	0·587	0·5385	0·1580		5·969	0·6097	0·3857	0·1174		6·714	0·620	0·350	0·1080		7·612
	100	0·565	0·500	0·1413	0·340	$\times 10^9$	0·587	0·3466	0·1076	0·265	$\times 10^9$	0·609	0·335	0·1020	0·235	$\times 10^9$
2 A	150	0·554	0·470	0·1303	0·445		0·576	0·340	0·0979	0·395	~~6·714~~	0·598	0·320	0·0957	0·350	
	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		
	0	0·5174	0·655	0·1356		7·22	0·522	0·5076	0·1060		8·042	0·543	0·400	0·087		9·36
	100	0·500	0·623	0·1246	0·2450	$\times 10^9$	0·517	0·4848	0·1003	0·220	$\times 10^9$	0·533	0·390	0·83	0·195	$\times 10^9$
	150	0·489	0·5968	0·1168	0·3650		0·500	0·4706	0·0941	0·330		0·522	0·380	0·0793	0·285	
2·5 A	230	0·457	0·5429	0·0991	0·5600		0·467	0·4478	0·0837	0·505		0·496	0·370	0·733	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	
	490	0·391	0·4692	0·0734	0·9700		0·413	0·3714	0·0614	0·870		0·435	0·333	0·6270 - 0·0679	0·740	
	0	0·348	0·7925	0·0919		9·308	0·446	0·590	0·0877		10·98	0·500	0·500	0·0833		11·79
	100	0·337	0·7857	0·0882	0·1950	$\times 10^9$	0·439	0·5806	0·0850	0·165	$\times 10^9$	0·496	0·490	0·0810	0·150	$\times 10^9$
	150	0·330	0·7650	0·0843	0·2850		0·430	0·5737	0·0823	0·240		0·489	0·480	0·0783	0·225	
3 A	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	0·550		0·457	0·440	0·0670	0·510	
	430	0·272	0·6750	0·0612	0·745		0·380	0·5077	0·0644	0·640		0·435	0·438	0·0635	0·590	

Table of numerical results.

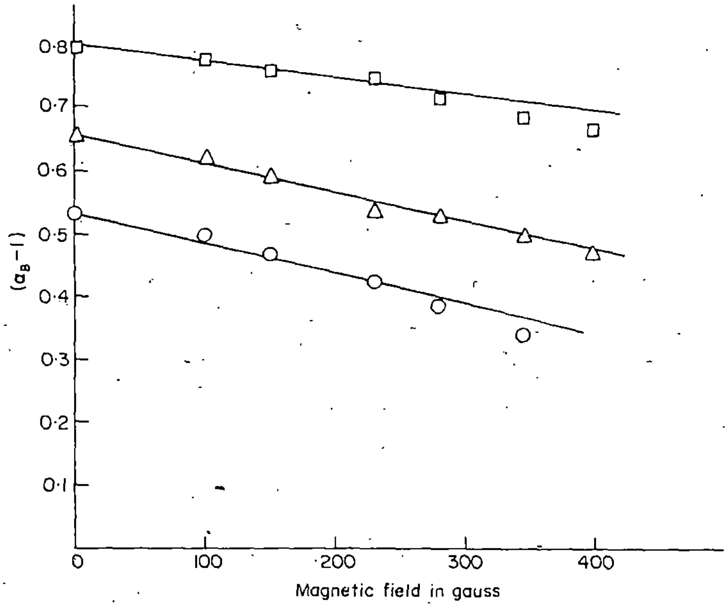

Figure 3. Variation of $(\alpha_B - 1)$ with magnetic field at $P = 0{\cdot}052$ Torr: arc current: 3 A (□); 2·5 A (△); and 2 A (○).

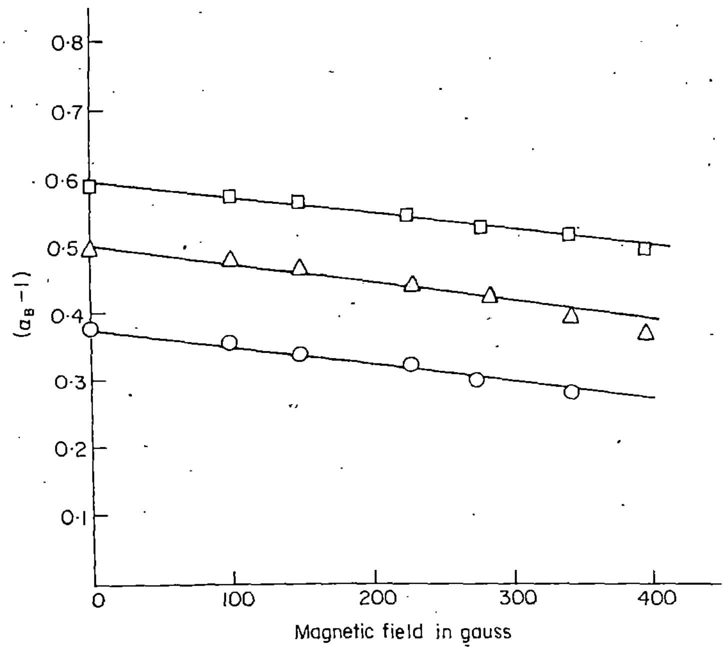

Figure 4. Variation of $(\alpha_B - 1)$ with magnetic field at $P = 0{\cdot}075$ Torr. Symbols as in Fig. 3.

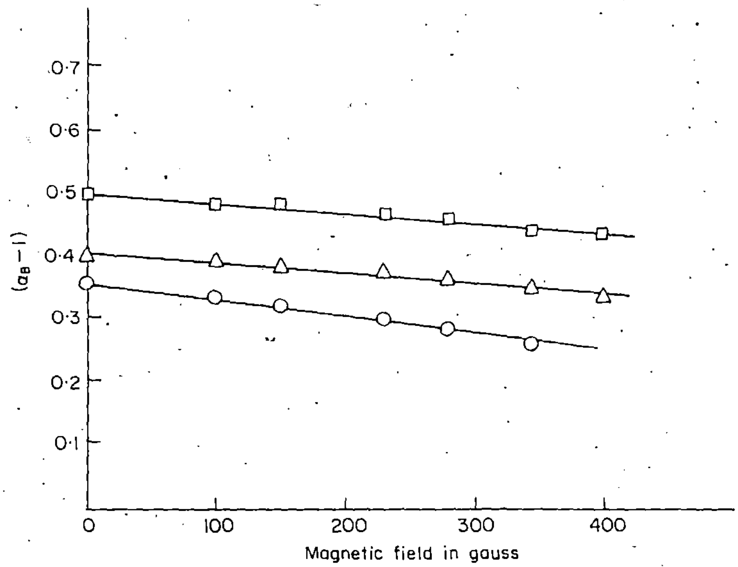

Figure 5. Variation of $(\alpha_B - 1)$ with magnetic field $P = 0{\cdot}17$ Torr. Symbols as in Fig. 3.

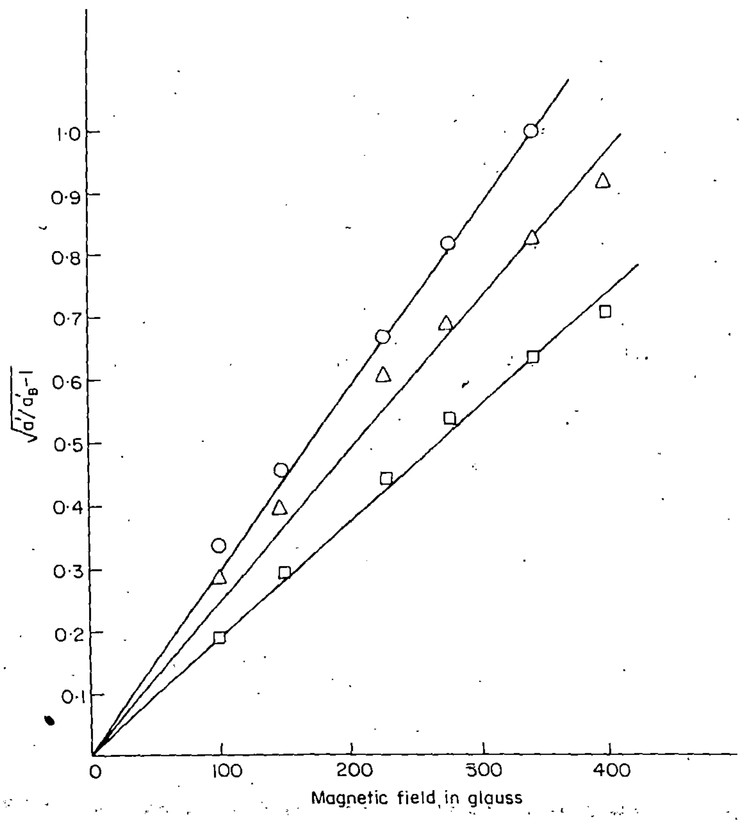

Figure 6. Variation of $[(a'/a'_B) - 1]^{1/2}$ with magnetic field at $P = 0{\cdot}052$ Torr. Symbols as in Fig. 3.

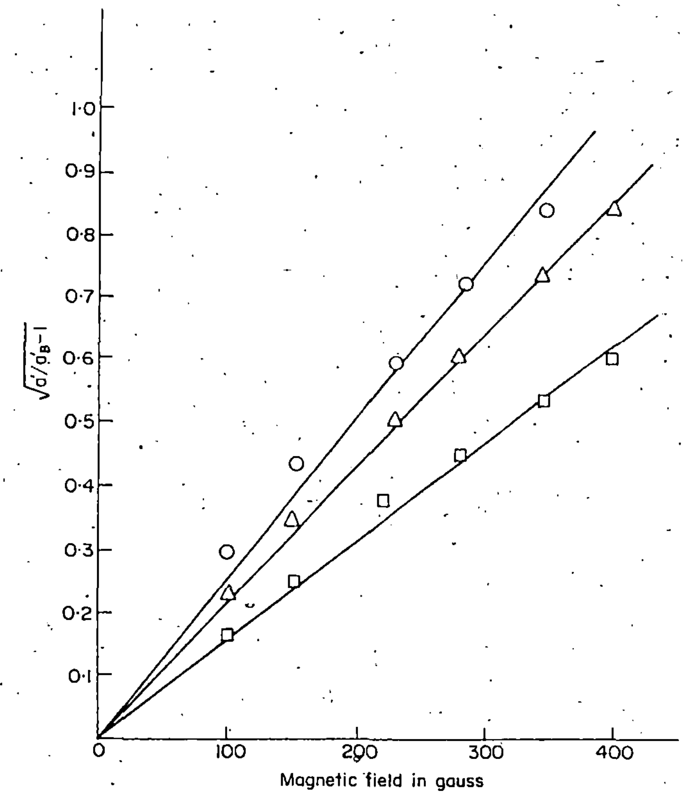

Figure 7. Variation of $[(a'/a'_B) - 1]^{1/2}$ with magnetic field at $P = 0{\cdot}075$ Torr. Symbols as in Fig. 3.

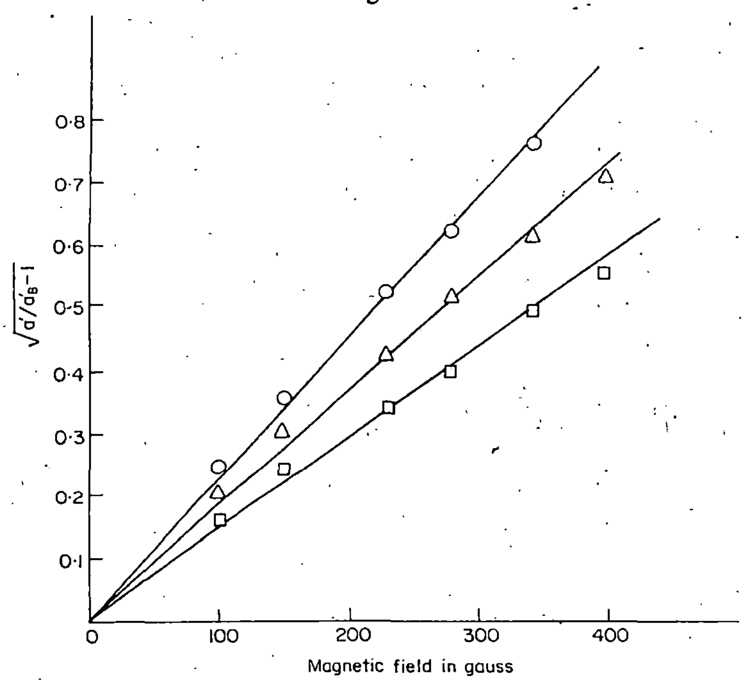

Figure 8. Variation of $[(a'/a'_B) - 1]^{1/2}$ with magnetic field at $P = 0{\cdot}17$ Torr. Symbols as in Fig. 3.

NO R/HEAD

obtained, it is evident that ν_{ce} increases with the increase of pressure for each value of current, which is quite natural. The increase of ν_{ce} with the increase of arc current could be due to the fact that as the current increases the mercury gets hotter. Other factors, however, are involved, such as the voltage across the arc and positive column and the arrangement for cooling. For this reason we have not tried to correlate ν_{ce} with arc current.

It is particularly noteworthy that although the axial magnetic field has been increased to 345 G, the value of ν_{ce} is nearly the same for a particular arc current. This justifies our use of a magnetic field as a probe. If still higher fields were used, the simple theory used would presumably break down at a certain stage.

We may conclude by saying that although the measurement procedure is rather elaborate it does enable us to measure not only the electron–atom collision frequency for momentum transfer with some accuracy, but also its variation with arc current and mercury vapour pressure.

ACKNOWLEDGMENT

The authors are indebted to Professor K. G. Emeleus for valuable comments and suggestions for the preparation of the paper.

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SEN, S. N., and JANA, D. C., 1978, Momentum transfer collision cross section for slow electrons in magnetic field from radiofrequency conductivity measurements. *Indian Journal of Physics* B, **52**, 288–295.

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 diagonostic 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 occurance 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 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 developes 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. <u>Transverse magnetic field</u>:-

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 Ω . 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 3.0A, 4.0 A and 5.0 A.

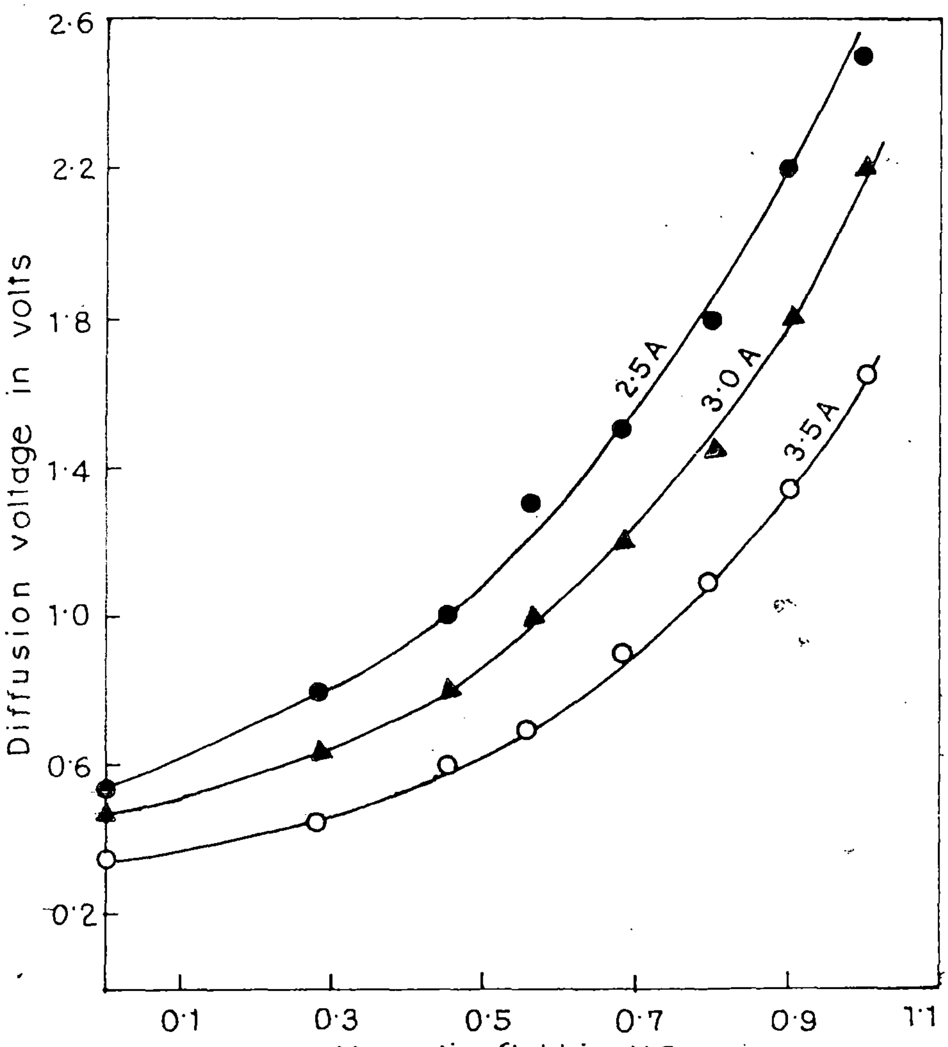
Table 6.1

Magnetic field in K.G	Arc current = 2.5 A		Arc current = 3.0 A		Arc current = 3.5 A	
	V_{RH} (exp.) in volts	V_{RH} deduced from eqn.(1) in volts	V_{RH} (exp.) in volts	V_{RH} deduced from eqn.(1) in volts	V_{RH} (exp.) in volts	V_{RH} deduced from eqn.(1) in volts
0.28	0.80	0.7075	0.65	0.6091	0.45	0.4562
0.45	1.00	0.9568	0.80	0.8134	0.60	0.6086
0.56	1.30	1.1807	1.00	0.9963	0.70	0.7450
0.68	1.50	1.4789	1.20	1.2413	0.90	0.9277
0.80	1.80	1.8357	1.45	1.5337	1.10	1.1458
0.90	2.20	2.1772	1.80	1.8137	1.35	1.3545
1.00	2.50	2.5590	2.20	2.1265	1.65	1.5878

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



2·6
2·2
1·8
1·4
1·0
0·6
0·2
Diffusion voltage in volts
2·5A
3·0A
3·5A
0·1
0·3
0·5
0·7
0·9
1·1
Magnetic field in KG

Fig. 6·1.

it can be assumed that an empirical relation of the form
$$V_{RH} = V_R[1 + m' H^2]$$

