Investigation on The Physical Properties of Glow Discharge and Arc Plasma

THESIS SUBMITTED FOR Ph. D. (SCIENCE)
DEGREE IN PHYSICS
OF THE
UNIVERSITY OF NORTH BENGAL
1990

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Dedicated to my Parents
—Whose blessing was
The only Strength
behind my Success

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I have pleasure to certify that Shri Biswarup Ghosh has carried out the research work under my guidance for the Ph.D. thesis entitled "Investigation on the Physical Properties of Glow Discharge and Arc Plasma" which he is submitting for the Ph.D. degree (Science) of the University of North Bengal. Shri Ghosh has fulfilled all the requirements for the submission of his thesis as laid down by the University.

In character and temperament he is fit to submit the thesis.

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ACKNOWLEDGEMENT

This compilation of the research work in the form of a thesis has been possible due to the guidance of my supervisor and Teacher Professor S.N.Sen, Senior Professor of Physics, North Bengal University. I do acknowledge my deepest sense of solemn gratitude to him for his abiding interest, initiation, encouragement and advice.

In the process of my research work I have received help and encouragement from Prof. B. Bhattacharjee, Professor of Physics,NBU, Dr. R. Ghosh, Reader in Physics,NBU, Mr.Subhash Chandra Saha, Sr.Glass Blower, Mr. N.N.Maitra, Tech.Superintendent, Mr. S. K. Sarkar, Sr. Tech. Asstt., Mr. N. Pal, Senior Tech. Asstt., Mr. B.K. Nag, Tech. Superintendent and Mr.G.Basak, Tech. Asstt.,NBU.

I remember the co-operation received from my Labmate late Sanak Kumar Ghosh during the course of the work.

I am overwhelmed by the inspiration~~x~~ received from my sister Miss Manju Roy Choudhury. I always remember the inspiration received from Mrs. Sarbani Mazumdar, my little cousin sister, Miss. Nabaneeta Mazumdar and my friend Mr. Nemai Das.

I am extremely thankful to Mr. S.L.Sipahimalani, Marketing Director of my present employer, M/s. Toshniwal Instruments (Bombay) Pvt.Ltd. for providing me study leave to complete my thesis.

I also extend my thanks to my friend Mr. Debiprasad Boot, Mr. Naresh Ghosh for drawing the figures for my thesis and Mr. S.Choudhury, Physics Dept.,NBU for typing my thesis.

I extend my thanks to Mr. Samir K.Sarkar of USIC,NBU for his valuable help.

Lastly, I remember the moments of inspiration and sacrifice from my wife Mrs. Mousumi Ghosh, I owe a lot to her. I remember my sweet little daughter Miss Sreyoshi Ghosh who smilingly beared the absence of her father on an unknown hope of getting something following the completion of my thesis.

Biswarup Ghosh

Dated: 30.4.90.

(Biswarup Ghosh)

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CHAPTER I

REVIEW OF THE PREVIOUS WORK:-

The object of the present work is to study some of the physical properties of glow discharge and arc plasma and it is proposed to undertake the following lines of investigation.

(A) HEAT FLOW PROCESS IN THE POSITIVE COLUMN OF GLOW DISCHARGE.

The phenomenon of heat conduction in gaseous plasma was investigated by Goldstein and Sekiguchi (1958) in order to study the problem of mutual electron interaction. In addition to the technique of interaction of pulsed microwaves in decaying plasmas the phenomenon of 'After Glow Quenching' is exploited in the experiments. The experimental values of the thermal conductivity in low - gas pressure neon and xenon plasma having high charge density was determined by two different methods. The values have been found to be of the order of 10^{-6} to 10^{-5} (Joules/cm. sec. degree) for the electron density range $10^{11} \sim 10^{13}$ (cm^{-3}) at room temperature ($\sim 300^{\circ}K$). The experimentally obtained values of the thermal conductivity are in agreement within less than one order of magnitude with those given by the theory of Spitzer and Harm. (1962).

The most significant result of these experiments is that the thermal conductivity in plasma of low gas pressure but adequately high charge density (degree of ionization 10^{-6} to 10^{-5}) is determined by the heat flow chiefly in the electron gas of the plasma. Indeed the rate at which thermal energy is transferred from a small volume of warm electron gas to equal volumes of cool electrons within the same plasma is considerably faster (at least one order of magnitude faster) than the rate of heat transfer to any of the two other heavy plasma constituents (ions and neutral atoms).

The conclusion is also borne out by the experimental fact that at the same electron density n_e in one gas (here Xenon) no gas pressure dependence of thermal conductivity is observed. A further support for the above conclusion is provided by the fact that again at the same charge density the mass of the gas (here xenon and neon) has little or no influence on the thermal conductivity in these plasmas. A rather stray dependence of this thermal conductivity on the electron density however is apparent. The most appropriate comparison of the experimentally obtained coefficient of thermal conduction in the above mentioned plasmas can be made with the result obtained by the detailed calculations of 'Spitzer and Harm.

These calculations are for plasmas in fully ionized gases. The comparison of experimental results with this theory is appropriate because in the plasmas described in their work the interaction of electrons with the charged constituents (electrons and ions) pre-dominates over that with the neutral gas constituents of the plasma owing to the long range of Coulomb force. This comparison shows that the experimentally obtained values of thermal conductivity are in agreement within less than one order of magnitude with the theoretical calculation.

Persson (1961) had developed a method of measuring the conductivity in a high electron density plasma. He had shown that the interaction between the solenoidal electric field and circular cylindrical plasma column was used as the basis for the design of a pulse operated bridge, suitable for measurement of the electrical conductivity in the high electron density plasma. The upper limit for the measurable conductivity is determined by the skin depth of the plasma while the lower limit is determined by the noise level and the maximum allowed signal on the bridge. A Gaussian like pulse with a width of approximately 0.1 μ sec. is applied to the solenoids which are critically damped in the corresponding frequency range in a time resolution of less than 1/3 of a μ sec. for the conductivity measurement maxima. Krinberg (1967) had shown effects of ionization reactions on the thermal conductivity of a plasma. He had shown that the expression K (the thermal conductivity) is of the same form as for transport via dissociation inspite of the some-what different initial system of equations for the case of ionization. Rand (1966) et al had worked on plasma thermal conductivity taking into consideration some collective effects. They had studied electron thermal conductivity of a fully ionized Lorentz gas. The energy transfer among regions of the gas at different local temperature had been determined by considering the emission and absorption of longitudinal plasma waves. The waves are both collision and Landau damped, the later type of damping effects the energy transfer only secondarily, since the resulting energy does not go directly into the heating of the gas. It was found that beyond the dependence obtained in conventional two body collision studies, the thermal conductivity exhibits an additional weak dependence on the plasma parameter.

Levinsky et al (1968) had shown the effect of electron * interaction on the plasma thermal conductivity. The application of longitudinal wave emission and absorption to the determination of the thermal conductivity of a fully ionised Lorentz gas is extended phenomenologically in order to include the effects of electron - electron interactions. A simple modification yields good agreement with the results of previous calculation which were found by means of formal expressions of the Boltzmann equation about the collision term.

Mahn et al (1968) had worked on the measurement of the thermal conductivity in a magnetic field. The thermal conductivity of a hydrogen plasma had been measured in a transverse magnetic field in the temperature range between 10000 and 50,000°K.

J. Raeder et al (1968) had shown increase of pressure and total thermal conductivity in symmetrical cylinders of hydrogen plasma in an axial magnetic field under thermal equilibrium. The increase of pressure and total thermal conductivity are calculated for an infinitely long hydrogen plasma column in an axial magnetic field. The calculations which are based on the first and third moments of the Boltzmann equation for atoms ions and electrons are carried out under the assumption of local thermal equilibrium. Numerical results are given for magnetic fields upto 150 KG and temperature upto $10^{6\circ}$K and external pressure ranging from 10^{3} to 10^{5} dyne/cm^{2}.

Comparison of these results with previous calculations which neglect thermal forces shows that they cause an increase of pressure also in the completely ionized plasma and therefore modify the thermal conductivity indirectly.

Asionsovsnii (1970) et al had studied the electrical and thermal conductivity of air plasma. An experimental set up was made by a stabilised d.c. arc in air at atmospheric pressure. Data relating to the electrical conductivity of air at 7000^{o}K to 11000^{o}K and thermal conductivity of air at 6000^{o}K to 14000^{o}K were presented.

Morris (1970) et al had measured electrical and thermal conductivity of H_2, N_2 and Ar at high temperature upto 14000^{o}K for pressures between 0.5 and 2.0 atmosphere using a wall stabilised electric arc as a plasma source. Generally satisfactory agreement was noted between theory and experiment for the electrical conductivity. Equally good agreementm was found for the thermal conductivity for N_2 and argon when the energy transfer by vacuum ultraviolet radiation is included in the energy transport calculation. For hydrogen a difference between theory and experiment of as much as a factor of '2' is observed at the lower temperature. The difference was dependent on arc current and might be the result of non equillibrium effects.