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 stastistical method, which is shown for a current of 2.5 A.

$$V_{RH} = V_R[1 + m' H^2]$$

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

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

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

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

$V_R = 0.55$ volts $\qquad \sum V_{RH} H^2 = 6.8005$

$\sum H^2 = 3.5069 \qquad \sum H^4 = 2.425$

$$m' = \frac{6.8005 - 1.928}{1.3338} = 3.6526.$$

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

$$V_R = 0.48 \text{ volts}$$

$$\sum V_{RH} H^2 = 5.6761 \text{ and } \qquad \sum H^2 = 3.5069$$

$$\sum H^4 = 2.425$$

$$\text{Hence} \quad m' = \frac{5.6761 - 1.6833}{1.164}$$

$$= 3.4302$$

And for 3.5 A arc current

$$V_R = 0.36 \text{ volts}$$

$$\sum V_{RH} H^2 = 4.2399, \qquad \sum H^2 = 3.5069$$

$$\text{and} \quad \sum H^4 = 2.425$$

$$m' = \frac{4.2399 - 1.2625}{0.873}$$

$$= 3.41062.$$

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

$$V_{RH} = V_R \, (1 + m'H^2) \qquad \ldots(6.1)$$

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

$$\sigma_r = \sigma_o \left[1 - \left(\frac{r}{R} \right)^2 \right]^n \qquad \ldots(6.2)$$

where σ_o is an axial conductivity, σ_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

$$V_R = -\int \frac{dn_e}{n_e} \frac{KT_e}{e} \qquad \ldots(6.3)$$

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

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

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

$$n_{eH} = n_e \exp(-\alpha H) \qquad \ldots(6.5)$$

where n_{eH} and n_e are the electron concentrations in the presence of and in absence of magnetic field respectively, and

$$\alpha = \frac{eEC_1^{1/2}\, r}{2KT_e P} \qquad \ldots(6.6)$$

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

$$V_{RH} = -\int \frac{dn_{eH}}{n_{eH}} \quad \frac{KT_{eH}}{e}$$

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

$$V_{RH} = -\frac{KT_{eH}}{e} \int_{(n_{eH})_o}^{(n_{eH})_r} \frac{d\left\{n_o\left(1-\frac{r^2}{R^2}\right)^n \exp(-aH)\right\}}{n_o\left(1-\frac{r^2}{R^2}\right)^n \exp(-aH)}$$

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

Hence

$$T_{eH} = \frac{e}{K} \quad \frac{V_{RH}}{\left(2n \log \frac{R}{\sqrt{R^2-r^2}} + aH\right)} \qquad \ldots(6.7)$$

And when $H = 0$ it reduces to

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

From eqns. (6.7) and (6.8)

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

Putting the value of V_{RH} from eqn. (6.1)

$$\frac{T_{eH}}{T_e} = (1 + m'H^2) \; \frac{X}{X + aH}$$

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

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

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 $E = 37/26.5$ volts/cm, $r = 0.6$ cm, $C_1 = 2.0 \times 10^{-6}$, $p = 0.3731$ torr, when arc current is 3.0 A, with $E = 35.5/26.5$, volts/cm, $r = 0.6$ cm, $C_1 = 0.5946 \times 10^{-6}$, $P = 0.3731$ torr; similarly for arc current 3.5 A with $E = 34.0/26.5$ volts/cm, $r = 0.6$ cms., $C_1 = 0.49 \times 10^{-6}$, $P = 0.3731$ torr (values taken from an earlier paper (Sadhya and Sen, 1980) and $T_e = 10131\ ^oK$ for arc current 2.5 A, $T_e = 9573\ ^oK$ for arc current 3.0A, and $T_e = 9000\ ^oK$ for arc current 3.5 A, given by Sen, Gantait and Acharyya (1988), the values of 'a' becomes 1.83×10^{-3} while for 3.0 A and 3.5 A arc currents it becomes 1.013×10^{-3} and 0.937×10^{-3} respectively taking the corresponding values of the above quantities. And the values of $x = 2n \log \dfrac{R}{\sqrt{R^2 - r^2}}$ 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.

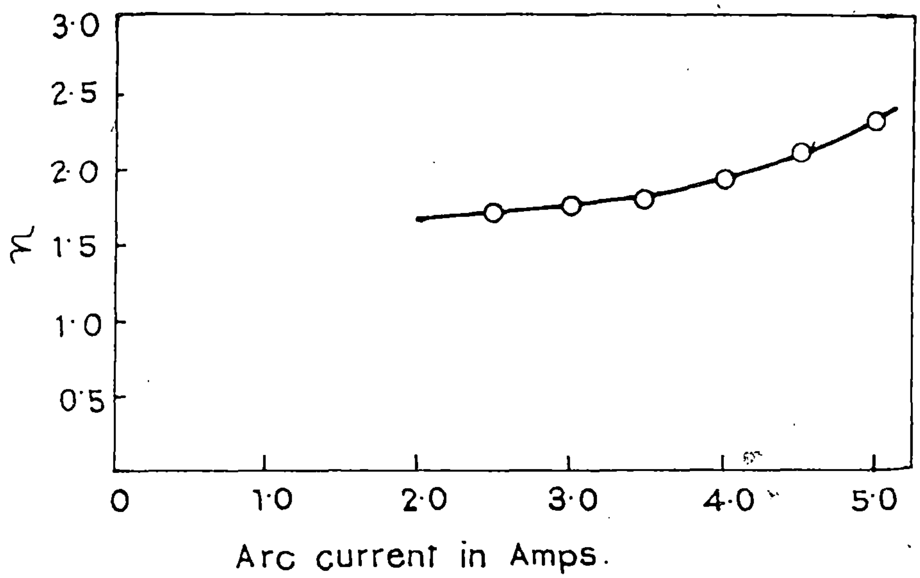


Fig. 6·2.

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.

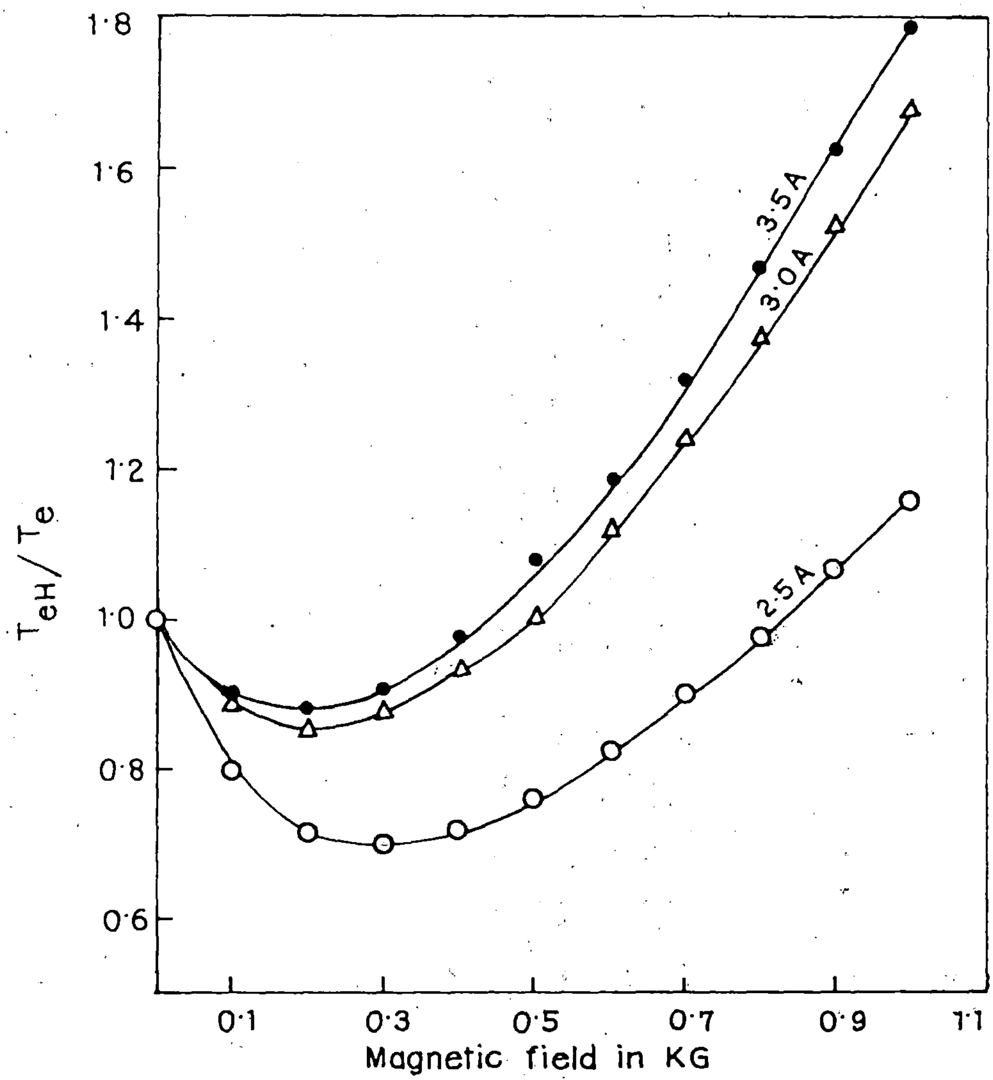
6.3.1. <u>Axial magnetic field:-</u>

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 σ_H and σ_0 are the conductivities with and without magnetic field and the values of α 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

$$n_{eH} = n_0 \exp(-\alpha H)$$



1·8
1·6
1·4
1·2
1·0
0·8
0·6
T_{eH}/T_e
0·1
0·3
0·5
0·7
0·9
1·1
Magnetic field in KG
3·5A
3·0A
2·5A

Fig. 6·3.

then

$$V_{RH} = -\int_{(n_{eH})_o}^{(n_{eH})_r} \frac{dn_{eH}}{n_{eH}} \quad \frac{KT_{eH}}{e}$$

$$= -\frac{KT_{eH}}{e} \int \frac{d\left\{n_o\left(1-\frac{r^2}{R^2}\right)^n e^{-\alpha H}\right\}}{n_o\left(1-\frac{r^2}{R^2}\right)^n e^{-\alpha H}}$$

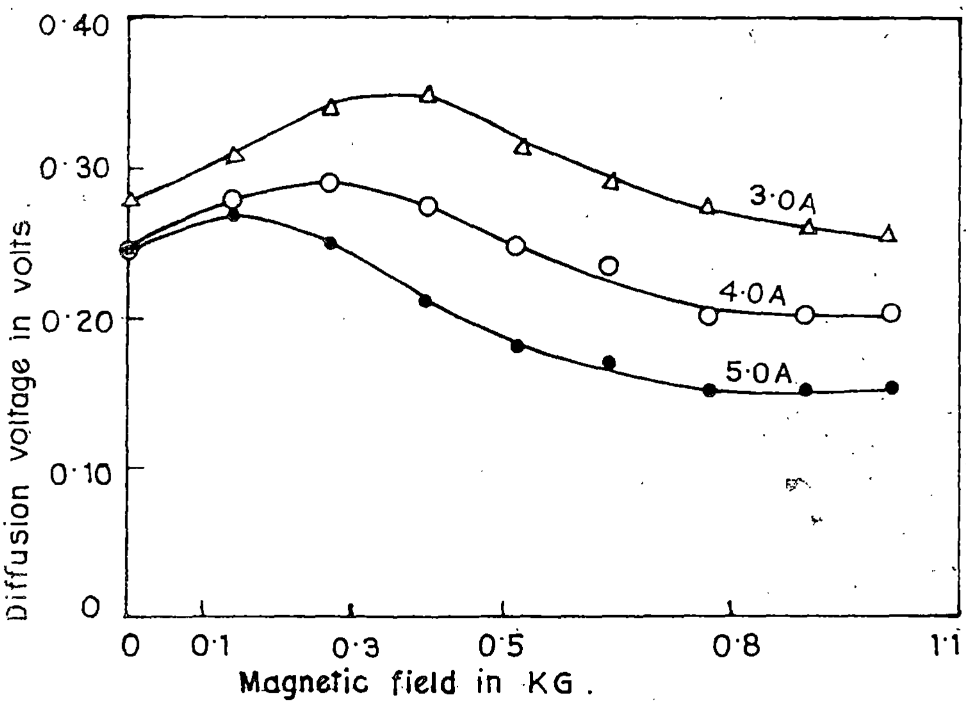
$$= -\frac{KT_{eH}}{e}\left[\log\left(1-\frac{r^2}{R^2}\right)^n + \log e^{-\alpha H}\right]$$

$$T_{eH} = \frac{e/K \quad V_{RH}}{2n \log \frac{R}{\sqrt{R^2 - r^2}} + \alpha H}$$

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

$$\frac{T_{eH}}{T_e} = \frac{V_{RH}}{V_R} \quad \frac{2n \log \frac{R}{\sqrt{R^2 - r^2}}}{2n \log \frac{R}{\sqrt{R^2 - r^2}} + \alpha H} \qquad \text{...(6.10)}$$

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 α 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.


0·40
0·30
0·20
0·10
0
Diffusion voltage in volts.
3·0A
4·0A
5·0A
0
0·1
0·3
0·5
0·8
1·1
Magnetic field in KG .
Fig.6·4.

The values of 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 T_{eH}/T_e for all the three arc currents a maximum in the value of 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

$$T_e (T_e - T_g) = C \lambda_e^2 E^2 \qquad \ldots(6.11)$$

where $C = \dfrac{\pi m_g\, e^2}{24\, m_e K^2}$

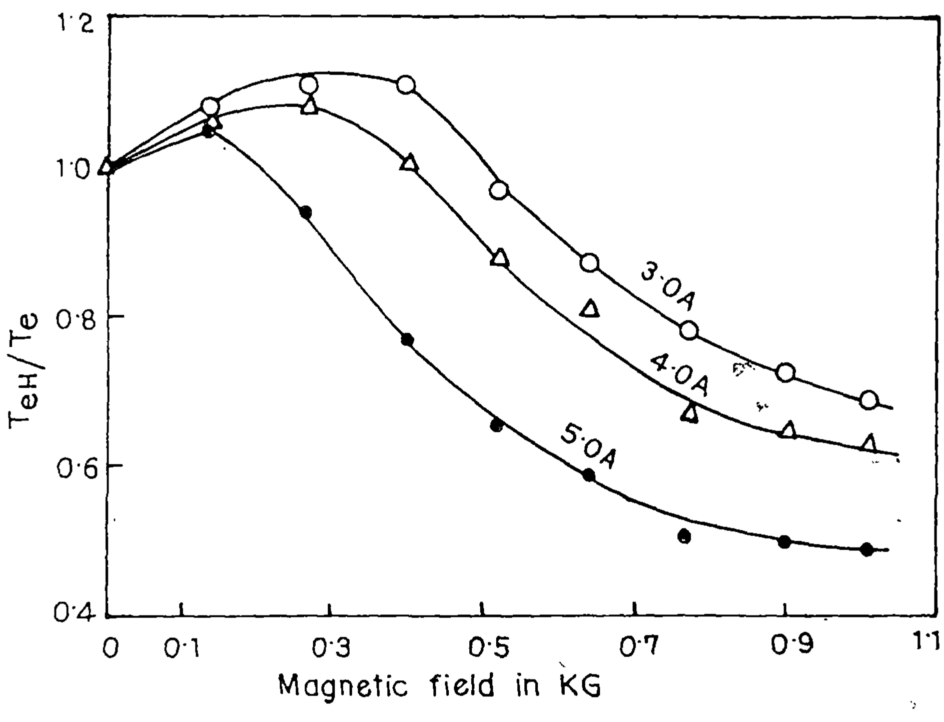

1·2
1·0
0·8
0·6
0·4
TeH/Te
0
0·1
0·3
0·5
0·7
0·9
1·1
3·0A
4·0A
5·0A
Magnetic field in KG

Fig.6·5.

In presence of magnetic field eqn. (6.11) can be modified as

$$T_{eH}(T_{eH} - T_g) = C\lambda_{eH}^2 E_H^2 \qquad \ldots(6.12)$$

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

$$(T_{eH} - T_e)(T_{eH} + T_e - T_g) = C\left[\lambda_{eH}^2 E_H^2 - \lambda_e^2 E^2\right]$$

with approximation that

$$T_{eH} + T_e \approx 2T_e$$

$$\left[\frac{T_{eH}}{T_e} - 1\right] = \frac{C}{T_e^2(2 - T_g/T_e)}\left[\lambda_{eH}^2 E_H^2 - \lambda_e^2 E^2\right] \cdots(6.13)$$

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

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

and $$\lambda_{eH} = \frac{\lambda_e}{(1 + C_1 H^2/P^2)^{1/2}}$$

[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

$$\frac{T_{eH}}{T_e} = 1+\beta\left[\frac{m^2H^2+2mH-C_1H^2/p^2}{1+C_1H^2/p^2}\right]$$

where $$\beta = \frac{CE^2\ \lambda_e^2}{T_e^2\left[2-\frac{T_g}{T_e}\right]}$$

then $$\frac{1}{T_e}\ \frac{dT_{eH}}{dH} = \frac{\beta\left[mC_1\frac{H^2}{p^2}-\left(m^2-\frac{C_1}{p^2}\right)H-m\right]}{\left[1+C_1H^2/p^2\right]} = 0$$

Hence

$$H = \frac{\left(m^2-\frac{C_1}{p^2}\right)+\sqrt{m^4+\frac{C_1^2}{p^4}+2m^2\frac{C_1}{p^2}}}{2mC_1/p^2} \quad \ldots(6.14)$$

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

$$\frac{1}{T_e}\ \frac{d^2T_{eH}}{dH^2} = \frac{-2\beta}{\left(1+C_1\frac{H^2}{p^2}\right)^3}\left[\left(1+C_1\frac{H^2}{p^2}\right)\left\{2mC_1\frac{H}{p^2}+\frac{C_1}{p^2}-m^2\right\} - \left\{mC_1\frac{H^2}{p^2}+\left(\frac{C_1}{p^2}-m^2\right)H-m\right\}4C_1\frac{H}{p^2}\right]$$

Putting the value of

$$H = \frac{m}{C_1 / p^2} \quad (\text{eqn. } 6\cdot 15)$$

$$\frac{1}{T_e} \frac{d^2 T_{eH}}{dH^2} = 2\beta \left[m^2 - \frac{C_1}{p^2} + \frac{m^4 p^2}{C_1} + \frac{m^6 p^4}{C_1^2} + \cdots \right]$$

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)

$$\frac{1}{T_e} \frac{d^2 T_{eH}}{dH^2} = 2\beta \left[0\cdot 087 \times 10^{-6} - 1\cdot 358 \times 10^{-7} + 5\cdot 4 \times 10^{-9} + \cdots \right]$$

= 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).

$$\frac{1}{T_e} \frac{d^2 T_{eH}}{dH^2} = 2\beta \left[30\cdot 8 \times 10^{-6} - 30\cdot 4 \times 10^{-6} + 31\cdot 15 \times 10^{-6} + 970\cdot 3 \times 10^{-6} + \cdots \right]$$

= 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_{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 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.

Arc current in amps.	H_{max} Exp. K.G.	H_{min} calculated K.G.
3	0.31	0.3285
4	0.2	0.2818
5	0.142	0.201
Transverse magnetic field		
2.5	0.288	0.2735
3	0.201	0.181
3.5	0.188	0.132

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_{max}, or H_{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.

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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 measuing 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

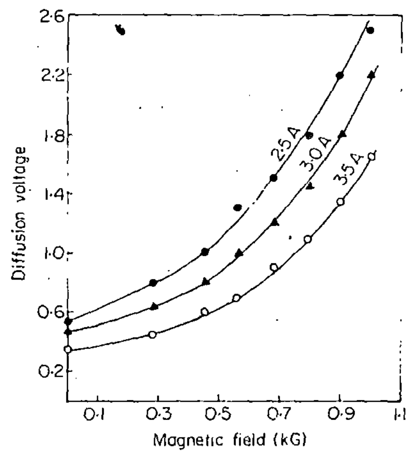

Figure 1. Variation of diffusion voltage with magnetic field for different arc currents (transverse magnetic field).

assumed that an empirical relation of the form $V_{RH} = V_R[1 + m'H^2]$, where V_R 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

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

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

Magnetic field (kg)	Arc current = 2·5 A		Arc current = 3·0 A		Arc current = 3·5 A	
	V_{RH} (exp.)	V_{RH} deduced from (1)	V_{RH}(exp.)	V_{RH} deduced from (1)	V_{RH}(exp.)	V_{RH} deduced from (1)
0·28	0·80	0·7075	0·65	0·6091	0·45	0·4562
0·45	1·00	0·9568	0·80	0·8134	0·60	0·6086
0·56	1·30	1·1807	1·00	0·9963	0·70	0·7450
0·68	1·50	1·4789	1·20	1·2413	0·90	0·9277
0·80	1·80	1·8357	1·45	1·5337	1·10	1·1458
0·90	2·20	2·1772	1·80	1·8137	1·35	1·3545
1·00	2·50	2·5590	2·20	2·1265	1·65	1·5878

Table 1.

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

$$\frac{T_{eH}}{T_e} = \frac{1 + m'H^2}{1 + \dfrac{aH}{x}} \tag{2}$$

where

$$a = \frac{eRC_1^{1/2}}{2KT_e P}, \quad C_1 = \left(\frac{e}{m} \cdot \frac{L}{v_r}\right)^2 \quad \text{and} \quad x = 2n \log \frac{R}{(R^2 - r^2)^{1/2}}$$

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_{eH}/T_e are plotted in Fig. 3. Each curve shows a minimum around 200–300 G.

3.2. *Axial magnetic field*

Values of V_{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

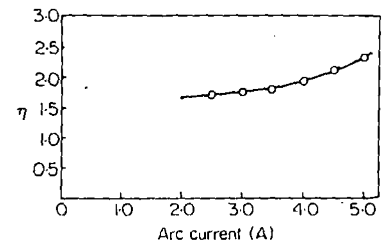

Figure 2. Variation of n with arc current.

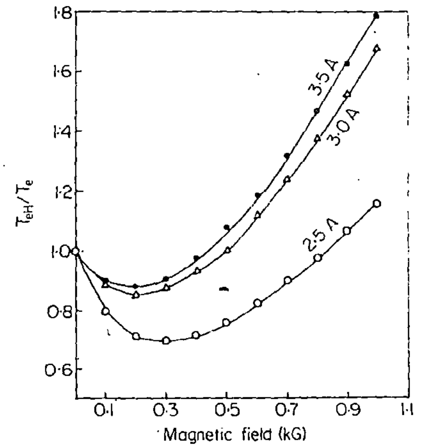

Figure 3. Variation of T_{eH}/T_e with magnetic field (Transverse magnetic field).

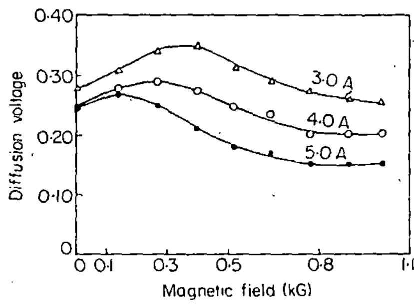

Figure 4. Variation of diffusion voltage with magnetic field (axial magnetic field).

Hirsh and Oskam (1978), energy balance considerations in the absence of a magnetic field lead to the equation

$$\frac{T_e - T_g}{T_e} = \frac{\pi m_g}{24 m_e} \cdot \frac{\lambda_e^2 e^2 E^2}{K^2 T_e^2} \tag{3}$$

and when a magnetic field is present

$$\frac{T_{eH} - T_g}{T_{eH}} = \frac{\pi m_g}{24 m_e} \cdot \frac{\lambda_{eH}^2 e^2 E_H^2}{K^2 T_{eH}^2} \tag{4}$$

Putting

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

(Sen and Gantait 1988) and

$$\lambda_{eH} = \lambda_e \Big/ \left(1 + C_1 \frac{H^2}{P^2}\right)$$

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

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

where

$$\beta = \frac{\pi m_g e^2 E^2 \lambda_e^2}{24 m_e K^2 T_e^2 \; 2 - \dfrac{T_g}{T_e}}$$

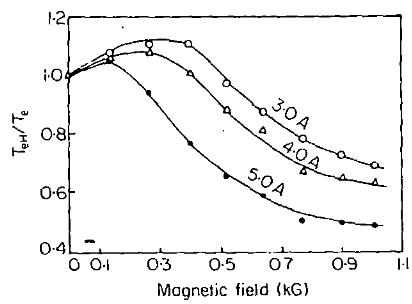

Figure 5. Variation of T_{eH}/T_e with magnetic field (axial magnetic field).

	Arc current (A)	H_{max} (exp.) (k-G)	H_{max} (calc.) (k-G)
Axial	3	0·31	0·3285
magnetic	4	0·2	0·2818
field	5	0·142	0·201
		H_{min} (expt.) (kG)	H_{min} (calc.) (kG)
Transverse	2·5	0·288	0·2735
magnetic	3	0·201	0·181
field	3·5	0·188	0·132

Table 2. Calculated and experimental values of H_{max} and H_{min} in axial and transverse magnetic fields.

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

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

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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CHAPTER VII

BREAKDOWN OF ARGON UNDER RADIOFREQUENCY EXCITATION IN TRANSVERSE MAGNETIC FIELD

7.1. Introduction:-

In a high frequency gas breakdown the electrons gain energy from the field by suffering collisions with the gas atoms and having their ordered oscillatory motion changed to random kinetic motion. Thus when this random kinetic energy exceeds the ionization potential, electron multiplication occurs. The breakdown of gases in high frequency electrical fields has been studied by many workers. In presence of the magnetic field, either longitudinal or transverse, the breakdown of a gas excited by a radio-frequency voltage has been studied by Townsend and Gill (1938) for two frequencies, 48 MHz and 30 MHz and within a range of pressure varying from a few m torr to 0.24 torr. In 1951 Llewellyn et al (1951) investigated the high frequency breakdown between wire and coaxial cylinders in air over the range of frequencies from 3.5 Mc/S to 70 Mc/S at pressure below 20 mm Hg. To interpret the results they assumed that the electronic mean free path is small compared with the linear dimension of the discharge tube and the collision frequency is very much greater than the frequency of the applied field. Bayet (1951) studied the breakdown mechanism in alternating fields, including u.h.f. fields and the role of deionization mechanisms (recombination, diffusion and the effect of electron attachment) was discussed. Haefer (1953) gave a detailed experimental and theoretical account of breakdown voltage measurements in coaxial cylindrical tubes in presence of an axial magnetic field. Using cylindrical electrodes Ferritti and Veronesi (1955) showed that the magnetic field has a strong influence on the breakdown voltage of the discharge. Measurements were made in air at 0.1, 0.5, 1.0 mm Hg. pressure and at 10, 15, 20, 25, 30 Mc/S and the magnetic field varying from 0 to 650 gauss. Hale (1947) computed the magnitude of breakdown voltage in rare gases when excited by a radio frequency voltage (frequency a few Mc/S to 400 Mc/S) for some fixed values of pressure such as 100μ, 150μ and 200μ. The main assumptions in this theory are that (a) the amplitude of oscillation of the electron must be equal to the mean free path of the electron at that pressure (b) energy gained by the electron between two successive collisions must be equal to or greater than the ionization energy of the gas. The values of breakdown voltage thus calculated are in fair agreement with his experimental results. It is the object of the present investigation to calculate the breakdown voltage of argon, following the procedure adopted by Hale (1947) where a steady transverse magnetic field is applied and calculate its variation over a range of radiofrequency for some chosen values of pressure. It will be of interest to see how the frequency at which the breakdown field becomes a minimum shifts with the increase of the magnetic field. The results are expected to provide information regarding the nature of interaction of a magnetic field with the motion of electrons in a radio frequency field.

7.2. Theoretical treatment:-

It is well known that the breakdown potential for high frequency fields is measured by those electrons in the gas which are able in acquiring the ionising energy in one mean free path. It is known as well that in presence of external transverse magnetic field electronic mean free path also decreases [Blevin and Haydon (1958), Sen and Ghosh (1963)]. Thus, the breakdown potential should be a function of the gas, gas pressure, electrode separation, frequency of the applied field and the magnetic field.

Under this consideration the solution of the equation of motion of the electron which moves in the high frequency field and magnetic field in the gas can be achieved provided before breakdown takes place the electric field is not distored by space charge. The applied radio frequency field is along the X-axis and the magnetic field is assumed along Z axis. The motion of electron under this assumption is given by

$$m \frac{dV_x}{dt} + HeV_y = eE \sin 2\pi ft \quad \cdots \quad (7.1)$$

$$m \frac{dV_y}{dt} - HeV_x = 0 \quad \cdots \quad (7.2)$$

According to Hale (1947) the electron is assumed to be at rest when the instanteneous value of the applied field is zero and all collisions which do not result in the formation of an ion pair are neglected because such collisions do not lead the breakdown of the gas concerned. The conditions are so imposed that the electrons which are at rest when the instantaneous field is zero will acquire ionising potential at the end of one electronic mean free path. However, this simplification does not eventually alter the results because the electrons which acquire the ionizing energy in gas in one mean free path cause the initial breakdown.

In presence of magnetic field the equation of motion of electron after differentiating equation(7.1)

$$m \frac{d^2 v_x}{dt^2} + He \frac{dv_y}{dt} = eE\, 2\pi f \cos 2\pi f t$$

or

$$\frac{d^2 v_x}{dt^2} + \frac{He}{m} \frac{dv_y}{dt} = \left(\frac{eE}{m}\right) 2\pi f \cos 2\pi f t$$

or

$$\frac{d^2 v_x}{dt^2} + \omega_B \frac{dv_y}{dt} = \left(\frac{eE}{m}\right) 2\pi f \cos 2\pi f t \qquad \ldots(7.3)$$

From eqn. (7.2)

$$m \frac{dv_y}{dt} = \left(\frac{He}{m}\right) v_x$$
$$= \omega_B v_x$$

substituting this into eqn.(7.3) we have

$$\frac{d^2 v_x}{dt^2} + \omega_B^2 v_x = (e/m) E \omega \cos \omega t$$

Hence

$$v_x = A \cos \omega_B t + B \sin \omega_B t + \frac{1}{\omega_B^2 - \omega^2} (e/m) E \omega \cos \omega t$$

Boundary condition

$$V_x = 0 \quad \text{at} \quad t = 0$$

$$\therefore \ A = -\frac{1}{(\omega_B^2 - \omega^2)} (e/m)\, \omega E$$

and from $\dfrac{dV_x}{dt} = 0$ at $t = 0$, $B = 0$.

$$\therefore \ V_x = \frac{1}{\omega^2 - \omega_B^2} (e/m) \omega E \cos \omega_B t + \frac{1}{\omega_B^2 - \omega^2} (e/m) E \omega \cos \omega t$$

...(7.4)

when $H = 0$, $\omega_B = 0$

then

$$V_x = \frac{1}{\omega^2} (e/m) \omega_E - \frac{1}{\omega^2} (e/m) E \omega \cos \omega t$$

$$\therefore \ V_x = (e/m) \frac{E}{\omega} (1 - \cos \omega t)$$

or

$$V_x = (e/m) \frac{E}{2\pi f} (1 - \cos \omega t)$$

or,

$$f = (e/m) \frac{E}{2\pi V_x} (1 - \cos 2\pi f t) \quad \ldots\ldots (7.4a)$$

From eqn. (7.4)

$$x = \frac{1}{\omega^2 - \omega_B^2} (e/m) \frac{\omega}{\omega_B} E \sin \omega_B t + \frac{1}{\omega_B^2 - \omega^2} (e/m) E \frac{\omega \sin \omega t}{\omega} + C$$

...(7.5)

At $x = 0$, $t = 0$ then $C = 0$.

$$\therefore \; x = \lambda_H = \frac{1}{\omega^2 - \omega_B^2}(e/m)\frac{\omega}{\omega_B} E \sin\omega_B t + \frac{1}{\omega_B^2 - \omega^2}(e/m) E \sin\omega t \quad \ldots (7.6\ a)$$

$$E = \frac{\lambda_H}{\dfrac{(e/m)}{(\omega^2 - \omega_B^2)}\left[\dfrac{\omega}{\omega_B}\sin\omega_B t - \sin\omega t\right]} \quad \ldots (7.6\ b)$$

Now

$$x = \frac{(\omega/\omega_B)(e/m) E \sin\omega_B t}{\omega^2(1 - \omega_B^2/\omega^2)} + \frac{1}{(\omega_B^2 - \omega^2)}(e/m) E \sin\omega t$$

$$= (e/m)\frac{1}{\omega^2}(\omega/\omega_B)\left(1 - \frac{\omega_B^2}{\omega^2}\right)^{-1} E\left(\omega_B t - \frac{\omega_B^3 t^3}{3!} + \cdots\cdots\right) + \frac{1}{(\omega_B^2 - \omega^2)}(e/m) E \sin\omega t$$

$$= (e/m)\frac{1}{\omega^2}(\omega/\omega_B) E\left[\omega_B t + \text{in terms of } \omega_B + \cdots\cdots\right] + \frac{1}{(\omega_B^2 - \omega^2)}(e/m) E \sin\omega t$$

$$= (e/m)\frac{1}{\omega^2}(\omega/\omega_B) E \omega_B t + \frac{1}{\omega_B^2 - \omega^2}(e/m) E \sin\omega t$$

$$\therefore\ x = (e/m)\frac{1}{\omega}Et + \frac{1}{\omega_B^2-\omega^2}(e/m)E\sin\omega t$$

when $H = 0$, $\omega_B = 0$

then

$$x = (e/m)\frac{1}{\omega}Et - \frac{1}{\omega^2}(e/m)E\sin\omega t$$

$$x = \lambda = (e/m)\frac{E}{4\pi^2 f^2}(2\pi ft - \sin 2\pi ft)$$

Substituting f from eqn. (7.4a) we get,

$$E = \frac{v_x^2}{\lambda(e/m)}\ \frac{2\pi ft - \sin 2\pi ft}{(1-\cos 2\pi ft)^2} \qquad \ldots(7.8)$$

eqn. (7.5) and (7.7) are identical with those provided by Hale (1947) in no magnetic field.

In light of eqn.(7.4) and (7.6) it is assumed that the gas under interest will undergo breakdown when the values of E and f are such that λ will be one electronic mean free path and the electron will acquire ionizing energy at the end of its mean free path.

Since $(1/2)mv^2 = eV_i$ where V_i is the ionization potential of a gas under study, ν is calculated.

With the help of eqn. (7.8) for an assigned value of λ which is a function of pressure, E the peak voltage has been computed taking ft as $\frac{1}{16}$, $\frac{2}{16}$, $\frac{3}{16}$ and so on for pressure 100μ, 150μ and 200μ and entered in table 7.1, and 7.2 and 7.3 respectively. Hence the value of f is calculated from eqn.(7.5) The value of ft for which E is minimum (in absence of magnetic field) comes out to be around 5/16 (Hale, 1947).