Baüder (1970) had studied thermal conductivity of high temperature gases from experiments with electric arc discharge. The cascade arc was made for measurement of plasma transport properties upto 26000°K and mathematical evaluation method of the measured data was described. Results were reported for hydrogen and nitrogen at 1 atomosphere pressure. The thermal and electrical conductivity of optically thin plasma and its radiation source a strength was determined as a function of gas temperature and pressure. Voltage/current characteristics of the arc column, total radiation temperature distribution across the column with those experimental data and numerical integration of the energy equation of the arc column yield the transport properties of the particular plasma under study.

Asonovsky et al (1970) had determined experimentally thermal conductivity in low temperature plasma. The measurements of the thermal conductivity of plasmas of argon, nitrogen and air were carried out at atmospheric pressure and in temperature range from 6500°K to 16500°K The source of plasma was an electric arc stabilized by water cooled copper walls. The dependence of the electric field intensity and the radial distribution of temperature on the current of the arc for different diameters of the stabilizing channels (for argon plasma d = 4,6,8 mm for N_2 plasma d = 3 and 5 mm for air plasma d = 5 mm) were studied. It was shown that in such arcs mechanism of heat transfer is not exclusively thermal conduction. The experimental results are compared with theoretical calculations.

Schreiber et al (1970) had investigated the plasma transport properties. An approach was outlined for the experimental determination of plasma transport properties such as electrical conductivity, thermal conductivity, radiation source strength and viscosity. A plasma source was designed and constructed to provide the required stable conditions for investigation. The required diagonostic techniques were developed and preliminary measurements were presented. Advantages include the determination of electrical conductivity without making assumptions about the analytical form of the transport properties or the validity of the non-absorbing energy equation. In addition radiation source strength was measured over the entire wavelength.

Delpech et al (1971) had studied theoretically and experimentally the thermal conductivity of a partially ionized gas (ionization coefficient between 10^{-7} and 10^{-5}. A technique had been developed for measuring the thermal conductivity K_e for a range of values of ν_{ei}/ν_{eo} where ν_{eo} and ν_{ei} are the electron neutral and electron ion collision frequency for momentum transfer. In an after glow plasma, theoretical and experimental results for helium were compared.

Asinovskii et al (1972) had worked on the measurement of coefficient of electrical and thermal conductivity of air, Co_2 gas plasma by means of stabilized electric arc. Based on the measurements of the electrical field intensity and the temperature profiles in a wall stabilized d.c. arc, the author derived the values of the coefficient of electrical and thermal conductivity of air and Co_2 gas plasma at atmospheric pressure in the 6000^o - 15000^oK temperature range.

Nizovskii (1973) et al had measured thermal conductivity of a hydrogen plasma in a stabilized electric arc. An explanation was proposed for the discrepancies between theoretical and experimental data on the thermal conductivity of a hydrogen plasma. It was shown that there was a temperature range between the disssociation and the ionization peak of the thermal conductivity, the discrepancy was due to the breakdown of chemical equillibrium in the region of the arc near the wall. At temperature beyond the ionization peak the concentration of neutral atoms varies by a factor of several units when there is even a small departure of the degree of ionization from the equilibrium value. This could lead to a large error in the measurement of the temperature and therefore the thermal conductivity.

Ghosal, Nandi and Sen (1979) had worked on heat flow process in the positive column of a low pressure mercury arc. The problem of heat flow process within a low pressure mercury arc with water cooled walls had been investigated utilizing the first order perturbation technique to Boltzmann transport equation incorporating the term for the observed high gradient of radial distribution of azimuthal electrical conductivity of the arc.

No regular and systematic observation has been done regarding the process of heat flow in a confined low pressure arc (where the electrons are far from being in thermal equilibrium with the heavier constituents). Ghosal, Nandi and Sen (1979) studied semi emperically the heat flow process occuring within a low pressure mercury arc plasma. The authors had shown previously (1978) that when an arc is formed within a tube, the current density is not uniform throughout the cross section but is maximum at the axis and minimum at the periphery. This phenomenon gives rise to selective self heating at the axis of the arc plasma. The arc continuously absorbs power from the source and gives it away to the surroundings. In a weekly ionised plasma both the electronic and molecular contributions to thermal conductivity are to be considered. There might be present another mechanism of heat flow other than thermal conduction, radiation and convection which arises owing to the fact that electron density distribution within the arc may cause diffusion and energy might be carried away by the electrons. In contrast to the case of high pressure arc this mechanism of heat flow might play a significant role in case of low pressure arcs.

Ghosal, Nandi and Sen (1978) had shown that the radial electrical conductivity distribution function can be well represented by

$$\sigma(r) = \sigma_0 \left[1 - \left(\frac{r}{R}\right)^2\right]^n \qquad (1.1)$$

r → radial position

R → radius of the tube

σ_0 → the conductivity at the axis.

The experimentally determined term η is found to be dependent on discharge currents. Based on this deduction the authors had shown that radial distribution of electrical conductivity gives rise to a distribution of the rate of heating inside the plasma cylinder defined by the radii r and r + dr. The rate of heating per unit length $d\dot{Q}_0$ within the annular space can be represented as

$$d\dot{Q}_0 \propto f(r)$$

$f(r)$ → electrical conductance of the annualar plasma cylinder

$$f(r) = 2\pi r \, dr \, \sigma(r)$$

$$d\dot{Q}_0 = C r \, \sigma(r) \, dr$$

where C is a constant

The rate of heating inside the plasma cylinder of radius r is given by

$$\int_0^r C r \, \sigma(r) \, dr = C F(r) \qquad (1.2)$$

Electronic contribution of heat flux is obtained by using the relation

$$H_e = \iiint_{-\infty}^{+\infty} n_0 \left(\frac{1}{2} m_e v^2\right) v_z \, f_e \, dv_x \, dv_y \, dv_z$$

which is obtained as

$$H_e = -\frac{5}{2} \frac{n_0 \phi(z) K^2}{m_e v_{me}} T_e \frac{dT_e}{dz} - \frac{5}{2} \frac{n_0}{m_e} \frac{K^2}{v_{me}} T_e^2 \frac{d\phi(z)}{dz} + \frac{5}{2} n_0 K T_e \mu_e \frac{D_e - D_i}{\mu_e + \mu_i} \frac{d\phi(z)}{dz}$$

ν_{me} ?

(1.3)

or

$$H_e = -K_e \frac{dT_e}{dz} - \frac{5}{2} D_e \frac{d\phi(z)}{dz} n_0 K T_e + \frac{5}{2} n_0 K T_e \mu_e \frac{D_e - D_i}{\mu_e + \mu_i} \frac{d\phi(z)}{dz}$$

(1.4)

where

$$K_e = \frac{5}{2}\,\frac{n_0\,\phi(z)\,K^2}{m_e\,\vartheta_{me}}\,T_e$$

where K_e is the thermal conductivity of plasma, where we have used the relation

$$D_e = \frac{K\,T_e}{m_e\,\vartheta_{me}}$$

Under relevant approximations

$$\frac{T_e}{m_e} \gg \frac{T_i}{m_i} \qquad \mu_e \gg \mu_i$$

$$H_e = -K_e\,\frac{dT_e}{dz} - \frac{5}{2}\,n_0\,K\,T_e\,D_A\,\frac{d\phi(z)}{dz} \qquad (1.5)$$

where $D_A = \frac{\mu_i}{\mu_e} D_e$ is the approximate ambipolar diffusion coefficient. The flux of electrons Γ_e executing ambipolar diffusion is given by

$$\Gamma_e = -D_A\,\frac{dn(z)}{dz} = -D_A\,n_0\,\frac{d\phi(z)}{dz}$$

Heat flux

$$H_{amb} = - \text{Constant}\ K\, T_e\, n_0\, D_A \frac{d\phi(z)}{dz}$$

The total heat flux H will contain H_e and H_n for the ion species and the neutral particle species respectively.

$$H = H_e + H_n$$

$$H = -\frac{5}{2}\frac{n_0}{m_e}\frac{K^2}{\nu_{me}}\phi(z)\, T_e \frac{dT_e}{dz} - \frac{5}{2} n_0 K T_e \frac{\mu_i}{\mu_e} D_e \frac{d\phi(z)}{dz} - K_n \frac{dT_n}{dz}.$$

Assuming cylindrical symmetry Z can be replaced by the radial variables r,

$$H = -\frac{5}{2}\frac{n_0}{m_e}\frac{K^2}{\nu_{me}}\phi(r)\, T_e \frac{dT_e}{dr} - \frac{5}{2} n_0 K T_e \frac{\mu_i}{\mu_e} D_e \frac{d\phi(r)}{dr} - K_n \frac{dT_n}{dr}$$