In presence of magnetic field, λ decreases with magnetic field. From the concept of equivalent pressure as provided by Blevin and Haydon (1958), Sen and Ghosh (1963) λ is given by

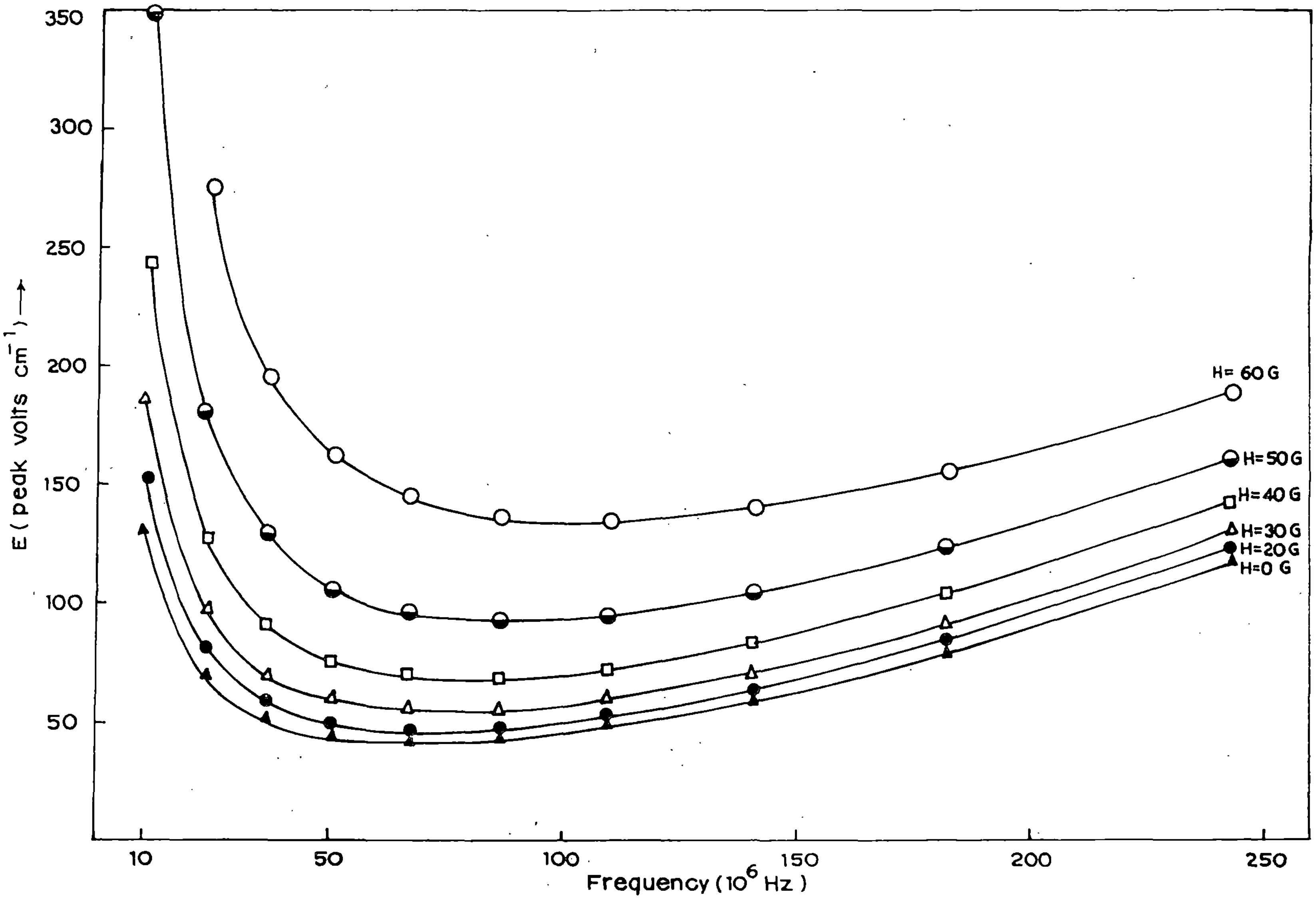
$$\lambda_H = \frac{\lambda}{(1 + C_1 H^2/P^2)^{1/2}} \qquad \ldots(7.9)$$

where $C_1 = (e/m \cdot L/v_r)$ and v_r is the random velocity and L is the mean free path of electron at 1 torr. From literature value for respective parameters in eqn. (7.9) values for λ_H have been computed and are entered in Table 7.4. Similarly E has been estimated from eqn.(7.6) for three pressures

100 μ , 150 μ , 200 μ and entered into the tables 7.1 7.2 and 7.3 and the results are plotted in figures (7.1), and (7.2), and (7.3) respectively. It is seen that minimum breakdown field increases with increasing magnetic field and the minimum shifts to higher frequencies when magnetic field is increased.

7.3. Discussion:-

On the basis of this model it is also possible to calculate the minimum breakdown field (V/cm) in presence of magnetic field. The theoretical investigation has been carried out for three pressures namely 100 μ 150 μ and 200 μ and magnetic field upto 60 gauss in 100 μ ; 80 gauss in 150 μ and 120 gauss in 200 μ Fig. 7.1, 7.2 and 7.3 show the general characteristics of E vs. frequency of the applied electric field where magnetic field is a parameter. It is observed that all the characteristics show that the minimum breakdown potential increases with magnetic field and also with frequency. From another approach the increase in break down voltage with magnetic field in high frequency field has been observed by Deb and Goswami (1964). They used electrodeless high frequency discharge at low pressure in transverse magnetic field. It is shown that with increase in α , the ratio of the cyclotron frequency to the frequency of the applied field, the breakdown


E (peak volts cm^{-1}) ⟶
350
300
250
200
150
100
50
10
50
100
150
200
250
Frequency (10^6 Hz)
H= 60 G
H=50 G
H=40 G
H=30 G
H=20 G
H=0 G
Fig. 7·1.

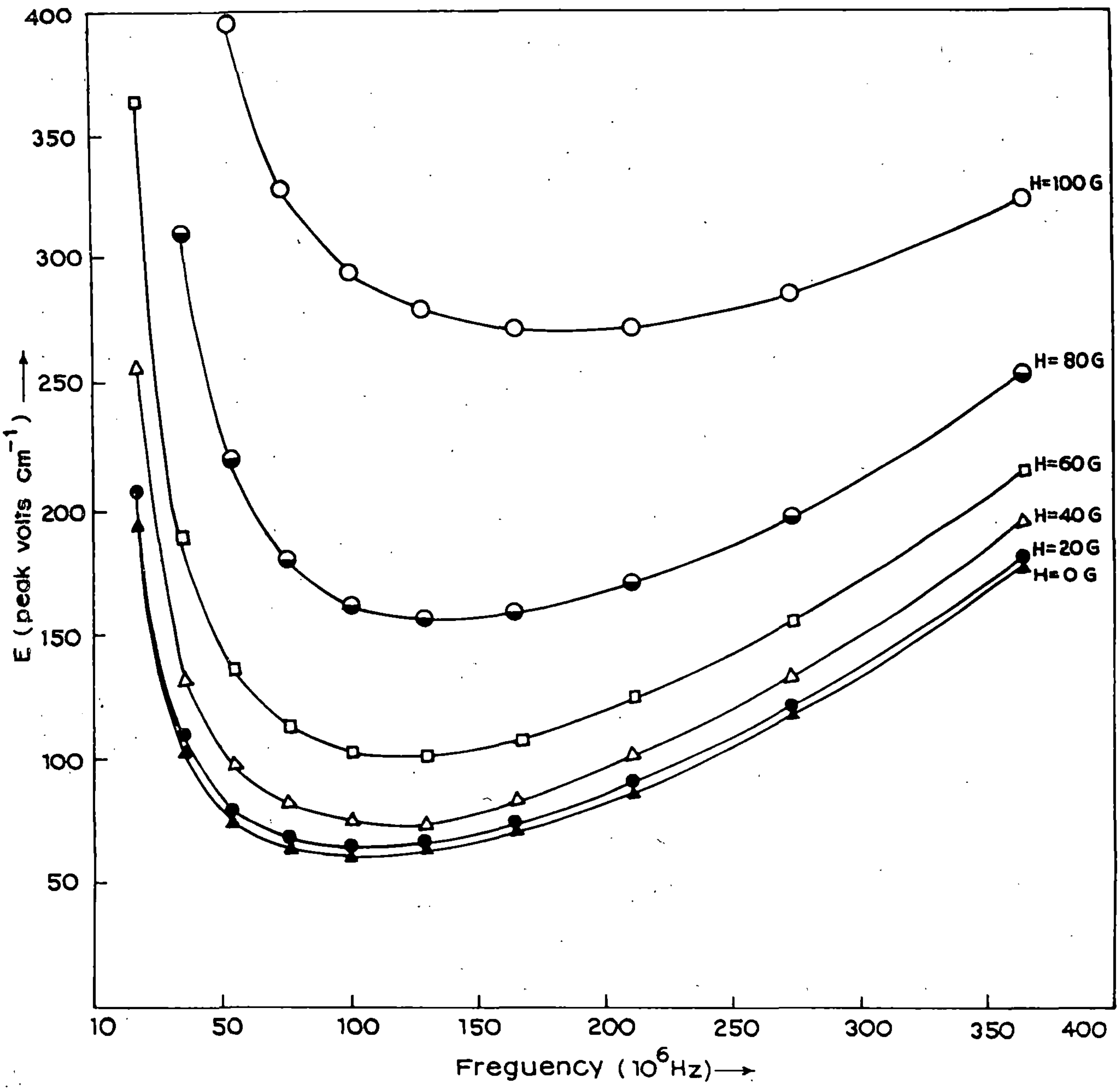
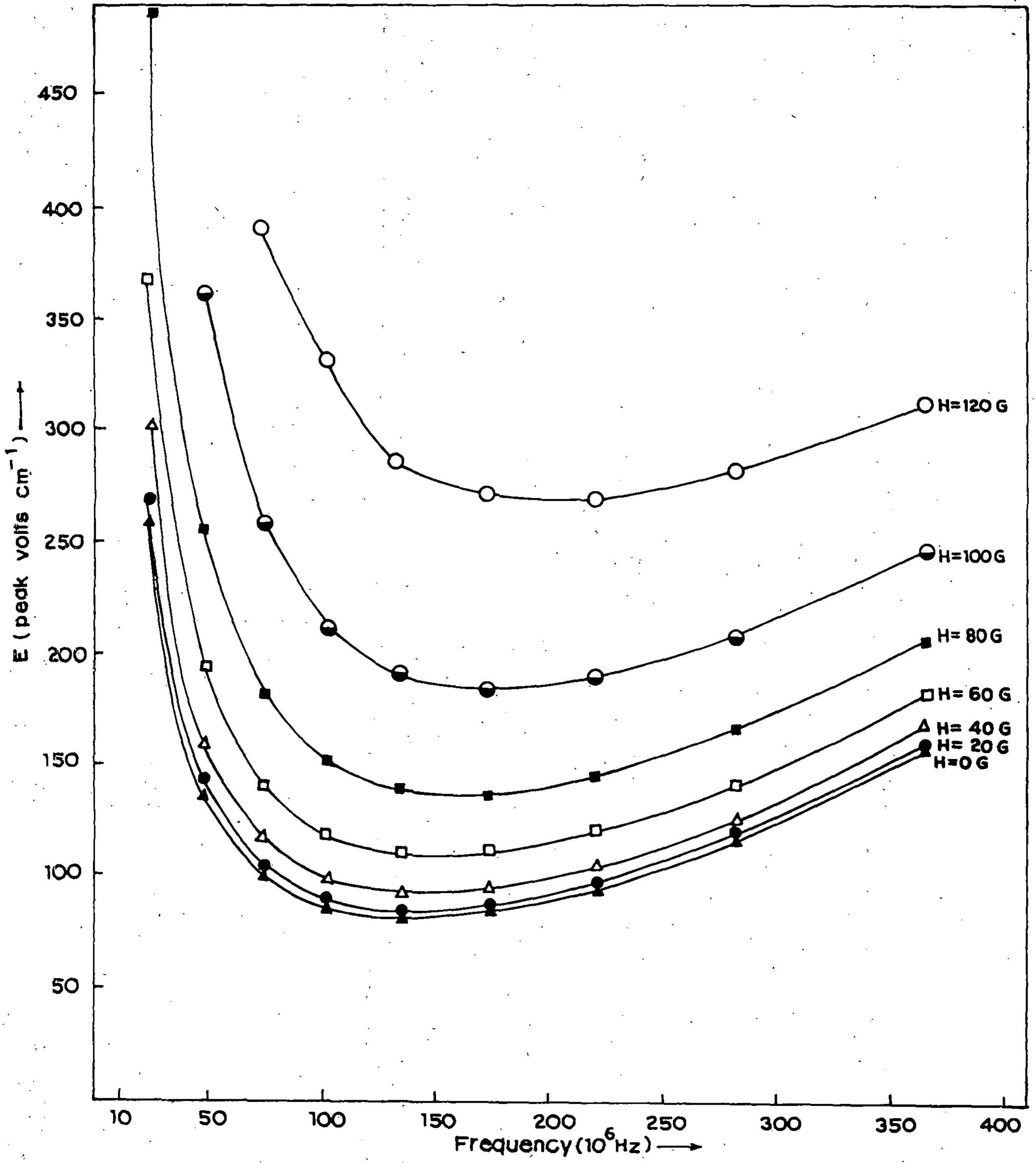

400
350
300
250
200
150
100
50
E (peak volts cm^{-1})
H=100 G
H= 80G
H=60 G
H=40 G
H=20 G
H=0 G
10
50
100
150
200
250
300
350
400
Freguency (10^6Hz)

Fig. 7·2



450
400
350
300
250
200
150
100
50
E (peak volts cm^{-1})
H=120 G
H=100G
H= 80G
H= 60 G
H= 40 G
H= 20 G
H=0 G
10
50
100
150
200
250
300
350
400
Frequency (10^6 Hz)

Fig. 7·3

field tends to increase and the main region of the curve is displaced towards longer wavelength. The increase of breakdown voltage of a low pressure ac discharge in neon with frequencies ranging from 100 Hz. to 20 KHz. has been observed by Kelkar (1970). He used neon glow lamp protected by a series resistance R_s.

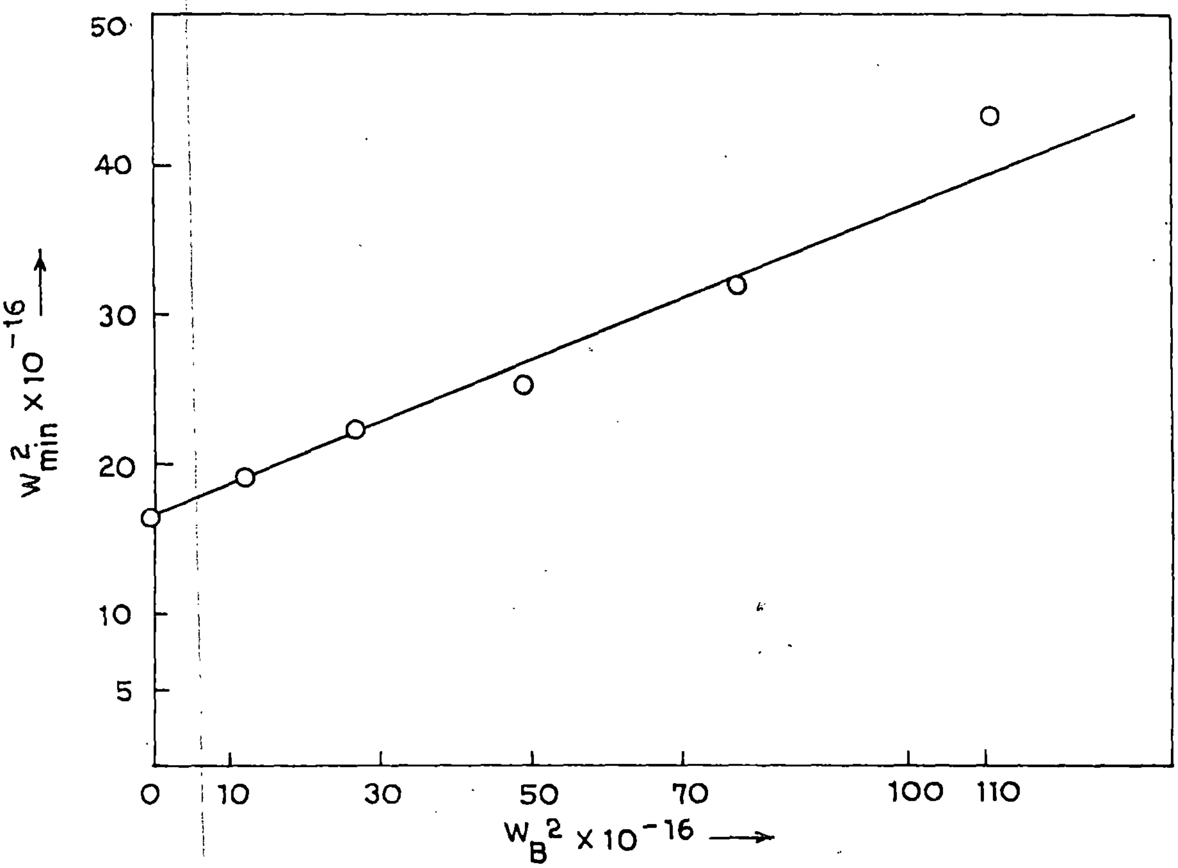
The limitations of this model which we have described is linked with validity of the relation for λ_H . As it is strictly restricted for low value of H/P, the whole model is valid for small values of H/P. The values of breakdown voltages have been calculated by making the same assumptions as those of Hale (1947). The effect of magnetic field on the motion of the electrons has been taken into consideration by the concept of equivalent pressure which is the direct outcome of the calculation that the mean free path of the electron in presence of magnetic field is related with the mean free path, in absence of magnetic field by the relation

$$\lambda_H = \frac{\lambda}{(1 + C_1 H^2/P^2)^{1/2}}$$

It has been shown by Sen and Ghosh (1963) that their experimental results for measurement of radiofrequency breakdown voltages in a non-resonant magnetic field in air and nitrogen can be quantitatively explained satisfactorily by introducing the concept of equivalent pressure. Unfortunately we could not get any experimental data in literature of breakdown voltages over this range of frequencies pressure and magnetic field for rare gases so that a comparision between the two could be made. But it was noted by Sen and Ghosh (1963) that the breakdown voltage increases with magnetic field for all values of pressure for the frequency of radio frequency voltage used. It is worthwhile to make some experimental measurements in this frequency region.

From the curves in figures (7.1), (7.2) and (7.3), the values of ω_b^2 and ω^2_{min} where ω_B is the electron cyclotron frequency and ω_{min} is the frequency at which the breakdown voltage becomes a minimum have been calculated for each curve for the three pressures and the results are entered in Table (7.5). The variation of ω^2_{min} against ω_B^2 has been plotted for three pressures (100μ, 150μ, and 200μ) in figures (7.4), (7.5) and (7.6). They are all straight lines making different intercepts along the X-axis and can be represented by the relation

$$\omega^2_{min} = C - m\omega_B^2$$



50
40
30
20
10
5
0
10
30
50
70
100
110
$W^2_{min} \times 10^{-16}$
$W_B^2 \times 10^{-16}$

Fig. 7·4

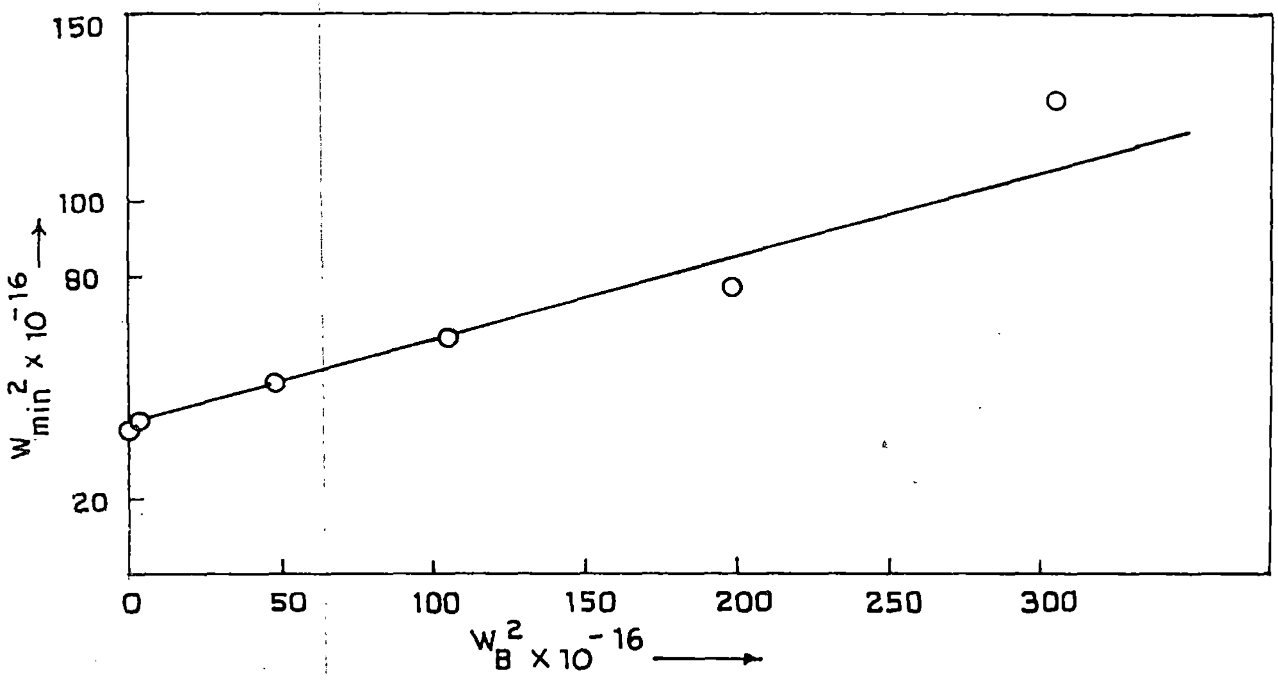
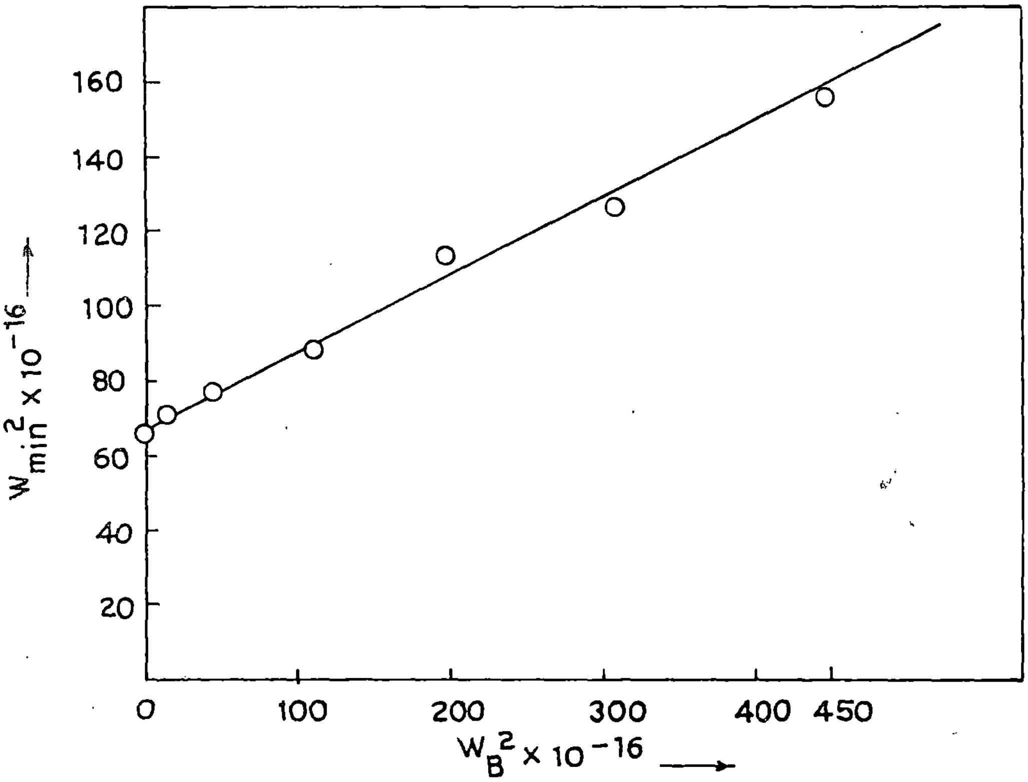

150
100
80
20
$W_{min}^2 \times 10^{-16}$
0
50
100
150
200
250
300
$W_B^2 \times 10^{-16}$

Fig. 7·5



160
140
120
100
80
60
40
20
0
100
200
300
400
450
$W_{min}^2 \times 10^{-16}$
$W_B^2 \times 10^{-16}$

Fig. 7·6

$$\text{or} \quad \omega_B^2 = \frac{c}{m} - \frac{\omega_{min}^2}{m}$$

if it can be assumed that c/m is the collision frequency in analogy with the term for lower highbrid frequency as in the theory of plasma oscillations then $\delta_c^2 = c/m$ where C is the intercept and m is the slope of the respective curve. As C and m can be obtained from the curves the values of δ_c can be calculated and results are entered in table (7.6). The values of δ_c are entered in the fifth column of table (7.6) and the results are consistent with the values reported by McDaniel (1964) The last column gives the ratio δ_c /p which is almost constant as it should be.

An alternative theory for the breakdown of gases under high frequency field has been put forward by Holstein (1946) and later on developed by Brown and his coworkers (1947, 1948). The theory assumes that a gas breaks down when the rate of generation of electrons by collision of electrons with gas molecules is just compensated by the loss of electrons by diffusion. The theory predicts that when a transverse magnetic field is superimposed in addition to high frequency electric field, then for certain values of magnetic field and applied frequency a resonance will occur when $\omega_B = \omega$. Physically this means that the magnetic field reverses the direction of the electron without loss of energy and as the applied field reverses the electron can rapidly gain energy from the field provided its motion is not interrupted by frequent collisions of electrons with gas molecules and when collision is not taken into consideration the resonance condition is expected when

$$\omega_B = \omega_{min}$$

The above mathematical analysis thus shows that resonance condition is modified when collision of electrons with molecules of the gas is taken into consideration specially when collision frequency is greater than the frequency of the applied field.

The analysis further shows that Hale's theory should be modified by taking into consideration the collision of electrons with neutral molecules. However, the two main assumptions that the amplitude of oscillation should be equal to mean free path and the energy gained in traversing a mean free path should be equal to ionising energy of the gas are valid in presence of a transverse magnetic field as well. As the concept of equivalent pressure is valid for low values of (H/P) the above theoretical calculation will hold for low values of (H/P) as well.

Table 7.1

Values of E with and without magnetic field at pressure $P = 100\mu$

ft	1/16	2/16	3/16	4/16	5/16	6/16	7/16	8/16	9/16	10/16
$E_H = 0$	129.660	68.490	50.042	42.818	40.792	42.449	47.956	58.916	79.385	119.285
$f \times 10^{-6}$	11.801	23.962	36.947	51.197	67.440	86.646	110.286	140.892	182.615	243.482
$t \times 10^{9}$	5.296	5.217	5.076	4.883	4.634	4.328	3.967	3.549	3.080	2.567
$E_H = 10$	134.713	71.032	51.910	44.307	42.119	43.690	49.145	60.147	80.648	120.599
$E_H = 20$	151.494	79.668	57.966	49.224	46.419	47.691	53.052	64.068	84.651	124.621
$E_H = 30$	184.526	96.694	69.900	58.807	54.780	55.417	60.495	71.423	92.045	131.958
$E_H = 40$	243.825	127.260	91.273	75.922	69.614	68.967	72.000	83.845	104.181	143.684
$E_H = 50$	348.091	181.251	129.118	106.260	95.875	92.728	95.399	104.582	123.691	161.743
$E_H = 60$	526.225	274.431	195.701	160.738	145.446	136.301	135.312	140.813	155.751	189.571

Table 7.2

Values of E with and without magnetic field at pressure P = 150 μ

ft	1/16	2/16	3/16	4/16	5/16	6/16	7/16	8/16	9/16	10/16
$E_H = 0$	194.495	102.736	75.063	64.230	61.188	63.673	71.934	88.374	119.078	178.929
$f \times 10^{-6}$	17.703	35.943	55.406	76.796	101.16	129.969	165.430	211.339	273.925	365.226
$t \times 10^{9}$	3.531	3.478	3.384	3.255	3.089	2.885	2.645	2.366	2.054	1.711
$E_H = 20$	208.320	109.785	79.529	68.322	64.789	67.031	75.200	91.671	122.443	182.399
$E_H = 40$	256.857	134.771	97.685	82.453	77.148	71.464	86.284	102.760	133.706	196.783
$E_H = 60$	365.692	190.893	136.912	113.916	104.416	103.458	109.407	125.748	156.279	215.530
$E_H = 80$	596.573	310.494	220.982	181.528	163.055	156.501	159.045	171.606	198.910	254.464
$E_H = 100$	1045.433	549.103	395.374	328.262	295.643	279.389	271.925	271.813	285.634	325.229

Table 7.3

Values of E with and without magnetic field at pressure P = 200 μ

ft	1/16	2/16	3/16	4/16	5/16	6/16	7/16	8/18	9/16	10/16
$E_H = 0$	259.324	136.980	100.083	85.635	81.583	84.897	95.911	117.832	158.769	238.570
$f \times 10^{-6}$	23.603	47.924	73.874	102.384	134.879	173.291	220.291	281.783	365.231	486.965
$t \times 10^{9}$	2.648	2.608	2.538	2.442	2.317	2.163	1.984	1.774	1.540	1.284
$E_H = 20$	269.365	143.532	103.820	88.630	84.247	87.378	98.264	120.303	161.301	241.174
$E_H = 40$	2.993	159.483	115.934	98.399	92.840	95.472	106.103	128.126	169.294	249.225
$E_H = 60$	369.021	193.495	139.801	117.592	109.529	110.706	121.009	142.851	184.091	263.931
$E_H = 80$	487.677	254.632	182.545	151.822	139.222	137.963	145.895	167.669	208.370	287.327
$E_H = 100$	696.078	362.447	258.209	212.567	191.752	185.475	190.785	209.002	247.357	323.392
$E_H = 120$	1052.353	548.962	391.331	321.632	287.603	272.641	272.681	281.628	311.673	379.216

Table 7.4

Values of λ_H at different pressures and magnetic fields.

Value of C_1	Magnetic field in gauss	P = 100μ $\lambda_H = \frac{\lambda}{(1+C_1H^2/P^2)^{1/2}}$	P = 150μ $\lambda_H = \frac{\lambda}{(1+C_1H^2/P^2)^{1/2}}$	P = 200μ $\lambda_H = \frac{\lambda}{(1+C_1H^2/P^2)^{1/2}}$
	0	0.4152	0.2768	0.2076
	20	0.4074	0.2745	0.2066
	30	0.3982	-	-
0.97×10^{-6}	40	0.3863	0.2677	0.2037
	50	0.3525	-	-
	60	0.3575	0.2575	0.1991
	80	-	0.2451	0.1932
	100	-	0.2314	0.1862
	120	-	-	0.1787

Values of λ has been taken from vacuum technology by A.Roth (North-Holland Publishing Company, 1976).

Table 7.5.

Magnetic field in Gauss	$\omega_B^2 \times 10^{-16}$	P = 100μ $\omega_{min}^2 \times 10^{-16}$	P = 150μ $\omega_{min}^2 \times 10^{-16}$	P = 200μ $\omega_{min}^2 \times 10^{-16}$
0	0	16.65	39.44	66.75
20	12.39	19.27	42.64	70.89
30	27.77	22.18	—	—
40	49.42	25.30	52.99	77.26
50	77.26	31.92	—	—
60	111.30	43.43	62.73	88.74
80	197.68		77.26	114.06
100	309.06		127.91	127.92
120	444.79			157.75

Table 7.6.

Pressure in μ	$C \times 10^{-16}$	m	$\delta_c^2 \times 10^{-16}$	$\delta_c \times 10^{-8}$	$\frac{\delta_c}{p} \times 10^{-9}$
100	16.5	0.205	80.49	8.97	8.97
150	40	0.2327	171.89	13.11	8.74
200	66	0.2105	313.54	17.71	8.86

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CHAPTER VIII

INTENSITY ENHANCEMENT OF SPECTRAL LINES WITH INCREASING ARC CURRENT IN ARC PLASMA.

8.1. Introduction:-

The dependence of the intensity of spectral lines on discharge current in either a glow discharge or in an arc plasma has been investigated by several authors viz. Sen and Gantait (1987); Fowler and Duffendack (1949), Rocca et al (1981); and Sadhya and Sen (1980). They found a linear increase in line intensities with current in all the cases. However, it has been observed by Sen and Gantait (1987) and by Sen and Sadhya (1986) that not only there is variation in the intensity profiles of spectral lines for different elements, but there is variation in the rate of increase of intensity among the spectral lines of the same element with the increase in discharge current. This variation was attributed to the reabsorption of the spectral lines and an analytical theory was developed which could explain the experimental results. [Sen and Sadhya (1986), Sen and Gantait (1987)] . In order to see whether the rate of intensity variation with the variation of arc current also occurs in metallic arcs burning at atmospheric pressure the spectral line intensity variation has been investigated in the present work for spectral lines (λ 5465.5 Å, λ 5209.1 Å) in case of silver arc (λ 5218.2 Å and λ 5153.2 Å in case of copper arc and λ 5369.9 Å, λ 5018.4 Å and λ 4383.5 Å in case of iron arc with increase of arc current from 2.5 A to 7.0 A. It is also proposed to examine the role of self absorption in the spectral intensity of these elements.

8.2. Experimental description:-

Two respective metal electrodes of a particular arc have been fixed with a vertical stand as described in chapter II (art. no.2.13) where upper metal electrode is attached to a vertically movable bench arrangement with the help of a screw. Initially the two electrodes are brought into contact by this screw. A d.c. source with an adjustable rheostat and an ammeter is utilized to produce the arc namely Ag-Ag, Cu-Cu and Fe-Fe in air. An accurately calibrated constant deviation spectrograph has been used to measure the wavelength of the spectral lines of the arc sources. Each line was focussed on the cathode of the photo multiplier tube M10 $FS29V_{\lambda}$ and intensities were then obtained by measuring the output of the photomultiplier which was noted by a difference amplifier. The whole arrangement of this part of spectroscopic arrangement and its electronic circuit is given by Sen, Das and Gupta (1972). The output micro-ammeter current recorded in the difference amplifier was observed to be linearly proportional to the known spectral line intensities and the slit-width of the spectrograph has been adjusted to obtain a large deflection in the microammeter, thereby enhancing the desired level of sensitivity in the measurement of the line intensity ratio. The arc current was varied from 3A to 7 A in case of silver electrodes and 2.5 to 5.0 A in case of copper and iron electrodes.

8.3. Results and Discussions:-

When there is appreciable self absorption spectral intensity I_{ul} of a line with upper level u and lower level l is given as

$$I_{ul} = \text{const.}\, A_{ul} \int_{-R}^{R} n_u(r) \left[\int_{-\infty}^{\infty} \alpha(\nu) \exp\left\{ -\beta(\nu)\sigma \int_{r}^{R} n_l(r)\,dr \right\} d\nu \right] dr. \qquad \ldots(8.1)$$

where $n_{u,l}(r)$ are the local number densities of the upper radiating level and the lower level as a function of position along the line of sight. A_{ul} is the transition probability of the line and $\alpha(\nu)$ is the normalised spectral emission profile $\int \alpha(\nu)d\nu = 1$. The fraction of emitted line which reaches the detector after traversing the medium from position r is

$$\exp\left(-\sigma\beta(\nu)\int_r^R n_l(r)\,dr\right)$$

σ is the absorption cross-section per atom at the line centre, independent of r and $\beta(\nu)$ is the line profile of absorption normalised to unity at the line centre $\beta(\nu_0) = 1$, and $r = 0$ at the centre of the discharge.

When there is no self-absorption

$$I_{ul} = \text{const. } A_{ul}\int_{-R}^{R} n_u(r)\left[\int_{-\infty}^{\infty}\alpha(\nu)\,d\nu\right]dr$$

$$= \text{const. } A_{ul}\int_{-R}^{R} n_u(r)\,dr \qquad \ldots(8.2)$$

Considering a parabolic distribution of $n_u(r)$ we get

$$I_{ul}^{o} = \text{const. } A_{ul}\,\frac{4}{3}\,n_u(o)R \qquad \ldots(8.3)$$

Here $n_u(o)$ is the number density of radiating atoms at the axis of the discharge tube.

Now self-absorption A_s of a spectral line is defined as

$$I_{ul} = (1 - A_S)\, I^{o}_{ul}$$

$$= \text{const.}(1 - A_S)\, n_u(o)\, A_{ul} \qquad \ldots(8.4)$$

If both the upper and lower level population densities are parabolic

$$n_x(r) = n_x(o)(1 - r^2/R^2)$$

we are assuming the source in which the radiating and absorbing atoms are distributed in the same manner.