The heat flow across the plasma cylinder of unit length of radius ' r ' is given by

$$C F(r) = 2\pi r \left[-\frac{5}{2} \frac{n_0}{m_e} \frac{K^2}{\vartheta_{me}} \phi(r)\, T_e \frac{d T_e}{dr} - \frac{5}{2} n_0 K T_e \frac{\mu_i}{\mu_e} D_e \frac{d\phi(r)}{dr} - K_n \frac{d T_n}{dr} \right]$$

assuming $T_r(e) = T_e$ i.e. some suitable value of electron temperature within the plasma column

$$e \int_0^R \frac{F(r)\, dr}{r} = 2\pi \left[\frac{5}{2} \frac{n_0}{m_e} \frac{K^2 \phi(r)}{\vartheta_{me}} T_e (T_{e0} - T_{ew}) + \frac{5}{2} n_0 K T_e \frac{\mu_i}{\mu_e} D_e (\phi_0 - \phi_w) + K_n (T_{e0} - T_{nw}) \right] \tag{1.6}$$

where the suffixes 0 and w denote the values of the relative quantities at the axis and at the wall respectively. From equation (1.2)

$$\int_0^R c\, r\, \sigma(r)\, dr = C F(R) = \dot{Q}_0$$

where $\dot{Q}_0$ is the total rate of heating inside the plasma column of unit length. Thus

$$\mathcal{C} = \dot{Q}_0 / F(R) \tag{1.7}$$

From equation (1.7) and (1.6)

$$\Lambda \dot{Q}_0 = 2\pi \Big[\alpha \phi(r)\, T_e \,(T_{e0} - T_{e\omega}) + \beta\, (\phi_0 - \phi_\omega) + K_n\, (T_{n0} - T_{n\omega}) \Big]$$

where $\Lambda = \int_0^R \frac{F(r)}{r} \frac{dr}{F(R)}$ (1.8)

and the electrical conductivity at the axis of the plasma is given by

$$\sigma_0 = n_0 e^2 / m_e \nu_{me} \tag{1.9}$$

Thus

$$\alpha = \frac{5}{2} \frac{\sigma_0 K^2}{e^2} \tag{1.10}$$

$$\beta = \frac{5}{2} \frac{\sigma_0 K^2}{e^2} \frac{\mu_i}{\mu_e} T_e^{\,2} \tag{1.11}$$

Assuming $\phi(r) = \frac{1}{2}$ to a first approximation

$$\Lambda \dot{Q}_o = \frac{5}{2} \pi \frac{K^2}{e^2} \sigma_0 T_e \left(T_{eo} - T_{e\omega} \right) + 5\pi \frac{\mu_i}{\mu_e} \frac{K^2}{e^2}$$

$$T_e^{\,2} \left(\phi_o - \phi_\omega \right) \sigma_0 + 2\pi K_n \left(T_{no} - T_{n\omega} \right)$$

(1.12)

" $T_{no} - T_{n\omega}$ " was determined by using thermometers.

If the longitudinal electric field of the plasma is assumed to be uniform throughout the cross-section of the plasma the quantity (T_e - T_n) becomes a constant parameter

$$T_{eo} - T_{e\omega} = T_{no} - T_{n\omega}$$

$$\dot{Q}_o = \frac{5}{2} \pi \frac{K^2}{e^2} \frac{\sigma_0}{\Lambda} T_e \left(T_{no} - T_{n\omega} \right)$$

$$+ 5\pi \frac{\mu_i}{\mu_e} \frac{K^2}{e^2} \frac{\sigma_0}{\Lambda} T_e^{\,2}$$

$$+ 2\pi \frac{K_n}{\Lambda} \left(T_{no} - T_{n\omega} \right)$$

(1.13)

where $\phi_0 = 1$ & $\phi_\omega = 0$ according to the proposed distribution function

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

$$\overset{\circ}{Q}_0 = \overset{\circ}{Q}_K + \overset{\circ}{Q}_D + \overset{\circ}{Q}_r \tag{1.14}$$

where $\overset{\circ}{Q}_K = \frac{5}{2}\,\pi\,\frac{K^2}{e^2}\,\frac{\sigma_0}{\Lambda}\,T_e\,(T_{n0} - T_{n\omega})$

$\overset{\circ}{Q}_K \rightarrow$ rate of heat flow from plasma per unit length to the wall due to the electronic thermal conductivity.

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

$\overset{\circ}{Q}_D \longrightarrow$ is the heat flow rate due to ambipolar diffusion of electrons

$$\dot{Q}_n = 2\pi \frac{K_n}{\Lambda} (T_{no} - T_{n\omega})$$

$\dot{Q}_n \rightarrow$ is the heat flow rate due to thermal conduction of neutral particles.

The experimental procedure was very straight forward. The platinum resistance thermometer is first calibrated and water is made to flow through the condenser. The arc is then drawn along the tube. Some time is allowed to pass to achieve the thermal equilibrium of the platinum thermometer with the mercury vapour at the axis.

The temperature of the platinum thermometer reads T_{no} , the temperature at the axis. The mercury thermometer reads the temperature θ of the flowing water. Owing to the finite conductivity of glass this θ is not the actual peripheral temperature of the plasma; knowing the thickness and the conductivity of glass of the tube, the actual peripheral temperature is calculated. The experiment was repeated for different discharge currents. In each case the rate of supply of heat $\dot{Q}_o$ is calculated by knowing the discharge current and the voltage across the plasma column under study.

The results obtained by Ghosal et al (1979) corroborate with the result obtained by Margenau and Adler (1950) who predicted an occurance of maxima in the region of lower electron energies from where Brode's measurements of collision cross section begin. The obtained high values of electron atom collision cross sections at lower electron energies also explains the sudden fall of electron temperature at higher discharge currents, since as the current is increased, the vapour pressure of Hg increases and thereby lowers the electron energy to some extent. These low energy electrons again suffer greater number of collisions due to a sharp rise of ν_e at lower electron energies, thereby lowering the electron energy again and the process continues until the equilibrium is reached.

(B) EVALUATION OF ELECTRON TEMPERATURE IN GLOW DISCHARGE FROM MEASUREMENT OF DIFFUSION VOLTAGE.

The Langmuir probe has long been used as a fundamental diagnostic tool for measuring local properties of plasma. The experimental arrangements generally are very simple. A small metallic electrode is placed in the plasma at the location of interest. External circuit is provided to vary its electric potential. The current flowing to the probe is measured as a function of applied voltage. The current voltage diagram or the probe characteristic may provide important information about local properties of the plasma such as electron and ion number densities n_e and n_i, electron temperature, T_e, the plasma potential V_S and electron distribution function.

A thin layer around the probe exists where electron and ion number densities differ and the layer called as a sheath can sustain large electric fields. So the number of possibilities for a meaningful use of probes is subject to many restrictions otherwise the results of probe measurements may be erroneously interpreted.

To every point in the plasma there is a corresponding potential V_S with respect to a given reference point (for example a large electrode in contact with the plasma). This is known as space potential. If a probe (a small cylindrical conductor) is inserted at a point in plasma due to unequal motions of electrons and ions, the probe quickly attains a potential negative with respect to V_S this potential is known as floating potential V_f and a sheath is formed due to space charge effect. If the probe potential is raised to V_S by external source, the probe is at the same voltage as the plasma and there is no sheath. If the probe is biased more negatively then V_S an increasing fraction of electrons is repelled and the probe current falls. The logarithmic slope of the characteristic in this region is equal to the local electron temperature. At V_f, the currents of electrons and ions drawn to the probe are equal and the net current is zero. With increasing negative bias no electron can reach the probe and ion saturation current is drawn. From electron and ion saturation current plasma local density can be determined.

Langmuir's (1924, 1926) pioneering work, (the theory of probes in the absence of magnetic fields) has been extensively developed. In the absence of magnetic fields the response of a probe depends on a number of parameters. These parameters determine the various domain at which electric probe can operate. In the collisionless limit $[\lambda \gg r_p , \ \lambda \gg \lambda_D]$

where λ is the meanf free path of the charged particles, r_p is the probe radius and λ_D is the Debye shielding length given by

$$\lambda_D = 4.9 (T_e / n_e)^{1/2} \text{ in cm.}$$

the theory is practically complete and extensive computed results are available.

The continuum case $(\lambda \ll \lambda_D \ll r_p)$ has been treated by Su and Lam (1963) and Cohen (1963) Wasserstrom, Su, Probatien (1965), Chou, Jalbot and Willis (1966), Bicukowski and Chage (1968) . A systematic account of probe theories is given by Chung, Talbot and Touryan (1975).

Chen et al (1968) had shown that probe theory is particulurly simple when $\xi_p = r_p / \lambda_D$ called as "Debye ratio" is large $(\gg 10)$ and the sheath is thin so that the particle collection area is essentially the geometric area of the probe, or when ξ_p is small $(\ll 1)$ and the sheath very thick so that probe current is governed by orbital motion theory of Langmuir.

Schott (1968) has enumerated conditions to be satisfied for an ideal probe operating in orbital motion experiments. (a) The plasma is to be homogeneous and quasi neutral in the absence of the probe. (b) Electrons and ions to have Max - wellian velocity distribűtions with temperatures T_e and T_i respectively with $T_e \gg T_i$ (c) The mean free paths of electrons and ions λ_e and λ_i to be large compared to all other relevant characteristic lengths. (d) Each charged particles hitting the probe is to be absorbed and not to react with the probe material. (e) The sheath has a well defined boundary. Outside this boundary the space potential is constant. (f) The sheath thickness is small compared to the lateral dimensions of the probes so that edge effects can be neglected.

For comparatively hot plasmas tungsten as probe material is a suitable choice. Nevertheless the probe which is immersed in the plasma disturbs the plasma and the measurements as well.

Chung, Talbot and Touryan (1975) have reviewed the present state of knowledge about these disturbances.

Sen and Jana (1977) while investigating the current voltage characteristic of glow discharges in an axial magnetic field (B $\leqslant$ 800 G) in air (p = 0.5 to 1 torr) had observed that radial distribution of electron can be represented by Bessel function (Schottky's theory) in the presence of longitudinal magnetic field as well.

Sen and Gupta (1969) had shown from r.f. conductivity measurements in helium, neon and argon (P = 0.7 torr) ~~x~~ in a longitudinal magnetic field (B $\leqslant$ 550 G) that Schottky's ambipolar diffusion theory is valid for these discharges in magnetic field and from particle balance equation the authors found electron temperature to decrease with increasing magnetic field.

Sen and Sadhya et al (1979) have measured electron temperature and electron density in low temperature plasmas in air, hydrogen, oxygen and nitrogen magnetised by either a transverse or a longitudinal magnetic field by probe method. The limitations of the probe theory and the precise method in measuring electron temperature and electron density both in the absence and in the presence of the magnetic field have been discussed and experiments have been performed under the conditions in which the assumptions of the probe theory are strictly valid. The general conclusion arrived at is that in x case of transverse magnetic field, the electron temperature increases whereas the radial electron density decreases and in case of longitudinal field, the electron temperature decreases and the radial electron density increases. The results are also quantitative in agreement with the theoretical deductions of Beckmann (1948) in case of transverse magnetic field (Sen and Gupta (1969)) and (Sen and Jana (1977)) in case of longitudinal magnetic field. Further it was noted that in case of molecular gases the electron energy distribution is Maxwellian in presence or in the absence of magnetic field but in the former case it becomes a function of (H/P) where H is magnetic field and P is the pressure.

The ideal experimental method would be one in which the probing mechanism does not disturb unduly the processes to be investigated. Consequently a spectroscopic method is preferred to other diagnostic methods. Spectroscopy of laboratory plasmas covers a wide area of work, varying from atomic structure to plasma physics. It is the presence and interactions between ions, neutrals, electrons and photons that lead to atomic processes which both affect the plasma and provide information on plasma state.

For glow discharge in which electron temperature (1 - 5 eV) and electron density (10^8 - 10^9 cm^{-3}) are comparatively small, electron temperature can be deduced from relative intensities of spectral lines. To determine T_e from relative intensity method, spectral lines are selected for which relevant atomic process is understood and also the excited state continuity equation. Considering all of the collisional and radiative processes that populate and depopulate the state concerned is written down. The process of solving the excited state continuity equations thus obtained, is very complex, simplifications may be made by weighting the relative contributions of separate process and establishing a certain type of equilibrium to prevail inside the discharge tube by considering dominating particle gain and loss terms.

Two types of equilibrium that are of interest are the local thermodynamic equilibrium model (LTE) and Corona equlibrium model (CE).

When a plasma is in LTE, there exists a unique temperature which determines the velocity, distribution function for species with the dominating reaction rate (usually the electrons). If such equilibrium exists, the analysis of the state of plasma is particularly simple since it is only such local plasma parameters as electron density, electron temperature and composition x that determine the relevant populations.

The number density of electrons necessary to obtain complete LTE has been calculated by Griem (1964). This electron density is given by

$$n_e \geqslant 9 \times 10^{17} \left(E_2 / \chi_H \right)^3 \left(k\,T_e / \lambda_H \right)^{1/2} \text{cm}^{-3} \tag{1.15}$$

with E_2 the ~~a~~ energy of the first excited level and χ_H the ionisation energy of hydrogen and K is ~~t~~ the Boltzmann constant. E_2, λ_H and K , T_e all expressed in eV. To calculate this criterion, Griem considered that for lowest excited state (reasonance level) the collisional excitation rate is ten times the radiative rate from that level. Later on this criterion was corrected by Hey (1976) by considering finer values of Gaunt factor appearing in collisional excitation rate coefficient and incorporating the effect of metastable collisions.

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

$$n_e \geqslant 6 \times 10^{13} \chi_i \left(k\,T_e \right)^{1/2} \tag{1.16}$$

χ_i is the ionisation energy of atom in eV. From these criteria a single criterion for electron density necessary to maintain complete LTE in the discharge tube is

$$n_e \geqslant C\,(KTe)^{1/2}\,\chi_i^{3}\ cm^{-3}$$

(1.17)

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.

Richter (1968) has shown that the occupation number for states over this critical level are as in LTE with temperature T_e but the ground level is over populated by a factor. So the states over the critical level is considered to be in partial LTE. The electron density required for a level with quantum number p to be in partial LTE with higher levels is after Griem (1964) approximately

$$n_e \geqslant 7 \times 10^{8}\,\frac{Z^{7}}{p^{8.5}}\,(KTe/\lambda_H)^{1/2}\ cm^{-3}$$

(1.18)

here (Z) is the charged state of atom. Strictly speaking this applies only for hydrogen ions. For other atoms, p is identified as effective quantum number of the level defined as

$$p_{eff} = Z \left(\frac{R}{T_\alpha - T_p} \right)^{1/2} \tag{1.19}$$

where R = Rydberg constant, T_α is the ionisation limit, Tp is the term value of the level p and for neutral atoms Z = 1.

Fujimoto (1973) treated LTE on the basis of a collisional radiative model for hydrogen ions and observed that LTE is identical with that ennunciated by Griem.

When electron densities are too low for establishment of LTE it is possible to obtain equilibrium whereby the collisional excitation and ionisation is balanced by radiative decay and recombination respectively. This type of equilibrium generally prevails in solar corona so it is known as Corona equilibrium (CE) model. In CE, the population of an excited level which can emit allowed spectral lines is usually governed by collisional excitation from ground level and spontaneous radiative decay but since the decay is the faster process the population is mainly in the ground level. CE can also be applied under restricted conditions to the line intensities of spectra from low density plasmas created in the laboratory. ~~x~~ An approximate criterion for CE to be valid for all excited levels is given by Wilson (1962) as

$$n_e \leqslant 1.5 \times 10^{10} \chi_i (KTe)^4 \ cm^{-3} \tag{1.20}$$

where again χ_i is the ionization potential of the atom in eV. 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 level is

$$n_e \leqslant 10^{11} \chi_i^{1.5} (KTe)^2 \ cm^{-3} \tag{1.21}$$

Mowhirter (1965) proposed another condition for CE and Fujimoto (1973) interpreted CE interms of collisional radiative model.

For spectroscopic diagnostics two assumptions are generally made and those assumptions make the problem easier to handle.

(a) The plasma is optically thin. The optical thinness or thickness of radiation is generally treated in terms of optical depth. In case of an optically thin plasma the absorption of radiation is negligible. So the radiation of each individual atom leaves the plasma and contributes to observed intensity. It is generally believed that for CE all the light sources and for LTE all light sources above 10,000°K are quite transparent even in the central parts of the line.

(b) Additional simplification can be achieved if it is assumed that electron energy distribution is Maxwellian.

For probe diagnostics the nature of electron energy distribution function is experimentally determined whereas for spectroscopic methods a knowledge of electron energy distribution function is necessary because the distribution function enters directly in large collision integrals. Also the presence of a magnetic field can effectively influence the distribution function. Elton (1970) has described at least four criteria to be satisfied of the free electrons in plasma to have a Maxwellian velocity distribution. These are

$$t_{ee} << t_{ff}\ ,\quad t_{en},\quad t_{part}\ ,\quad t_{inel}$$

where t_{ee} is the energy relaxation time for colliding electrons. For specific experiment it must be much less than (a) t_{ff} , the energy decay time for free- free process (b) t_{en} the characteristic electron heating time (c) t_{part} the characteristic containment time for particles and lastly (d) t_{inel} the relaxation time for electron impact including atomic processes ~~wx~~ such as ~~x~~ excitations and ionization when the electron number density is comparatively high.

Tonks and Allis (1937) investigated the effect of an external magnetic field on the electron velocity distribution function and Bernstein (1962) justified the use of a Maxwellian distribution for strong magnetic field in the approach via. Boltzmann equation. It was experimentally observed by 'r.f.' probe method that at least in longitudinal magnetic field electron energy distribution function is nearly Maxwellian.

Drawin and Ramethe (1979) had shown an analysis of the profiles of certain He spectral lines emitted from a low pressure (p = 0.5 torr) after glow plasma submitted to a magnetic field of 10^5 G. The authors observed that a strong magnetic field leads to a profound modification of the line profiles and complicates the diagonostics.

Tonks and Allis (1937)'s - expression for electron drift in transverse magnetic field was utilized by Beekman (1948) and he had shown that the field deflects the column towards the wall with the result that the total loss of electrons and ions is increased. This causes an increase in electron temperature and axial electric field strength. Beckman (1948) observed that the axial electric field E is changed to $E\left(\alpha + \beta^2/\alpha\right)^{1/2}$ in presence of a transverse magnetic field and electron density at a distance 'r' from the axis and in field B is given by

$$n_\beta = n_0 \exp\left(-\frac{C_r \cos\phi}{2 D_a}\right) J_0\left(2.405\, r/R\right) \tag{1.22}$$

n_0 is the electron density at the axis, C is a constant depending on ion mobility, D_a is the ambipolar diffusion coefficient, J_0 is the Bessel function of zero order and of first kind and ϕ is the azimuthal coordinate. By measuring the voltage across a fixed distance by floating probe Beckmann (1948) observed that the electric field increases in a transverse magnetic field ($B \leqslant 1000$ G) in gases like hydrogen, nitrogen and helium, neon.