Now

$$1 - A_S = \frac{I_{ul}}{I^{o}_{ul}}$$

$$= \frac{\left\{\int_R^h n_u(r)\left[\int_{-\infty}^{\infty} \alpha(\vartheta)\exp\left(-\beta(\vartheta)\sigma\int_r^R n_l(r)\,dr\right)d\vartheta\right]dr\right\}}{4/3\, R\, n_u(o)} \qquad \ldots(8.5)$$

Putting $\qquad y = r/R$

$$\sigma\int_r^R n_l(r)\,dr = \sigma R n_l(o)\left[\frac{2}{3} - y\left(1 - \frac{y^2}{3}\right)\right]$$

Putting this value in (8.5) and replacing the exponential by the power series we get

$$\int_{-\infty}^{\infty} \alpha(0) \exp\left\{-\beta(\nu)\sigma n_l(0)\left[\frac{2}{3} - y\left(1-\frac{y^2}{3}\right)\right]\right\} d\nu$$

$$= -\int_{-\infty}^{\infty} \alpha(\nu) \sum_{n=0}^{n=\infty} \frac{(-1)^n R^n \sigma^n \beta^n(\nu)}{n!} n_l(0)^n \left[\frac{2}{3} - \left(y - \frac{y^3}{3}\right)^n\right] d\nu$$

$$= \sum_{n=0}^{n=\infty} \frac{(-1)^n R^n \sigma^n n_l(0)^n}{n!} \left[\frac{2}{3} - \left(y - \frac{y^3}{3}\right)\right]^n \int_{-\infty}^{\infty} \alpha(\nu) \beta^n(\nu) d\nu$$

For the discharge type which is under consideration we assume that emission and absorption profiles are identical and Gaussian in nature which is the outcome of Doppler broadening being neglected. For a Gaussian profile of absorption and emission it can be shown (Mosbery and Wilkie (1978)) that

$$\int_{-\infty}^{\infty} \alpha(\nu) \beta^n(\nu) d\nu = \frac{1}{n+1}$$

Then from (8.5) we get

$$1 - A_S = 1 - \frac{3}{4} \sum_{n=1}^{n=\infty} \frac{(-1)^{n+1} \sigma^n n_L(0)^n R^n}{n!(n+1)} \left[\int_{-1}^{1} \frac{2}{3} - \left(y - \frac{y^3}{3}\right)\right]^n (1-y^2) dy$$

$$= 1 - \frac{3}{4} \sum_{n=1}^{n=\infty} \frac{(-1)^{n+1} \sigma^n n_l(0)^n R^n}{(n+1)!} \left[\int_{-2/3}^{2/3} \frac{2}{3} - \left(y - \frac{y^3}{3}\right)\right]^n d\left(y - \frac{y^3}{3}\right) \quad \cdots (8.6)$$

Values of $n_l(o)$'s are calculated utilizing Forrest and Franklin's (1969) equations. Here collisional integral $\langle Q_{ij\phi} \rangle$ as given by Johnson et al (1978) has been utilised. The density of electrons at the axis $n_l(o)$ is calculated from the expression of current considering a parabolic distribution

$$i = \mu e E 2\pi \int_0^R n_l(o) r \, dr$$

where μE is the drift velocity of electrons at the corresponding (E/P) value[Nakamura and Lucas (1978).].

Again σ the cross-section of absorption at the line centre, when Doppler broadening is considered the sole mechanism for the broadening of the spectral line is given as

$$\sigma = \pi r_o c f_{lu} \lambda_{ul} \left(\frac{M}{2\pi K T_g} \right)^{1/2} \quad \text{...(8.7)}$$

where r_o is the classical electron radius (2.818×10^{-13} cm), C is the velocity of light f_{lu} and λ_{ul} are the absorption oscillator strength and the wavelength of transition respectively, M is the mass of radiating atom and K is the Boltzmann constant. Taking the values of the transitions from Gruzdev (1967) Sen and Sadhya (1986) obtained $K_o = \sigma n_l(o)$ where K_o is the absorption coefficient of radiation at the line centre. It is evident from their calculation that $K_o R$ ($R = 0 \cdot 75$ cm.) which may be called optical depth is much smaller than unity. Since the series in eqn. (8.6) is a converging one.

Sen and Sadhya (1986) have however, shown that the self-absorption of a spectral line can be defined as

$$I_{ul} = I^{o}_{ul} \left[1 - A_s \right] \qquad \text{...(8.8)}$$

where I^{o}_{ul} is the intensity of the spectral line without self-absorption I_{ul} is the observed intensity of the spectral line and A_s has been calculated

$$A_s = f_{lu} \; \lambda_{ul} \, \rho \, n_l(o)$$

where f_{lu} is the absorption oscillator strength, λ_{ul} is the wavelength of radiation and $n_l(o)$ is the electron population density at the axis of the discharge tube.

$$\rho = \frac{1}{3} \pi r_o c \left[\frac{M}{2\pi K T_g} \right]^{1/2} R$$

where r_o is the classical electron radius, C is the velocity of light, M is the mass of radiating atom, K the Boltzmann constant and T_g is the temperature of the gas and R is the radius of the discharge tube. Further

$$I^{o}_{ul} = n \frac{g_u}{Z_o} A_{ul} h \nu_{ul} \exp\left[- \frac{(E_U - E_L)}{KT_e}\right] \quad \cdots (8 \cdot 9)$$

where n is the number density of the radiating atoms at the axis of the discharge tube. T_e the electron temperature, Z_o the internal partition function and g_u is the statistical weight factor of the upper level. E_u and E_l are the energies of the upper level and lower level between which respective transition occurs, A_{ul} is the Einstein coefficient of transition probability and ν_{ul} is the frequency of emitted line under interest.

If I_o denotes the intensity of the spectral line at the initial current (say 2.5 Å or 3 amp.). Then from eqn. (8.8)

$$I_{ul} = (1 - A_S)_i \, I^{o}_{ul}$$

$$I_o = (1 - A_S)_o \, I^{o}_{o}$$

Putting the values of I^{o}_{ul} and I^{o}_{o} from eqn.(8.9)

$$\frac{I_{ul}}{I_o} = \frac{(1-A_S)_i}{(1-A_S)_o} \quad \frac{n_i}{n_o}$$

Denominator is a constant because I_o is a constant and the number density of radiating atoms at the axis of the discharge tube is independent of current. Then,

$$\frac{I_{ul}}{I_o} = c\,[1-A_S]$$
$$= c\,[1-\alpha T_g^{-1/2} n_l^{o}]$$

where C is a constant

$$\alpha = f_{lu}\,\lambda_{ul}\,\frac{1}{3}\,\pi r_o c \left(\frac{M}{2\pi K}\right)^{1/2}$$

$$\frac{d}{di}\left(\frac{I_{ul}}{I_o}\right) = \frac{1}{2}\,c\alpha\left[T_g^{-3/2}\frac{dT_g}{di}\,n_l^{o} - 2T_g^{-1/2}\frac{dn_l^{o}}{di}\right]$$

$$i = \mu e E\, 2\pi \int_0^R n_l^{o}\, r\, dr$$

$$n_l^{o} = \frac{i}{\mu e E \pi R^2}$$

where μ is the mobility of the electron and E is the voltage across the discharge per unit length, then

$$\frac{dn_l^o}{di} = \frac{1}{\mu e E \pi R^2}$$

then $$\frac{d}{di}\left(\frac{I_{ul}}{I_o}\right) = \frac{1}{2}\,\frac{c\alpha}{T_g^{1/2}}\left[\frac{1}{T_g}\,\frac{dT_g}{di}\,n_l^o - \frac{2}{v e \pi R^2}\right]$$

where v is the drift velocity of the electron as

$$i = n_l^o v e \pi R^2$$

Hence

$$\frac{d}{di}\left(\frac{I_{ul}}{I_o}\right) = \frac{1}{2}\,\frac{c\alpha}{Tg^{1/2}}\left[\frac{1}{Tg}\,\frac{dTg}{di}\,n_l^o - \frac{2n_l^o}{i}\right] \quad \cdots (8{\cdot}10)$$

The quantity within the bracket will be a constant for all the spectral lines and we observe that as $\frac{dTg}{di}$ will be same for the spectral lines of a given source investigated, the rate of variation of intensity with discharge current will depend upon the value of α.

From the expression used for α , it is further evident that for all the spectral lines of a particular element all parameters except f_{lu} and λ_{ul} are constants, and hence

$$\frac{d}{di}\left[\frac{I_{ul}}{I_o}\right] \propto \lambda_{ul} f_{lu}$$

or

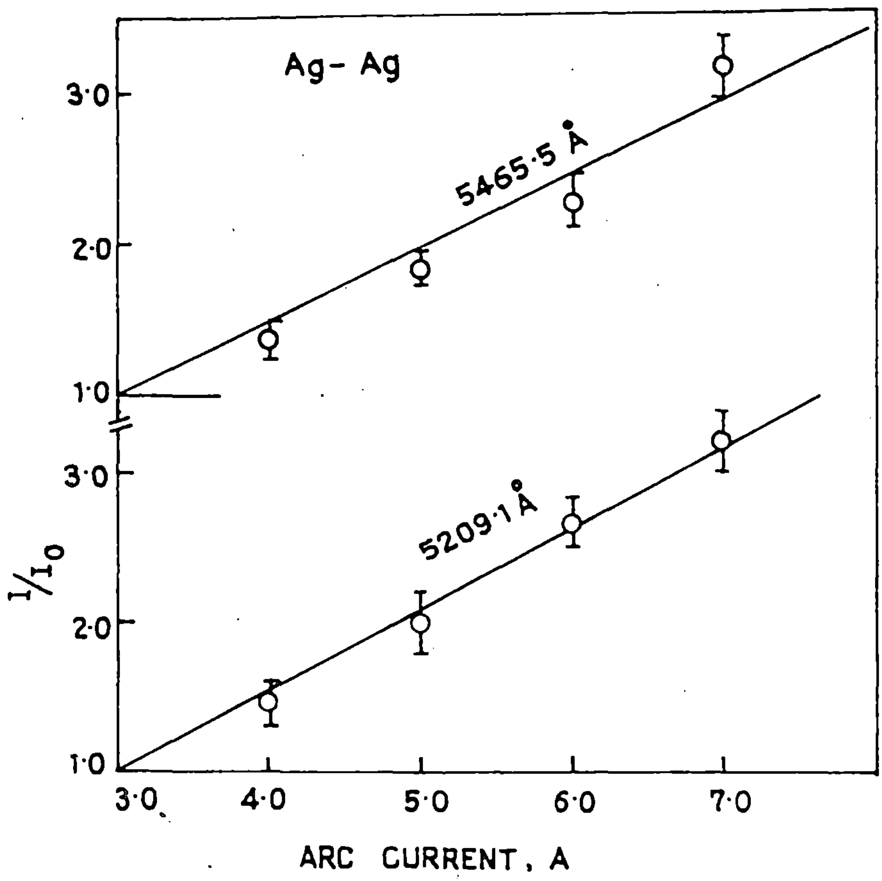
$$\frac{d}{di}\left[\frac{I_{ul}}{I_o}\right]_{\lambda_1} \Big/ \frac{d}{di}\left[\frac{I_{ul}}{I_o}\right]_{\lambda_2} = (\lambda_{ul} f_{lu})_{\lambda_1} \Big/ (\lambda_{ul} f_{lu})_{\lambda_2} \qquad \ldots(8.11)$$

The variation of intensity of the spectral lines with arc current in case of Ag-Ag, Cu-Cu and Fe-Fe electrodes has been plotted in figures 8.1, 8.2 and 8.3 respectively and the estimated slope of enhancement of the intensity ratio has been calculated statistically. The value of f_{lu} for individual spectral line has been calculated from the relation given by Kuhn (1964).

$$f_{lu} = \frac{A_{ul}(g_u/g_l)}{3\gamma}$$

where

$$\gamma = 8\pi^2 e^2/3mc\lambda^2$$



Ag- Ag
5465·5 Å
5209·1 Å
3·0
2·0
1·0
3·0
2·0
1·0
1/I0
3·0
4·0
5·0
6·0
7·0
ARC CURRENT, A

FIG. 8·1.

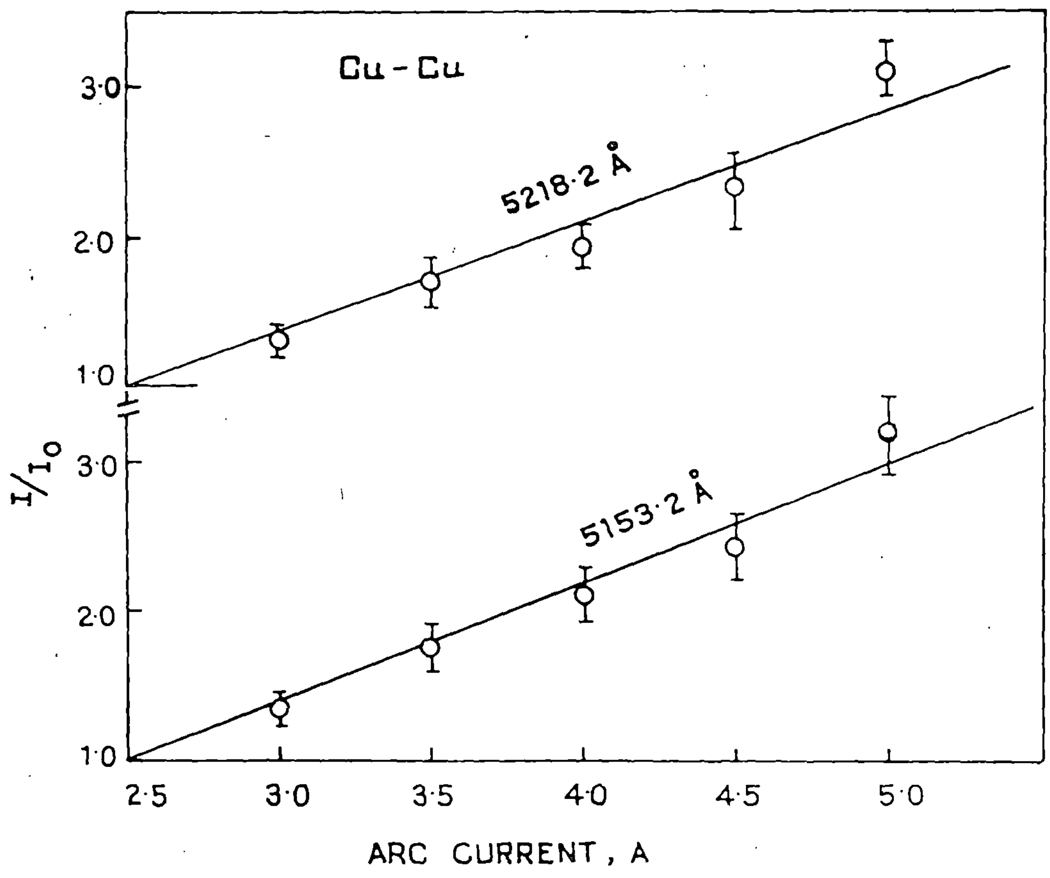
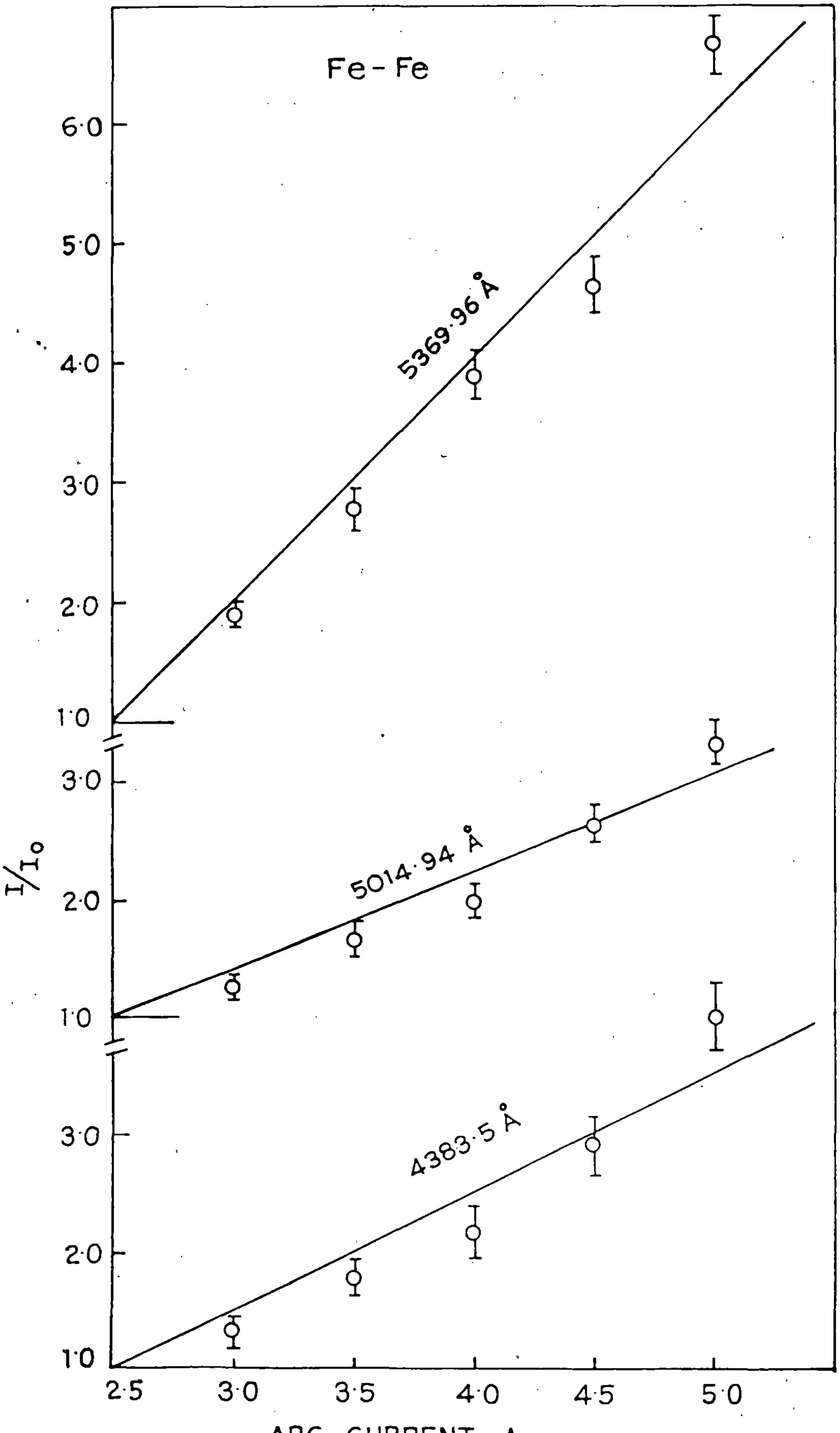

Cu - Cu
5218·2 Å
5153·2 Å
I/Io
3·0
2·0
1·0
3·0
2·0
1·0
2·5
3·0
3·5
4·0
4·5
5·0
ARC CURRENT, A

FIG. 8·2 .



Fe - Fe
6·0
5·0
4·0
3·0
2·0
1·0
3·0
2·0
1·0
3·0
2·0
1·0
I/I₀
5369·96 Å
5014·94 Å
4383·5 Å
2·5
3·0
3·5
4·0
4·5
5·0
ARC CURRENT, A

FIG. 2·3

where A_{ul} is transition probability, g_u and g_l are statistical weights of upper and lower levels. The values of the above terms are provided by Reader et al (1980) in case of silver, copper and iron. The results are entered in Table 8.1. It is evident from columns 6 and 7 of Table 8.1, that the agreement between the theoretical and experimental results is very close in case of all the three arcs investigated here. Similar results have also been obtained in case of mercury arc investigated by Sen and Gantait (1987). It is concluded that self absorption plays a dominant role in determining the intensities of spectral lines in case of optically thick plasma and particularly its effect on intensity variation when the arc current is changed.