Effect of a transverse magnetic field on low pressures glow discharges in different gases like hydrogen, helium, oxygen and neon was also investigated by Sen et al (1971, 1972). The authors measured the discharge current and intensities of certain spectral lines in presence of field. Both the discharge current and spectral intensities were observed to increase first and after attaining a maximum at a certain magnetic field gradually decreases. In case of discharge current measurements it was observed that the field (B max) at which the current becomes maximum is same for all gases and independent of pressure for the same initial discharge current. For spectral line intensity measurements, B_{max} differs for different wavelength of lines of the same gas.

Keneda (1977, 1977, 1978, 1979) had studied in a series of papers the effect of transverse magnetic field ($B \geqslant 300$ G) on neon glow discharges ($p = 0.3 - 10$ torr). By measuring axial electric field strength by floating probes, Keneda observed that the axial field increases considerably with transverse magnetic field at lower pressures and the author modified Beckman's expression by taking account of electron loss as well.

Sadhya and Sen (1981) measured the electron temperature in glow discharge in transverse magnetic field by spectroscopic method. Electron temperature was deduced from relative intensities of spectral lines. Electron temperature enters into the emission line intensities through excitation rate coefficients which also depend on electron number density. Both T_e and n_e are affected by a transverse magnetic field. When the ratio of spectral intensities of two lines of the same element is considered, it is possible to calculate T_e. Dependence of T_e on transverse magnetic field was determined by this method.

Wild et al (1983) had measured electron temperature using a 12 channel array probe. They have studied electron temperature in a pulsed high $\beta \, (\beta \equiv 2\mu n k T / B^2 \simeq 1)$

plasma as a function of time using a miniature array of 12 ~~sk~~ planar Langmuir probes. Instead of sweeping the bias voltage on the collectors, each is set at a different voltage corresponding to points along the characteristic I - V curve. An arrangement of fast analog multiplexer together with a computerized data equisition system allowed measurement of T_e to within a few percent accuracy with a time resolution of 1 μsec.

Sengupta et al (1981) had studied direct display of electron temperature oscillation in plasma. A simple differential technique was used using a floating Langmuir probe and a hot probe was used to obtain direct oscillographic display of electron temperature oscillations in plasma. The relability of the method had been tested in artificially moving stariations in the positive column of a cold cathode argon discharge.

($Id = 8mA$, $p = 0{\cdot}1$ torr, $2r = 5cm$)

Watson et al (1980) had measured electron temperature in laser produced plasmas suitable for spectrochemical analysis. In laser spectrochemical analysis it is desirable for the plasma excitation conditions to be reproducible and for 'Local thermodynamic equilibrium(LTE) to exist over all the diagonostic line transitions of interest. Thus emission line ratios can be used to determine the concentration of trace element. To assess the validity of the LTE model and to characterise plasma conditions the time integrated electron temperature was measured for the normal and Q switched modes of plasma production, both with or without auxiliary spark excitation. A steel target was used and the temperature was estimated using emission spectroscopy of Fe I and Fe II lines.

R. Boes et al (1983) applied a glass laser emitting periodic pulse train of 1 mS duration and energy 200 J is applied to a HF produced plasma with $n_e \cong 10^{13} cm^{-3}$ and $T_e \cong$ 20 eV. In combination with a 'Si-avalanch diode', T_e measurements were possible.

Lamourenx et al (1984) had revised the current electron temperature diagnostics based on the continuous spectrum for plasmas not in local thermal equilibrium. The authors study as an example a Nd Laser produced aluminium plasma at the critical density of 10^{21}/cc considering the equilibrium (electron distribution function) of the form

$$e^{-(v/v_0)^5}$$

when inverse Bremsstrahlung is the dominant heating process. The choice of the atomic physics approximation used to determine the radiative power losses P ($h\nu$) either for Bremsstrahlung or for radiative recombination has little influence on the temperature T_e given by the current diagnostic

$$d \operatorname{Log} P(h\nu) / d(h\nu) = 1/K T_e \qquad (1.23)$$

On the contrary substituting the non LTE distribution to the Maxwellian leads to a strong modification of the above slope. Therefore, when the discussed diagonostic is uncarefully applied to the non LTE plasma, it leads to large systematic x errors in the evaluation of the temperature.

Veldhuizon et al (1985) had made optogalvanic determination of electron temperature in a hollow cathode glow discharge. The determination of electron energies in a hollow cathode glow discharge has always been a difficult problem. This is mainly due to complex nature of the discharge in which a Non-Maxwellian electron energy distribution is present. Electrons originating from the cathode are accelerated in the cathode dark space and specially when the discharge is running at a higher cathode current densities enter the glow with energies corresponding to the full cathode fall. The major part of this energy is lost in inelastic collisions with neutral atoms. When the electron energy gets below the excitation threshold, elastic collisions take over but a strong exchange results in a quasi-Maxwellian low energy part of the distribution. The authors have utilised the opto galvanic effect to measure the ambipolar transport of plasma within the glow. From the ambipolar diffusion coefficient it is possible to derive an average electron energy.

Eddy (1985) had determined electron temperature in LTE and non LTE plasmas. A method was presented by the author for calculating electron temperature (T_e) in dense plasmas, which does not assume equivalance with the excited level distribution temperature. The method involves the upper-level Saha ionization equation at the ionization limit, the limiting weighted population density (N_1/g_1) obtained from measured population densities and experimentally obtained electron density. Electron temperatures calculated for 0.1 bar hydrogen helium and argon arcs are found to be upto twice as large as excited level distribution temperatures.

For sub atmospheric argon arcs, the calculated T_e is equivalent to the excitation temperature of the middle levels, but are two to three times smaller than the quoted T_e for the highest levels. Reasons are discussed for the apparent invisibility of true electron temperatures and for differences between them and the excitation temperatures.

This review thus provides the different plasma diagonistic methods for the measurement of electron temperature and also the limitations from which they suffer. In the present work an alternative method will be presented for the measurement of electron temperature.

(C) MEASUREMENT OF PLASMA PARAMETERS IN GLOW DISCHARGE BY SONIC PROBE.

Surdin in 1962 first studied the propagation of ultrasonic waves in plasma. The investigation of the interaction of ultrasound waves with a plasma had provided information on plasma properties that lead to a better understanding of re-entry problems and in certain cases lead to the development of a plasma diagnostic method.

Surdin had made an experimental arrangement where an ultrasonic wave of variable frequency was launched in a plasma by a transmitter. The ultra sound signal was received by a receiver. The analysis was made by the following approximations:-

(a) The charge neutrality is preserved within the plasma to a very high degree. Deviations from electrical neutrality are considered only in poisson's equation.

(b) m/M is neglected as compared to 1 (m and M are the electron and the ion masses respectively).

(c) The electrical resistivity of the plasma is taken to be zero.

(d) The plasma considered is isothermal i.e. $T_e = T_i = T$ and the ion and electron gases have the same number of degrees of freedom i.e. $\gamma_e = \gamma_i = \gamma$

To derive the disperson equation collisions between plasma constituents were neglected. Under these conditions the equation of propagation of the total pressure p (the sum of the partial pressures of the ion and electron gases) is

$$\frac{1}{\gamma K T} - \frac{1}{m} \nabla^2 \frac{\partial^2 p}{\partial t^2} + \frac{\gamma K T}{m M} \nabla^4 p + \frac{\omega_p^2}{\gamma K T} \frac{\partial^2 p}{\partial t^2} - \frac{2 \omega_p^2}{M} \nabla^2 p = 0 \tag{1.24}$$

where $\omega_p{}^2 = 4 \pi n e^2/m$.

Let us consider a longitudinal plane wave solution of the form

$$p = p_0 \exp \left[i \omega (t - x/v) \right] \tag{1.25}$$

Combining the above equation, the dispersion equation is obtained

$$\frac{1}{\gamma K T}\left(\omega^2 - \omega_p^2\right) V^4 + \left(\frac{2\omega_p^2}{M} - \frac{\omega^2}{m}\right) V^2 + \frac{\gamma K T}{m M} = 0$$

(1.26)

from the above equation~~x~~ it can be seen that when ω increases from 0 to ω_p the velocity of propagation decreases from $\sqrt{2}\, V_0$ to V_0, $V_0 = (\gamma K T/M)^{1/2}$ is the velocity of propagation of sound in the un-ionized gas.

For $\omega > \omega_p$, the ultrasonic wave is propagated with a velocity Ve

$$V_e^2 = \frac{\gamma K T}{m} \frac{1}{1 - \omega_p^2/\omega^2} \qquad (1.27)$$

The plasma under consideration contains positive ions, electrons and neutral atoms. For relatively low plasma densities considered (10^8 - 10^{12} per cm^3)

the prevailing energy - loss mechanism is considered to be momentum transfer during electron neutral atom elastic collisions. The power attenuations per unit length of plasma, α , in the x-direction is

$$\alpha \cong \frac{\omega^2}{\omega^2 \tau^2 + 1} \quad \frac{4 \eta}{3 n M v^3}$$

(1.28)

where η is the electron gas viscosity due to momentum transfer during electron-neutral atom collisions, $1/\tau$ is the frequency of these collisions. Let λ be the mean free path of electrons, then

$$\eta = \frac{1}{3} n m \bar{v} \lambda = \frac{1}{3} n m \bar{v}^2 \tau$$
$$= \frac{1}{3} n \tau (8/\pi) KT$$

For low frequency or "ion ultrasonic waves" there are two cases of interest

(a) $\omega \tau < 1$ for which

$$\alpha_1 \cong \frac{16}{9\pi} \quad \frac{\omega^2 \tau}{\gamma V} \qquad (1.29)$$

and

(b) $\omega\tau > 1$ where $\alpha_2 \cong \frac{32}{9\pi} \frac{1}{\gamma v \tau}$ (1.30)

However, a number of workers (Champion, 1962, Bhatnagar, 1964, Saxena and Gour, 1969, Gour and Saxena, 1970 and Saxena and Saxena 1974) developed a new sonic probe plasma diagnostic technique in which characteristics of ion-sound waves in plasma played a most important role. Related theories were also developed. These diagnostic studies involve transmission of sonic and ultrasound waves (externally excited by transducers) through a plasma slab sandwitched by the unionized medium. Due to reflections at the plasma neutral gas interfaces the sonic waves get attenuated and from the knowledge of this attenuation much information on plasma parameters was obtained. This new diagonistic technique is somewhat similar to the microwave technique (Heald and Wharton, 1965), but instead of microwaves, sonic signals are employed to explore the ionized medium. Propagation of sonic signals through plasma was first studied by Champion(1962). He used an arrangement where an ultrasonic wave of variable frequency was launched by an ultrasonic transducer in one end of a r.f. excited plasma. The signal was received by a receiver at the other end.

The theoretical analysis of this experiment was available when Surdin (1962) who studied the sonic propagation at frequencies both below and above ion plasma frequency profounded his theory which we had already discussed. The principal drawback of this analysis is that all the constituent particles of the plasma were assumed to be in thermal equilibrium ($T_e = T_i = T$) which cannot be conceived at least in the case of ordinary discharge plasma. While the detailed report of the unpublished work of Champion is not available to the present author, the experiment of other authors in this line may be discussed. As mentioned earlier, the main principle underlying these experimental techniques is that the transmission of a plane acoustic wave from air into loss less plasma and into air again is studied. Due to reflections which occur due to change of acoustic impedance (product of the gas density and the sonic speed) the wave encounters at the plasma-neutral gas interfaces, the transmitted waves are found to get attenuated. For a fully ionized plasma clearly, the attenuation depends on the phase velocity of ordinary sonic wave and that of ion acoustic wave; this means, the amount of attenuation contains informations on plasma parameters.

Following this guideline, Bhatnagar (1964) presented a method (theoretically) in detail in determining electron and ion temperatures (T_e and T_i) of a plasma. The temperatures T_e and T_i were evaluated from measured values of relection coefficients of the sonic waves at the plasma - neutral gas interfaces for two frequency regions; one a low frequency and the other a high frequency compared to the electron - plasma frequency. The formula relating T_e and T_i with the reflection coefficients were derived from the single fluid model of a plasma with certain simplifying assumptions. Later the formula was modified in the case of plasma slabs. Saxena and Gour (1969) on the other hand obtained the ratio of the pressure amplitude of the incident wave (A_1) to that of the transmitted wave (A_3) for the propagation of sonics through plasma slab from some what simpler considerations (Kinsler and Fray). The formula was given by $A_3/A_1 = \frac{4r}{(r+1)^2}$ where 'r' is the ratio of the characteristic impedance of the plasma and air. To compute the characteristic impedance the knowledge of the sonic speed through these two mediums was necessary. Sonic speed in the plasma medium was taken to be equal to

$$\left[\gamma K\,(T_i + Z\,T_e)/m_i\right]^{1/2}$$

where Z is the ionic charge. This is the speed of the ion waves (Venkatarangan,1964) for a non isothermal plasma medium. The above equation involving ratio (r) of the characteristic impedances of the medium was indicated to yield electron temperature. In their experiments sonics (1 - 40 KHz) were transmitted through a particularly ionized glow discharge plasma in a vacuum chamber. The sonics were produced by an audio-oscillator, feeding a small loudspeaker kept in the vacuum chamber at right angles to the discharge column. The transmitted signal was detected by a small microphone. The output was measured by a galvanometer/VTVM/CRO after due amplifications of the signal. The propagation of sonics through plasma resembled in many respects that of microwave propagation. A preliminary report of the estimated electron temperature was also given. Following the same experimental procedure and with minor modifications, an experimental study (Gour and Saxena,1970) of the variations of attenuation of acoustic signal through a discharge plasma with the applied potential showed a minimum at the state of the plasma when $\omega = \omega_{pi}$ where ω_{pi} is the ion plasma frequency (ω_{pi} changes with applied potential through a change in electron or ion density n_{io}). Beyond this frequency the attenuation increased asymptotically indicating the transition of the plasma from the state of transparency to to opacity. The variation of the percentage of attenuation with the acoustic frequency was found to be an oscillatory function and the amplitude of this function showed a regular decrease with the increase in the applied voltage of the plasma. The experiment thus suggestss a method for determining ion density of a plasma. Later Saxena and Saxena (1974) made a comparative study of the sonic probe and the Thomson - Malter (1950) double probe technique under the same experimental conditions by determining the electrons temperature in a weekly ionised plasma produced in a vacuum chamber (Rivin 1962). A fair agreement in the results obtained by these two methods was observed. It was also indicated that the sonic probe technique proved to be a very sensitive device for exploring weekly ionized plasma as compared to double probe. The above authors had considered theoretically the case of a fully ionised plasma. But if the ionization is weak as in the case of ordinary laboratory plasma the theory should be modified by two major factors -

(a) Due to the presence of large neutral background the expression of the phase velocity of ion wave obtained earlier should be modified and

(b) since the elasticity of the ion fluid greatly differs from that of the neutral particle species, the wave in a weekly ionised plasma should not be described by waves having a single propagation constant. Secondly a number of papers both theoretical and experimental 'Ingard 1966, Schultz and Ingard 1969, Ishida and Idehara 1973, Sakuntala and Jain 1978) are now available which proclaim the change of phase velocity of the pure acoustic mode through the neutral particles in a plasma, due to energy transfer from the charged particles to the neutrals. When sonics are generated by transducers, this pure acoustic mode cannoth be ignored in the case of partially ionized plasma. Ingard et al (1966) have derived the dispersion relation for this wave theoretically taking the modification due to charged particles into account andh have shown that thiswx wave may be driven unstable under certain conditions if the electrons are maintained at a higher temperature than the neutrals. Experimental evidence to support this fact is also available (Fitare and Mantei 1972). However, Kaw (1969) pointed out that the increase of equilibrium temperature due to the energy transfer from electrons to neutrals must not be neglected. The verification of Kaws theory i.e., the effect of increased equilibrium temperature of the neutrals on the propagation of sonic wave through plasma is available after Ishida and Idehara (1973) and due to Sakuntala and Jain (1978). Ghosal and Sen (1976) had derived the general wave equation and the dispersion relation using the macroscopic variables of plasma $\vec{U}, \vec{J}, \rho, P$ etc) and made an unified treatment of the subject as a whole for a non-isothermal plasma taking the effect of collisions of the charged species with the neutral particles and then obtained from the general dispersion relation the phase velocity and attenuation constant of ion acoustic waves at frequencies much below the ion plasma frequencies. From these equations of motion the wave equation in '$\mathfrak{p}$' (the macroscopic pressure perturbation) and the corresponding dispersion relation had been obtained by Ghosal and Sen (1976). The dispersion relation shows that the propagation constant has four roots of which two correspond to two distinct modes of propagation in the positive direction and the other two corresponding to two modes of propagation in the negative direction. Considering the ~~ir~~ frequency region much below the ion plasma frequency it has been observed that one of the roots which is a ~~s~~ solution of the particular mode of the general equation corresponds to a sonic speed which closely simulates the Tonks - Langmuir speed for ion acoustic~~s~~ wave and shows a considerable dispersion and damping. The solution indicates however that both the dispersion and the damping can be reduced either by increasing the percentage of ionization or by lowering the background pressure. The phase velocity V_p and attenuation χ'' derived by Ghosal and Sen (1976) are

$$V_p^2 = \frac{\omega^2}{\chi'^2} = \frac{\dfrac{2\gamma K (T_i + T_e)}{m_i}}{1 + \sqrt{1 + V_{Pa}^2/\omega^2}} \tag{1.31}$$

$$\chi''^2 = \frac{\left(\sqrt{1 + V_{Pa}^2/\omega^2} - 1\right)}{2\,\dfrac{\gamma K (T_i + T_e)}{m_e}} \cdot \omega^2 \tag{1.32}$$

where T_e and T_i are electron temperature and ion temperature respectively and ω is the plasma frequency.