Table 8.1

Arc electrodes	Wavelength Å	Transition	$\frac{d}{di}\left[\frac{I_{ul}}{I_o}\right]$ Expt.	f_{lu}	$\frac{\frac{d}{di}\left(\frac{I_{ul}}{I_o}\right)_{\lambda_1}}{\frac{d}{di}\left(\frac{I_{ul}}{I_o}\right)_{\lambda_2}}$	$\frac{(f_{lu}\lambda_{ul})_1}{(f_{lu}\lambda_{ul})_2}$
Silver	5465.5	$5^2D_{5/2} \rightarrow 5^2P_{3/2}$	0.49037	0.5771	0.91	0.99
Silver	5209.1	$5^2D_{3/2} \rightarrow 5^2P_{1/2}$	0.53986	0.6102		
Copper	5218.2	$2D_{5/2} \rightarrow 2P_{3/2}$	0.74224	0.4595	0.93	0.97
Copper	5153.2	$2D_{3/2} \rightarrow 2P_{1/2}$	0.79415	0.4777		
Iron	5369.94	$z^5G - e^5H$	2.04073	0.2536	$\frac{d}{di}\left(\frac{I_{ul}}{I_o}\right)_{\lambda_1}$	$(f_{lu}\lambda_{ul})_1:$
Iron	5014.94	$z^3F - e^3D_2$	0.83426	0.0835	$:\frac{d}{di}\left(\frac{I_{ul}}{I_o}\right)_{\lambda_2}$	$(f_{lu}\lambda_{ul})_2:$
					$:\frac{d}{di}\left(\frac{I_{ul}}{I_o}\right)_{\lambda_3}$	$(f_{lu}\lambda_{ul})_3$
	4383.5	$a^3F - z^5G^o$	1.0873	0.1620	2:0·82:1	1·92:0·59:1

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Intensity enhancement of spectral lines with increasing arc current in arc plasma

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The enhancement of intensity of the spectral lines λ 5465 and 5209Å in case of silver arc, 5218.2 and 5153.2Å in case of copper arc and 5369.9, 5018 and 4383.5Å in case of iron arc with increase of arc current from 2.5 to 7.0A has been investigated. Assuming self absorption, an analytical expression for the variation of intensity of the spectral lines with increasing arc current has been deduced which predicts results in close agreement with those observed experimentally.

The dependence of the intensity of spectral lines on discharge current in either a glow discharge or in an arc plasma has been investigated by several workers[1-4]. A linear increase in line intensities with current is found in all the cases. However, it has been observed by Sen and Gantait[1] and by Sen and Sadhya[5] that not only there is a variation in the intensity profiles of spectral lines for different elements, but there is a variation in the rate of increase of intensity among the spectral lines of the same element with the increase in the discharge current. This variation was attributed to the reabsorption of the spectral lines and an analytical theory was developed[5] which could explain the experimental results. In case of optically thick plasma, particularly in the case of arc plasma, Sen and Sadhya[5] have shown that the self absorption of a spectral line can be defined as

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

where I^0_{ul} is the intensity of the spectral line without selfabsorption, I_{ul} is the observed intensity of the spectral line. A_s has been calculated and found to be

$$A_s = f_{lu} \lambda_{ul} \rho n^0_l$$

where A_s is the selfabsorption coefficient of the spectrical line, f_{lu} the absorption oscillator strength, λ_{ul} the wavelength of radiation and n^0_l is the electron population density at the axis of the discharge tube:

$$\rho = \frac{1}{3} \pi r_0 c \left[\frac{M}{2\pi k T_g}\right]^{1/2} R$$

where r_0 is the classical electron radius, c the velocity of light, M the mass of radiating atom, k the Boltzmann constant, T_g the temperature of the gas and R is the radius of the discharge tube. Further

$$I^0_{ul} = n \frac{g_u}{Z_0} A_{ul} h \nu_{ul} \exp\left[-\frac{(E_u - E_l)}{kT_l}\right] \qquad \ldots (2)$$

where n is the number density of the radiating atoms at the axis of the discharge tube, T_e the electron temperature, Z_0 the internal partition function, g_u the statistical weight factor of the upper level, h Planck's constant, E_u and E_l the energies of the upper and lower level respectively between which respective transition occurs, A_{ul} Einstein coefficient of transition probability and ν_{ul} is the frequency of emitted line under investigation.

If I_0 denotes the intensity of the spectral lines at the initial current (say 2.5 or 3A) then from Eq. (1) we can get

$$I_0 = (1 - A_s)_0 I^0_0$$

Putting the values of I^0_{ul} and I^0_0 from Eq. 2

$$\frac{I^0_{ul}}{I_0} = \frac{(1 - A_s)_i}{(1 - A_s)_0} \frac{n_i}{n_0}$$

Denominator is a constant because I_0 is a constant and the number density of radiating atoms at the axis of the discharge tube is independent of current. Then

$$\frac{I_{ul}}{I_0} = \bar{c}[1 - A_s]_i = \bar{c}[1 - \alpha T_g^{1/2} n^0_l]$$

where $\bar{c}$ is a constant and

$$\alpha = f_{lu} \lambda_{ul} \frac{1}{3} \pi r_0 c \left(\frac{M}{2\pi k}\right)^{1/2} R$$

there

$$\frac{d}{di}\left(\frac{I_{ul}}{I_0}\right) = \frac{1}{2} c\alpha \left[T_g^{-1/2} \frac{dT_g}{di} n^0_l - 2T_g^{1/2} \frac{dn^0_l}{di}\right]$$

where i is the discharge current and e is the electronic chagrge.

$$i = \mu e E 2\pi \int_0^R n^0_l r\,dr$$

$$n^0_l = \frac{i}{\mu e E \pi R^2}$$

where μ is the mobility of the electron and E is the voltage across the discharge per unit length. Then

$$\frac{dn^0_l}{di} = \frac{1}{\mu e E \pi R^2}$$

and

$$\frac{d}{di}\left(\frac{I_{ul}}{I_0}\right) = \frac{1}{2} \frac{c\alpha}{T_g^{1/2}} \left[\frac{1}{T_g} \frac{dT_g}{di} n^0_l - \frac{2}{ve\pi R^2}\right]$$

where v is the drift velocity of the electron as

$$i = n^0_l e v \pi R^2$$

$$\frac{d}{di}\left(\frac{I_{ul}}{I_0}\right) = \frac{1}{2} \frac{\bar{c}\alpha}{T_g^{1/2}} \left[\frac{1}{T_g} \frac{dT_g}{di} n^0_l - \frac{2n^0_l}{T}\right] \qquad \ldots (3)$$

The quantity within the square brackets will be a constant for all the spectral lines and we observe that as dT_g/di will be the same for the spectral lines of a given source under investigatigation, the rate of variation of intensity with discharge current will depend upon the value of α. From the expression used for α it is further evident that for the spectral lines of a particular element all parameters except f_{lu} and λ_{ul} are constant. Hence,

$$\frac{d}{di}\left[\frac{I_{ul}}{I_0}\right] \propto \lambda_{ul} f_{lu}$$

or

$$\frac{d}{di}\left[\frac{I_{ul}}{I_0}\right]_{i_1} : \frac{d}{di}\left[\frac{I_{ul}}{I_0}\right]_{i_2} = (\lambda_{ul} f_{lu})_{i_1} : (\lambda_{ul} f_{lu})_{i_2} \qquad \ldots (4)$$

CS in proportionality

Indian Journal of Pure & Applied Physics

We report here results of variation of spectral line intensity with discharge current in three metallic arc plasma sources, namely, Ag-Ag, Cu-Cu and Fe-Fe in air. A dc source with an adjustable rheostat and an ammeter are utilized to produce the arc. The experimental arrangement is given in Ref. 6. An accurately calibrated constant deviation spectrograph has been used to measure the wavelength of the spectral lines of the arc source. Each line was focussed on the cathode of the photomultiplier tube M10 FS29V_λ and intensites were thus obtained by measuring the output of the photomultiplier which was noted by a difference amplifier. The whole arrangement of this part of spectroscopic arrangement and its electronic circuit is given in Ref. 7. The output current of the difference amplifier measured by a microammeter was observed to be linearly proportional to the known spectral line intensities (*International Critical Table, Vol.* 4) and the slit width of the spectrograph had been adjusted to obtain a large deflection in the microammeter, thereby enhancing the desired level of sensitivity in the measurement of the line intensity ratio. The arc current was varied from (3 to 7A) in case of silver electrodes and 2.5 to 5A in case of copper and iron electrodes.

The variation of intensity of the spectral lines with arc current has been plotted in a least square fitted line in Figs 1-3 for Ag-Ag, Cu-Cu and Fe-Fe respectively, and the estimated slope of enhancement of the intensity ratio has been calculated statistically. The value of f_{lu} for individual spectral line has been calculated from the relation given by Kuhn[8].

$$f_{lu} = A_{ul}\left(\frac{g_u}{g_l}\right) \Big/ 3r$$

where

$$r = \frac{8\pi^2 e^2}{3mc\lambda^2}$$

where A_{ul} is the transition probability, g_u and g_l are statistical weights of upper and lower levels respectively. The values of the above terms are provided by Reader *et al.*[9] for siliver, copper and iron. The results are listed in Table 1. It is evident that the agreement between the theoretical (col. 7) and experimental (col. 6) results is very close in case of all the three arcs investigated here. Similar results have also been obtained in case of mercury arc[1]. Hence, self absorption plays a dominant role in determining the intensities of spectral lines in the case of optically thick plasmas and, particularly, its effect on intensity variation when the arc current is changed is pronounced.

The authors are indebted to Prof Peter L Smith, Centre for Astrophysics, Cambridge, Massachusetts, and R Jeffrey Führ of Data Centre on Atomic Transition Probabilities, Centre for Radiation Research, Gaithersburg, USA, for offering useful suggestions and relevant data sheets.

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Fig. 1—Variation of I/I_0 with arc current Ag-Ag

Fig. 2—Variation of I/I_0 with arc current Cu-Cu

Fig. 3—Variation of I/I_0 with arc current Fe-Fe

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Table 1 — Ratio of experimental and theoretical spectral line intensity variation with arc current

Arc electrodes	Wave-length λ	Transition	$\frac{d}{di}\left[\frac{I_{ul}}{I_0}\right]_{expt}$	f_{ul}	Variation of intensity ith current Experiment	Theoretical
Silver	5465.5	$5^2P_{5/2} \rightarrow 5^2P_{3/2}$	0.49037	0.5771	0.91	0.99
	5209.1	$5^2D_{3/2} \rightarrow 5^2P_{1/2}$	0.539[illegible]	0.6102		
Copper	5218.2	$2D_{5/2} \rightarrow 2P_{3/2}$	0.74224	0.4593	0.93	0.97
	5153.2	$2D_{3/2} \rightarrow 2P_{1/2}$	0.79415	0.4777		
Iron	5369.96	$Z^5G \rightarrow e^5H$	2.04073	0.2539	2:0.8:1	1.92:0.59:1
	5014.94	$Z^3F \rightarrow e^3D_2$	0.83426	0.835		
	4383.5	$a^3F \rightarrow Z^5G_0$	1.01873	0.1620		

Note: The formula used for cols. 6 and 7 are for:

Silver and copper: $\frac{d}{di}\left[\frac{I_{ul}}{I_0}\right]_{\lambda_1} \Big/ \frac{d}{di}\left[\frac{I_{ul}}{I_0}\right]_{\lambda_2}$ and $\frac{(f_{lu}\lambda_{ul})_{\lambda_1}}{(f_{lu}\lambda_{ul})_{\lambda_2}}$, respectively.

Iron: $\frac{d}{di}\left[\frac{I_{ul}}{I_0}\right]_{\lambda_1} : \frac{d}{di}\left[\frac{I_{ul}}{I_0}\right]_{\lambda_2} : \frac{d}{di}\left[\frac{I_{ul}}{I_0}\right]_{\lambda_3}$ and $(f_{lu}\lambda_{ul})_{\lambda_1} : (f_{lu}\lambda_{ul})_{\lambda_2} : (f_{lu}\lambda_{ul})_{\lambda_3}$, respectively.

CHAPTER IX

INVESTIGATION OF A GLOW DISCHARGE PLASMA SUBJECTED TO THE DISCHARGE OF A BANK OF CONDENSERS.

9.1. Introduction:-

The effect of the discharge of a bank of condensers charged to a high potential through a rarefied gas has been investigated by many workers. Nevodichauski et al (1968) considered the axial light emission from a plasma produced in a gas due to electrical explosion of thin metallic cylinders. The spectroscopic investigation of the light emission showed the presence of a series of local peaks which has been explained as due to commulative effect of converging shock waves. Showronck et al (1970) discussed the influence of plasma frequency on the light emitted by an exploding ionised gaseous filament. The plasma generated due to exploding wire is ascribed generally to the instantaneous heat generated and subsequent ionization by the process of thermal ionization. Some workers have measured the intensity of spectral lines emitted and have also been able to estimate the degree of ionization. Pinch effect of metallic plasma obtained by exploding wire has been studied by Aycoberry et al (1962). Emission of X-rays from exploding wires in a rarefied gas has been investigated by Vitov skii et al (1963) and Handebstenerhag and coworkers (1971). They ascribed the emission as due to decelerated electrons initially emanated from the early onset of ionization. The emission of light was also studied by Kerr cell shulter cameras. In case of glow discharge the enhancement of spectral lines by shock waves was observed by Miyashire (1984). It was observed that the glow diameter, discharge fluorescence and current are enhanced by shock wave. Enhancement of electrical conductivity in a glow discharge by alpha particle emission from radio isotope material was observed by August (1967).

The various changes brought about in the values of plasma parameters when a bank of condensers discharges through a glow discharge plasma has been little reported so far. The object of this investigation 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. The analysis of the data will enable us to understand the interaction between an ionised gas and a high current pulsed discharge.

9.2. Experimental arrangement:-

In this study a discharge tube of length 8 cm and provided with four electrodes has been used Fig.(2.16). Electrodes are circular in shape and parallel to each other. Air and hydrogen gas have been passed through dilute solution of caustic potash to remove traces of CO_2 and is then washed with water to remove further traces of CO_2, dust particles and organic matters. It has been dried by passing through a tower of fused $CaCl_2$ and finally through P_2O_5. The pressure inside the discharge tube has been kept constant by means of a needle valve and measured by a Mcleod gauge. The separation between the two electrodes (A.A.) to excite the discharge is 2.92 cm. and breakdown is carried out by a transformer. The other two electrodes (B.B) are separated by a distance of 0.85 cm. and eight condensers each of capacity 24 μF connected in parallel raised to different high voltages are discharged through the glow discharge. The main discharge current before and after the discharge of condensers is noted by the milliammeter which is connected in series with the power source used to excite the discharge. From these data the corresponding electron density has been calculated. In case of air two spectral lines λ 4447 Å and λ 4151 Å and in case of hydrogen two spectral lines λ 4861.29 Å and

and λ 4340.44 Å are focussed on the slit of the spectrograph and the corresponding intensities of the spectral lines have been measured by the photomultiplier circuit assembly which has been described in chapter two (2.16). The above procedure is repeated when the bank of condenser is excited by 1500 volts, 1750 volts, 2000 volts and 2250 volts and discharged through the plasma. In case of air the pressure is maintained at 0.2 torr and in case of hydrogen the pressure is maintained at 0.7 torr. From the photo multiplier readings which are proportional to spectral line intensities, electron temperatures have been computed.

9.3. Results and discussions:-

The measured experimental results are entered in Table (9.1) before the discharge of condensers. From the above data it is possible to calculate the electron temperature and electron density.

Calculation of T_e,

The electron temperature can be estimated from the equation

$$KT_e = \frac{E' - E}{\ln\left(IE^3\lambda^3 g' f' / I'E'^3 \lambda'^3 g f\right)} \qquad \ldots(9.1)$$

I $\longrightarrow$ spectral line intensity for wavelength λ

g $\longrightarrow$ statistical weight (of the lower state of the line)

f $\longrightarrow$ Absorption oscillator strength.

E $\longrightarrow$ Excitation energy, and the prime quantities denote the corresponding expressions for wavelength λ'

Table 9.1

Gas	Pressure Torr	Discharge current mA	Wavelength in Å	Photomultiplier current μA
Air	0.2	10	4447 (1P - 1D°)	8
			4151 (4P - 4S°)	10
Hydrogen	0.7	10	4861.0 (2S - 4 P)	10
			4340 (2S - 5P)	4

Calculation of T_e in case of air

$I' =$ Photomultiplier current = 8 μA

$E =$ 23.10 volts = $23.10 \times 1.6 \times 10^{-12}$ ergs.

$\lambda' =$ 4447×10^{-8} cms.

$g' = 3$

$f' = 0.587$

$I =$ Photomultiplier current = 10 μA.

$E = 13.26$ volts = $13.26 \times 1.6 \times 10^{-12}$ ergs.

$\lambda = 4151.5 \times 10^{-8}$ cms.

$g = 2J' + 1 = 2.\frac{5}{2} + 1 = 6.$

$f = 0.00301$

$T_e = 3.92 \times 10^4$ ^oK.

Calculation of n, the electron density, considering the distribution to be Bessalian,

$$i = \mu e E n$$

$$= \mu e E 2\pi \int_0^R n(0)\, J_0\left(2{\cdot}405\,\frac{r}{R}\right) r\, dr$$

$$= \mu e E 2\pi n(0) \times 0{\cdot}597 \Big| \text{ at } R = 1{\cdot}15 \text{ cms.}$$

$$= v_d\, e 2\pi n(0) \times 0{\cdot}597$$

n (average radially) = 0.597 n (0)

Breakdown voltage = 500 volts

Cathode fall = 375 volts

$$\frac{v_d}{u} = \left(\frac{1}{2}R\right)^{1/2}, \quad R = \frac{2m}{M}$$

$$\therefore \quad v_d = \left(\frac{m}{M}\right)^{1/2} u .$$

where , $u = \sqrt{2eE/m}$

$$= \sqrt{\frac{2 \times 4{\cdot}8 \times 10^{-10} \times 125}{9{\cdot}1 \times 10^{-28} \times 2{\cdot}95 \times 300}}$$

$$= \quad 3{\cdot}86 \times 10^{8}\ \mathrm{cm/s}$$

Hence, $v_d = \left(\frac{9{\cdot}1 \times 10^{-28}}{14 \times 1{\cdot}67 \times 10^{-24}}\right)^{1/2} \times 3{\cdot}86 \times 10^{8}$

$$= \quad 2{\cdot}408 \times 10^{6}\ \mathrm{cm/s}$$

$$i = v_d\, e\, 2\pi\, n(0) \times 0{\cdot}597$$

when $i = 10 \times 10^{-3}$ amp. (ammeter reading before discharge of condenser)

$$n(0) = \frac{10 \times 10^{-3}}{2.408 \times 10^{6} \times 1.6 \times 10^{-19} \times 2 \times 3.14 \times 0.597}$$

$$= 0.692 \times 10^{10}$$

$$\therefore \quad n = 0.597\, n(0)$$

$$= 0.597 \times 0.692 \times 10^{10}$$

$$= 0.4131 \times 10^{10}$$

Hydrogen

Calculation of T_e:-

$$KT_e = \frac{E' - E}{\ln\left(IE^3\lambda^3 g' f' / I' E'^3 \lambda'^3 g f\right)}$$

I = Photomultiplier current = 10 μA

E = 12.74 eV = 12.74 x 1.6 x 10^{-12} ergs.