The above equation for phase velocity of ion acoustic wave can be compared to that obtained by Bhatnagar and Shrivastava (1971) who considered fully ionized plasma and obtained the expression for phase velocity as

$$V_p^2 = \gamma K (T_i + T_e)/m_i \tag{1.33}$$

From the above relations it is easily seen that when ν_{pa} (affective plasma neutral collision frequency) $\longrightarrow 0$

$$V_p^2 \simeq \frac{\gamma K (T_i + T_e)}{m_i} \quad \text{and} \quad \chi'' = 0 \qquad (1.34)$$

as obtained by Bhatnagar and Srivastava (1971). Further it can be noted that keeping the percentage of ionization constant if the pressure is reduced, the assumption made by Ghosal and Sen (1976)

ν_{ia}', $\nu_{ea} << \omega_i^2$ (where ω_i is ion plasma frequency) becomes more valid and if the value of ω which usually lies in the sonic range be such that $\nu_{pa}^2 << \omega^2$, the phase velocity is found to be given by

$$V_p^2 \simeq \frac{\gamma K (T_e + T_i)}{m_i}$$

the wave shows no attenuation. Thus it is evident that both dispersion and damping of ion acoustic waves can be reduced in two ways: eiąher by increasing the percentage of ionization or by lowering the gas pressure.

It is further pointed out by Ghosal and Sen (1976) that in discharge plasma $T_e \gg T_i$ and neglecting, T_i it is possible that both electron temperature and the plasma neutral collision frequency can be calculated by measuring phase velocity and attenuation constant. The usefulness of the analysis for a sonic probe to obtain the plasma parameters had been discussed by Ghosal and Sen (1976).

Ghosal and Sen (1977) had treated theoretically the problem of transmission of sonic waves through a weakly ionized plasma bounded in each side by a neutral gas medium by assuming the plasma to be a mixture of two intermingled fluids i.e. neutral particle fluid and ion fluid in equilibrium. From a hydrodynamic analysis the wave equation for 'p', the macroscopic pressure perturbation has been obtained; it is shown that two independent wave motions one due to neutral particles and the other due to ions are propagated through the plasma with two different phase velocities. Assuming the usual boundary conditions at the interface, the amplitude of the transmitted wave has been calculated in case of weakly ionised plasma. The theory can be utilized for the determination of electron temperature from the measured value of attenuation if the percentage of ionization and collision cross section can be obtained independently. Ghosal and Sen (1977) had shown that if the fluid 'a' represents the background neutral particle fluid and the fluid 'b' represents the charge particle fluid or simply ion fluids, it can be written $\rho_b = \rho_i = \alpha\rho$ where α x 100 is the percentage of ionization and

$$\rho_a = (1-\alpha)\rho_1 \tag{1.35}$$

$$C_1 = V_a = \sqrt{\frac{\gamma K T}{m}} \tag{1.36}$$

$$C_b = V_i = V_b = \sqrt{\frac{\gamma K T_i}{m}} \tag{1.37}$$

$$Z_{1a} = \frac{1}{1-\alpha}, \quad Z_{ab} = \frac{(1-\alpha)}{\alpha}\sqrt{\frac{T}{T_i}}, \tag{1.38}$$

and $\quad \varkappa_b = \varkappa_i \dfrac{\omega}{V_i} \quad$ and $\quad \varkappa_a = \omega / V_a$

Thus for a rarefield gas the process of measurement of the electron temperature seems to be straighforward but in general we have to take into account the effect of δ_{pa} which is given by (Ghosal and Sen 1976)

$\nu_{pa} = \nu_{ea} + \nu_{ia}$ where ν_{ea} and ν_{ia} are the effective electron neutral and ion neutral collision frequencies. In terms of mean free path ν_{pa} is given by

$$\nu_{pa} = \sqrt{\frac{3KTe}{me}}\left(\frac{1}{\lambda_{ea}}\right) + \sqrt{\frac{3KT}{m}}\left(\frac{1}{\lambda_{ia}}\right) \qquad (1.39)$$

If the collision cross sections are assumed independent of particle energies and are known before hand, the mean free paths λ_{pa} and λ_{ia} can be calculated in terms of gas pressure and collision cross sections. Thus from the knowledge of T_i , T_e, the electron temperature can be determined. In any case however, it is necessary to know the percentage of ionization (α x100%). Ghosh and Sen (1984) had arranged an experimental set up to determine the plasma parameter by sonic wave through an ionised gas. By measuring the attenuation constant of a propagatory sonic wave through ionised air at different discharge currents varying from 1 mA to 8 mA and taking the values of the electron temperature for different (E/P) values from literature, the ion atom collision frequency, drift velocity, mobility and ion atom collision cross section have been obtained utilising the dispersion relation of ion acoustic waves at frequencies much below the ion plasma frequency as earlier deduced by Ghosal and Sen (1976). The values are consistent with literature values and the drift velocity had been found to be proportional to $(E/P)^{1/2}$ as calculated by Sena (1946).

Ghosal and Sen (1976) have derived the general wave equation and dispersion relation using macroscopic variables of the plasma and have provided a uniform treatment of the subject for a non-isothermal plasma taking the effect of collision of charged species with the neutral particles. Further it has been possible to obtain from the general dispersion relation the attenuation constant of the plasma when a sonic wave propagates through it. The attenuation constant is given by

$$\alpha_p^2 = \frac{\left[1 + \dfrac{\vartheta_{pa}^2}{\omega^2}\right]^{1/2} - 1}{\dfrac{2\gamma K(T_e + T_i)}{m_i}}\,\omega^2$$

where γ is the adiabatic gas constant, K Boltzmann constant, T_i the ion temperature, T_e the electron temperature, mi the mass of the ion, ν_{pa} the effective ion atom collision frequency and ω the frequency of incident sound wave.

It has been suggested by several authors that the study of acoustic wave propagation may lead to a diagonistic method for measuring plasma parameters.

Ghosh and Sen (1984) have measured the attenuation constant of a propagating sound wave through an ionised gas launched from an external source of sound. From the equation derived by Ghosal and Sen (1976) it is evident that if T_e the electron temperature is obtained from an independent measurement and if it is assumed that T_i to be equal to gas temperature which is valid in case of a gas discharge carrying small currents of the order of few milliamperes (von Engel, 1965) then the collision frequency ν_{pa} can be obtained from the measured value of α_p

Ghosh and Sen (1984) had used an experimental set up which consists of a discharge tube with hollow cylindrical brass electrodes. These electrodes are used to excite the discharge.

The discharge tube is fitted at one x end with a loud-speaker which is energised with a audio frequency generator. The loudspeaker acts as a source of sonic waves. At the other end a microphone is fitted to receive the audio signal. Both the loudspeaker and the microphone are fixed to the wall of the discharge tube through a sponge like material in the form of foam which effectively dampens the propagation of sound; so that no propagation of sound is possible through the body of the discharge tube. This was further tested by evacuating the discharge tube to a high degree of vacuum when it was observed that even for high input audio frequency voltage, the output at the receiver was too low to be detected. The output of microphone has been detected by an a.c. microvoltmeter and then connected to an oscilloscope which indicates whether any distortion in the wave shape has occurred during propagation. The discharge was excited by a transformer. Pure and dry air was passed through phosphorous pentoxide and calcium hydroxide to remove traces of water vapour. The pressure inside the tube was measured by a vacouscope. Initially the discharge tube was evacuated to a pressure of 0.2 torr and without exciting the discharge the attenuation for air at that pressure was measured. Similar observations have been taken for discharge currents varying from

1 mA to 8 mA. The experiment has been performed for two audio frequencies namely 360 cycles/sec and 460 cycles/ sec.

From the results obtained by Ghosh and Sen (1984) it can be observed that the values of ν_{pa} the ion atom collision frequency obtained by measurement of attenuation of sonic waves through the ionised gas, it is possible to obtain drift velocity, mobility and collision ~~x~~ cross section of ions with neutral molecules. The values thus obtained by Ghosh and Sen(1984) and their variation with (E/P) are consistent with literature values. It is thus observed that sonic probe method is a useful diagonistic tool in determining ion atom collision frequency from which it is possible to obtain ~~dx~~ drift velocity, mobility and ion atom collision cross section. Since it is extremely difficult to measure experimentally the drift velocity of ions at low (E/P) values, the technique is particularly useful to obtain drift velocity and mobility specially for low values of (E/P). The method is particularly applicable where the collision of plasma particles with neutral atoms and gas moleculea has to be taken into consideration.

Saxena and Suryanarayana (1982) have measured the electron temperature in high frequency (HF) discharges by using sonic probe technique. The results are compared with those obtained by the double probe technique.

The sonic probe method has been utilized mostly in case of d.c. discharges. In high frequency plasmas the electrons move in long trajectories through a positive space charge. The retarding forces are small with little disturbance of the electron energy distribution. Determination of the discharge parameters is of importance and specially for a comparison with the results obtained with a sonic probe and a double probe.

The experimental arrangement made by Saxena and Suryanarayana (1983) consists of a discharge tube of pyrex glass tube (40 mm dia. and 250 mm. long) and the discharge was produced by applying the output from a 25 W, 20 MHz oscillator to two aluminium strips 35 mm. apart. Two copper wire probes 0.1 mm. ~~tm~~ ~~d~~ in diameter separated by 10 mm and with an exposed length of 2 mm were inserted in the centre of the discharge.

A low pass filter was used in the probe circuit. A pair of identical loudspeakers, 50 mm in diameter were placed at both ends of the tube to act as the source and detector. The tube was evacuated with a rotary pump via a trap; a Maclead gauge was used to measure the pressure.