λ = 4861.29 Å = 4861.29 x 10^{-8} cms. (2S - 4 P)

g = statistical weight of the lower state of the line = 2.

f = Absorption oscillator strength = 0.1028

I' = 4 μA

E' = 13.05 eV = 13.05 x 1.6 x 10^{-12} ergs.

λ' = 4340.44 Å = 4340.44 x 10^{-8} cms. (2S - 5 P)

g' = 2

f' = 0.04193

$$KT_e = \frac{(13.05 - 12.74) \times 1.6 \times 10^{-12}}{\ln\left(\dfrac{10 \times (12.74)^3 \times (4861.29)^3 \times 2 \times 0.04193}{4 \times (13.05)^3 \times (4340.44)^3 \times 2 \times 0.1028}\right)}$$

T_e = 1.2599 x 10^{4} °K.

Calculation of electron density of hydrogen:

Breakdown voltage = 825 volts.

Cathode fall = 214 volts.

$$\frac{v_d}{u} = \left(\frac{1}{2}K\right)^{1/2}, \quad K = \frac{2m}{M}$$

$$v_d = \left(\frac{m}{M}\right)^{1/2} u$$

where $u = \sqrt{2eE/m}$

$$= \sqrt{\frac{2 \times 4.8 \times 10^{-10} \times 611}{9.1 \times 10^{-28} \times 2.95 \times 300}}$$

$$= 8.534 \times 10^{8}$$

$$\therefore \quad v_d = \left(\frac{9.1 \times 10^{-28}}{1.67 \times 10^{-24}}\right)^{1/2} \times 8.534 \times 10^{8} = 19.92 \times 10^{6}$$

$$i = v_d e 2\pi n(o) \times 0.597$$

$$\therefore \quad n(o) = \frac{10 \times 10^{-3}}{19.92 \times 10^{6} \times 1.6 \times 10^{-19} \times 2 \times 3.14 \times 0.597} = 0.8368 \times 10^{9}$$

and $n = 0.597 \; n\,(o)$

$$= 0.597 \times 0.8368 \times 10^{-9} = 0.4996 \times 10^{9}/cc$$

The values of electron density and electron temperature are entered in Table (9.2)

Table (9.2)

Gas	Electron density	Electron temperature ^oK
Air	4.131×10^{9}	3.92×10^{4}
Hydrogen	4.996×10^{8}	1.25×10^{4}

The measured values of discharge current and the corresponding values of photomultiplier current when discharge from the condenser is passed through the glow discharge are entered in Table (9.3).

Table 9.3

Gas	Pressure in torr	Wavelength Å	Initial discharge current in mA	Initial Photomultiplier current μA	Charging voltage in volts	Final discharge current in mA	Final Photomultiplier current μA
Air	0.2	4447	10	8	1500	22	57.5
		($1P-1D^{o}$)			1750	25	61.5
					2000	28	64.0
					2250	31	68.0
Hydrogen	0.7	4861.3	10	10	1750	65	80
		(2S - 4P)			2000	75	92
					2250	85	104

Calculation of n, the electron density:–when the bank of condensers is discharged through the glow discharge in case of air, for 2250 volts, from Table (9.3) the final discharge current is 31 m.A. then

$$n = 0.597\ n\ (0)$$

$$n\ (0) = \frac{31 \times 10^{-3}}{2.408 \times 10^{6} \times 1.6 \times 10^{-19} \times 2 \times 3.14 \times 0.597}$$

$$= 2.1461 \times 10^{10}$$

$$n = 0.597 \times 2.1461 \times 10^{10}$$

$$= 1.2812 \times 10^{10}$$

In the same way

n for 2000 volts = 1.15×10^{10}

n for 1750 volts = 1.033×10^{10}

n for 1500 volts = 0.909×10^{10}

Calculation of n, the electron density :

when the bank of condensers is discharge through the glow discharge in case of hydrogen

n for 2250 volts = 4.24×10^{9},

n for 2000 volts = 3.74×10^{9},

n for 1750 volts = 3.24×10^{9}.

For calculation of electron temperature when the bank of condensers is discharged we assume that due to presence of high density radiation some amount of self absorption may be present. We can thus assume after Sen and Sadhya (1986) that the intensity of spectral lines is given by

$$I_{ul} = \left\{ 1 - f_{lu} \lambda_{ul} \rho n_l(0) \right\} I_{ul}^{o}$$

where I_{ul} is the observed intensity and I_{ul}^{o} is the intensity without absorption, f_{lu} is the partition function, and $\rho = \frac{1}{3}\pi r_o C \left(\frac{M}{2\pi K T_g} \right)^{1/2} R$

So that

$$I_{ul} = [1 - \alpha n_1(0)] I_{ul}^{o}$$

and

$$I_{ul}^{o} = n \frac{g_u}{Z_o} A_{ul} h \nu_{ul} \exp\left(-\frac{U}{KT_e}\right)$$

where

$$\alpha = f_{ul} \lambda_{ul} \rho$$

$$U = E_U - E_l$$

$$I_{ul}^{o} = n\beta \exp\left(-\frac{U}{KT_e}\right)$$

where

$$\beta = \frac{g_u}{Z_o} A_{ul} h \nu_{ul}$$

$$I_{ul} = [1 - \alpha n_1(0)] n\beta \exp\left(-\frac{U}{KT_e}\right)$$

when the condenser is discharged

$$I'_{ul} = [1-\alpha n'_1(0)]\, n'\beta \exp\left(-\frac{U}{KT'_e}\right)$$

$$\therefore \frac{I'_{ul}}{I_{ul}} = \frac{[1-\alpha n'_1(0)]}{[1-\alpha n_1(0)]} \quad \frac{n'}{n} \quad \frac{\exp(-U/KT'_e)}{\exp(-U/KT_e)}$$

Putting the values of $f_{lu}\ \lambda_{ul}$, r_o, C, M, K, T_g, R_o,

$$\alpha = 2.52 \times 10^{-12}$$

So at 2250 volts, in case of air.

$$\frac{I'_{ul}}{I_{ul}} = 8.5 = \frac{0.945}{0.982} \times 3.101 \times \exp\left[\frac{9.84 \times 1.6 \times 10^{-12}}{1.37 \times 10^{-16} \times 3.92 \times 10^{4}} - \frac{9.84 \times 1.6 \times 10^{-12}}{1.37 \times 10^{-16} \times T'_e}\right]$$

$$T'_e = 6.095 \times 10^{4}\ {}^{o}K$$

In the same way

T'_e for 2000 volts = $6.11 \times 10^{4}\ {}^{o}K$

T'_e for 1750 volts = $6.2 \times 10^{4}\ {}^{o}K$

T'_e for 1500 volts = $6.4 \times 10^{4}\ {}^{o}K$

For hydrogen

$$T'_e \text{ for 2250 volts} = 4.27 \times 10^{4\,o}K$$

$$T'_e \text{ for 2000 volts} = 4.39 \times 10^{4\,o}K$$

$$T'_e \text{ for 1750 volts} = 4.58 \times 10^{4\,o}K$$

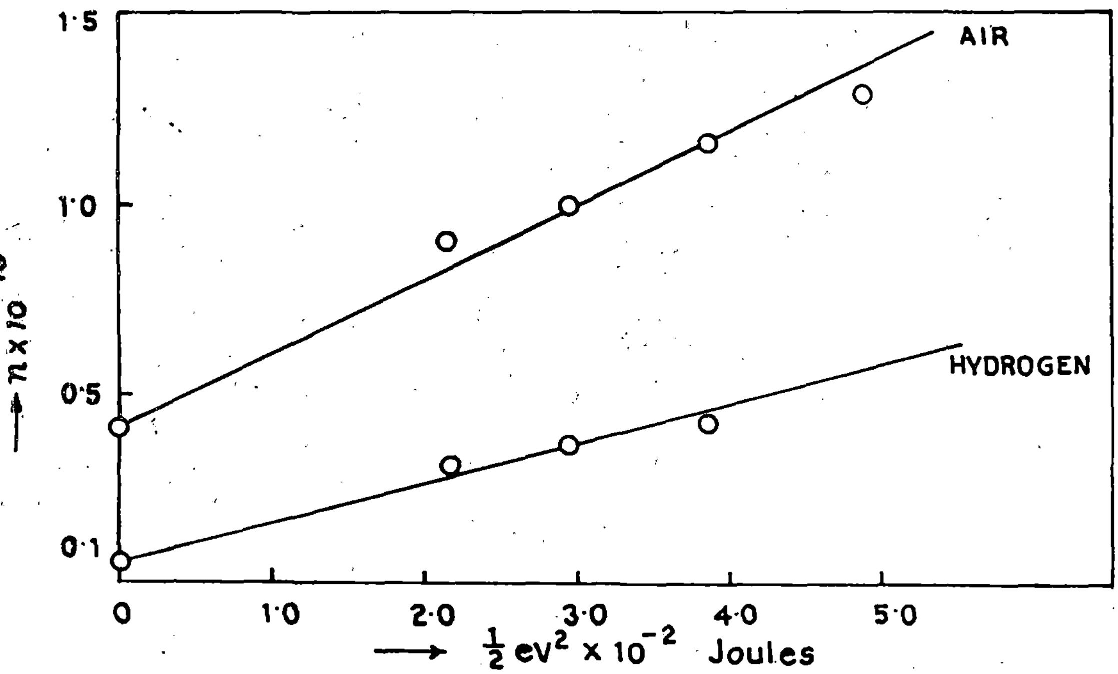
The values of electron density and electron temperature thus calculated are entered in Table (9.4)

Table 9.4

Gas	Voltage applied to condensers	Electron density	Electron Temp.
Air	0	4.131×10^9	3.92×10^4
	1500	9.091×10^9	6.4×10^4
	1750	10.33×10^9	6.2×10^4
	2000	11.52×10^9	6.11×10^4
	2250	12.82×10^9	6.09×10^4
Hydrogen	0	4.996×10^9	1.25×10^4
	1750	3.2473×10^9	4.58×10^4
	2000	3.74×10^9	4.39×10^4
	2250	4.24×10^9	4.27×10^4

From the calculated experimental results regarding the increase of discharge current the values of electron density for the extra input energy applied to the glow discharge by the discharge of the bank of condensers against the input energy is plotted in figure (9.1). It is observed that there is a linear increase of electron density with input energy. As there is already an ionised gas the free electrons may readily absorb the energy and transfer a part of the energy to atoms and molecules by collision but it may be analysed to show that this amount is exceedingly small compared to other processes which accompany the release of energy to the ionised gas from the discharge of the bank of condensers. The amount of energy supplied manifests itself in the form of a flash. An intense beam of light is produced

whose duration is of the order of a few microseconds or less. A spectroscopic examination of the lines shows that some ultraviolet lines are present. This may cause some amount of photoionization. A rough calculation regarding heat balance shows that there is a sudden rise of temperature of the order of 10^{4} °K. As in the case of exploding wire method there may be a process of thermal ionization which adds to the process of comulative ionization. It has been shown by some workers that when a bank of condensers under high potential discharges



1·5
1·0
0·5
0·1
$\longrightarrow n \times 10^{-10}$
AIR
HYDROGEN
0
1·0
2·0
3·0
4·0
5·0
$\longrightarrow \frac{1}{2} ev^2 \times 10^{-2}$ Joules

Fig. 9·1

through a gas a shock wave is usually generated. This shock wave may cause further ionization. These four processes such as ionization due to collision of electrons with neutral atoms and molecules with increased energy, photoionization, thermal ionization and ionization by shock waves may result in increased ionization which is reflected in the sudden rise of main discharge current. It is difficult to separate out the various processes and what is indicated is the total effect produced by the various ionization processes. The new electron density may be written as

$$n_e = n_{ion} + n_{colli} + n_{photo} + n_{thermal} + n_{shock}$$

It is evident that in the four ionising processes which have been listed above the electrons are involved in the augmentation of ionisation process only through collision. It is evident that the increased ionisation is mainly due to photoionisation, thermal ionisation and ionisation by shock wave. The electrons receive energy from the discharge of the condenser but the duration of the pulse is so small of the order of microseconds that the electrons, due to their finite inertia, cannot dispose of their additional energy and retain the same which results in an increase of electron temperature. When the condensers are discharged with higher and higher voltages it is observed that electron temperature practically remains constant which means that the electrons retain to themselves the additional energy gained and cannot transfer the same to the atoms and molecules and the sudden increase of ionization as recorded by the increase of electron density is due to photoionization, thermal ionization and ionization by shock waves.

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SUMMARY AND CONCLUSION

IN THE PRESENT WORK THE PHYSICAL PROCESSES OCCURING IN ARC PLASMA AND GLOW DISCHARGE HAVE BEEN INVESTIGATED BY ELECTRICAL AND SPECTROSCOPIC METHODS AND MATHEMATICAL ANALYSIS OF THE OBSERVED RESULTS HAS BEEN PROVIDED:-

A. MEASUREMENT OF PLASMA PARAMETERS IN AN ARC PLASMA BY PROBE METHOD.

A simple probe method has been used to measure the electron temperature and electron density in an arc plasma in mercury vapour for arc current varying from 2 A to 5 A and for three background pressures of 0.075 0.10 and 0.13 torr. Langmuir's expression (1925) for arc current has been found to be valid within the range of arc current investigated and the results have been utilised to calculate the mean free path of the electron in the gas. The open circuited diffusion voltage in the arc plasma has also been measured for the same range of current and voltage and utilizing the radial distribution function of conductivity as introduced by Ghosal, Nandi and Sen (1978) an analytical expression for the diffusion voltage has been calculated which can satisfactorily explain the observed results. The validity of the probe method for measurement of plasma parameters in an arc plasma has been discussed.

B. MEASUREMENT OF DIFFUSION COEFFICIENT OF ELECTRONS IN AN ARC PLASMA.

By measuring the diffusion voltage in an arc plasma as has been introduced in case of a glow discharge (Sen, Ghosh and Ghosh, 1983) and also the closed circuit diffusion current the diffusion constant of electrons in mercury has been calculated for the variation of arc current from 2 to 4.5 amps. for three background pressures of 0.075, 0.1 and 0.13 torr. The value of the diffusion constant is found to be smaller than the theoretical value by at least an order of magnitude which has been ascribed to the formation of induced dipoles due to motion of electrons through the gas. The increase in the value of diffusion coefficient with arc current has been explained as due to rise of temperature with arc current and the decrease with pressure has been ascribed to decrease of mean free path with increasing pressure.

C. MEASUREMENT OF ELECTRON ATOM COLLISION FREQUENCY IN AN ARC PLASMA BY RADIO FREQUENCY COIL PROBE IN CONJUNCTION WITH A LONGITUDINAL MAGNETIC FIELD.

The theory developed by Ghosal, Nandi and Sen (1976, 1978) regarding the radial distribution of conductivity of an arc plasma has been modified due to its tensorial behaviour when the arc is placed in a longitudinal magnetic field. A working formula has been developed to measure the electron atom collision frequency where the magnetic field has been used as a probe. Measurements are made in an arc plasma of arc current 2, 2.5 and 3 A and pressure 0.052, 0.075 and 0.17 torr. The values of electron atom collision frequencies are consistant with standard literature values and the method can be regarded as an alternative one for determining the electron atom collision frequency in an arc plasma.

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

The diffusion voltage in a mercury arc plasma has been measured for arc current varying from 2.5 A to 5 A in presence of (a) transverse and (b) axial magnetic fields varying from zero to 1.1 kilogauss. By assuming the radial distribution function of charged particles as proposed by Ghosal, Nandi and Sen (1978) and utilizing the method introduced by Sen, Ghosh and Ghosh (1983), electron temperature has been evaluated. It has been found that electron temperature becomes a maximum in axial magnetic field and then decreases whereas over the same range of magnetic field electron temperature shows a minimum in a transverse magnetic field and then increases with the increase of magnetic field. By utilizing the two fluid model of plasma an expression for electron temperature has been deduced in a variable magnetic field which can explain the occurance of maxima in case of axial magnetic field and minima in case of transverse magnetic field. The quantitative agreement between experimental and analytical expression is to a certain extent satisfactory.

E. BREAKDOWN OF ARGON UNDER RADIO FREQUENCY EXCITATION IN TRANSVERSE MAGNETIC FIELD.

The breakdown characteristics of argon gas under radio frequency excitation over a frequency range of applied electric field and for small H/P values have been calculated on a theoretical model suggested by Hale(1948).

Introducing the concept of equivalent pressure in presence of magnetic field breakdown voltages have been calculated for the range of frequencies investigated and for different magnetic fields. The results show the breakdown voltages increase with magnetic field and for higher frequencies. An analysis of the experimental results yields the value of electron atom collision frequency in the gas.

F. INTENSITY ENHANCEMENT OF SPECTRAL LINES WITH INCREASING OF ARC CURRENT IN ARC PLASMA.

The enhancement of intensity of the spectral lines λ 5465.5 Å, λ 5209.1 Å in case of silver arc, λ 5218.2 Å and λ 5153.2 Å in case of copper arc and λ 5369.9 Å, λ 5018.4 Å, λ 4383.5 Å in case of iron arc with increase of arc current from 2.5 A to 7.0 A has been investigated. Assuming self absorption, an analytical expression for the ratio of intensity of the spectral lines with increasing arc current has been deduced which predicts results in close agreement with those observed experimentally.

G. INVESTIGATION OF A GLOW DISCHARGE PLASMA SUBJECTED TO THE DISCHARGE OF A BANK OF CONDENSERS.

The effect of discharges of a bank of condensers charged to a high potential through a glow discharge in air and hydrogen has been investigated. The object of this investigation 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 interaction between an ionized gas and a high current pulsed discharge.