A signal from an audio oscillator which had a frequency range from 3 to 15 KHz was amplified and fed on to one of the loudspeakers. The sound wave travelled first through air then through the plasma, then again through air before reaching the detector loudspeaker. The amplified output from the detector was measured with an a.c. microammeter. A measure of the average electron temperature can be calculated from the amplitude of the detector signal without the plasma (A_1) and the amplitude (A_3) with the plasma. The attenuation (A_3/A_1) is plotted against the signal frequency for air pressures of 0.1 and 1.2 torr.

The attenuation and the reflection at the plasma boundaries depend upon the path length and the frequency of the waves. These parameters determine whether the wave transmitted across the air-plasma interface reinforces or reduces the wave amplitude reflected into the plasma from the plasma-air interface. Hence the attenuation (A_3/A_1) of the signal by the plasma will be an oscillatory function of the transmitted signal and will depend upon the gas pressure.

The values of T_e calculated from the I - V characteristics of the double probe are about 10% higher than the average value of T_e obtained from the measured value of the attenuation.

The constancy of T_e for different E/P was explained by Saxena and Suryanarayana. Electrons gain energy through an electric field and lose it by colliding with neutral molecules or atoms. From the assumption that the ratio of the drift velocity of the electrons to ~~be~~ the random velocity is proportional to the square root of the energy loss factor it can be shown that (von Engel 1955)

$$T_e = E/P \frac{\lambda}{\sqrt{2k}}$$

where T_e is the electron energy in V, E the electric field in V cm^{-1}, p the pressure of the gas in torr, λ the mean free path at 1 torr and K is the average fraction of electron energy lost in one collision. This equation is applicable in a limited range of E/P values. The constancy of T_e with increase in E/P indicates that K also increases with increasing E/P which is so because the number of ionising ~~d~~ collision increases.

The increase in electron (ion) density with increase in E/P (or decrease in p as in the present case) is shown graphically by Saxena.

The relation between v_r and v_d , the random and drift velocities along with the field direction is given by the following relation (Nasser, 1971)

$$v_r / v_d = 1{\cdot}44 / \sqrt{K}$$

Constancy of T_e as explained by Saxena indicates that if the distribution is taken as Maxwellian, the distribution of v_r is not affected by a change in E/P. Increasing E/P increases only the average energy loss factor. The increase in K leads to an increase in v_d and n_e

Since the electrons are lost mainly by diffusion in the discharge under study, the expressions mentioned above are applicable to a certain range of pressure and frequencies only.

(D) EFFECT OF CAPACITOR BANK DISCHARGE ON LOW TEMPERATURE PLASMA

Electrical and optical technique have been extensively utilized in analysing the complex phenomeaa associated with the various phases of wire explosion. Medved and Turnbull (1962) had introduced a diagnostic technique for monitoring the dynamics of an exploding wire. The method consists of measuring the microwave propagation characteristics of the $T\text{-}E_{10}$ mode in a wave guide in which the wire to be exploded is perpendicular to the $T\text{-}E_{10}$ mode electric field vector. Medved et al observed that in the course of these measurements there occurs an appreciable amount of microwave attenuation approximately of the order of 1.0 dB during the dwell time.The experimental arrangement made by Medved et al consists of a wave guide containing the wire as part of a microwave circuit in which the reflected and transmitted wave amplitudes are monitored. The entire wire exploding device consisting of spark gap trigger wire and wave guide holder is mounted on the top of a 0.1 μF capacitor directly. A coaxial current path to minimise parasitic inductance is obtained by mounting the spark gap trigger directly over the negative terminal of the capacitor. The wire holding device is directly above the gap and provision is made for feeding the wire through the narrow face of a K band wave guide by means of a plexiglass insulating bushing. The three inch diameter aluminium coaxial cylinder enclosing the apparatus serves to support the wave guide as well as provide the current return. Current and voltage measurements simultaneously with the micro wave reflection and transmission are obtained by utilizing an inductive probe and capacitive voltage divider respectively. The results were obtained with a wire 2.5 cm. long into which approximately 5 J are dumped in 0.2 μ sec.

Aycoberry et al (1962) had studied pinch effect of Metal plasma obtained by exploding wires. A 1 μF, 100 KV capacitor was discharged through a thin metallic wire. The ringing frequency was 200 KC/Sec. observation of the exploded wire showed a pinch effect during the first micro seconds. Oscilloscope was used to record current and voltage. The approximate temperature reached at the time of the first maximum pinch is estimated.

Iguchi and Kawamada (1967) had x developed techniques of streak photography for observing temporarily produced plasma. The beams of light emitted from a plasma in two directions and those from other luminous bodies are observed simultaneously with a streak camera by reflecting beams with some mirrors. The intense beam of light from the exploding wire is utilized as a time marker for high speed photography. In the study of exploding wire phenomenon an electrolytic capacitor of large capacitance 400 to 500 μF is charged upto several hundreds of volts was used as the source of energy.

W. Erb (1969) observed by X-ray flash and streak camera pictures the expansion velocity of the discharge plasma. Within a short time after the explosive vaporization (burst) the expansion velocity obtained by measurement of X-ray flashes and high speed photographs differ by a factor of 2. The deviation becomes greater when diameter of the wire increases and stretches over a wider time range.

Chekalin et al (1969) had investigated the optical and spectral properties of the dense plasma formed by exploding Cu and 'Al' wires in vacuum. High speed film of the process was taken and the time dependence and the electrical properties of the plasma were studied.

Niemeyer (1969) had made an experimental arrangement of exploding wire discharges in high vacuum ($P < 10^{-5}$ torr) Explosion of 0.03 - 0.25 mm. diameter wires of Cd, Al, Cu and W in high vacuum have been investigated. The time development of the discharge column is shown to be determined by two main processes (a) In the time preceding the explosion particles are emitted from the surface of the heated wire and initiate a peripheral discharge. The mechanism of particle emission is found to be evaporation of neutral atoms and/or thermaionic emission of charged particles. The latter process is influenced by the strong radial electric field which is caused by the coaxial discharge geometry at the wire surface.

(b) The wire material vaporizes explosively forming an expanding cloud of non conducting vapour which is subsequently converted to a plasma by the peripheral discharge penetrating into it from outside. The discharge column exhibits instabilities which are shown to be of MHD origin. They are significantly reduced by applying an axial magnetic field to the discharge column. A quantitative spectroscopic investigation is performed during the magnetic contraction phase of stabilized 0.05 mm. 'Al' wire explosions. The plasma temperature is found to be about 50,000^{o}K on the axis of the column and higher than 80,000^{o}K at its periphery. The mean electron density is estimated to be of the order of some 10^{19} cm^{-3}.

Erab et al had (1971) used wires of Ni, Mo, W instead of Cu in exploding wire experiments, results have been obtained on time dependence of current, voltage and resistance and the results have been explained by assuming that additional heat energy is produced by the combustion of these materials. By thermal heating evaporation of metal and electron emission, a conducting layer around the wire is built up.

An experiment was developed by Mc Dermott (1970) which makes possible the simultaneous measurement of the edge on intensity distribution and optical depth of a cylindrically symmetric plasma. The mathematical inversion procedure required to extract the distribution of the absorption and emission coefficients as a function of the radial position within the plasma was explained by Mc Dermott. The method is capable of obtaining these quantities as a function of wavelength over a wide spectral range and provides for resolution of these quantities as a function of time.

The generation of soft X-ray radiationf from wires exploded in a vacuum was first reported by Vitovitsky and Coworkers in 1962. Later Handel Stenerhag and coworkers (1971) found that the hard X-rays were emitted from exploding tungsten wires in vacuum. They found that the X-ray pulse emitted was extremely short with a half width of about 20 n sec. and that the emission appeared at the pronounced dip of the current derivative which was observed at the begining of the discharge on the oscilloscopes. Their calculations have shown that the X-ray emission happend near the point where the wire had reached its melting point. The emission of X-ray was explained by Vitkovitsky and Coworkers (1962) as the result of decelerated electrons initially emanated from the early onset of ionization. On the other hand Handel, Stenerhag and co-workers (1971) suggested that in the case of tungsten wires the emission of hard X-rays could be qualitatively explained by using a model based on thermoionic electron emission from the wire, a suggestion which is a possible explanation of the phenomenon. However, the above mentioned works are mainly based on studies on the oscilloscope recordings of the current derivative and the X-ray output converted to current pulses, using a scintillation crystal and a photomultiplier. Bennett (1968) in a review article has pointed out that the photographic methods are of great importance in performing exploding wire experiments. One of the reasons is that the phenomenological description of the different phases of exploding wires seems as yet to be incomplete. Vlastos (1973) agrees with Bennett and therefore in previous works done on exploding lithium, copper and constantan wires a rotating mirror streak camera and two Kerr-cell shutter cameras with short exposures were used to record the shape and development of the exploding wires. Working along the same lines, Vlastos (1973) has investigated the duration times and the initiation mechanism of the restrikes of thin tungsten wires exploded in air and came to the conclusion that the restrikes of the tungsten wires are always initiated at the exterrior wire, a fact which explains the short dwell times of these wires at high voltages.

The experimental arrangement of Vlastos consisted of a capacitor bank with a capacity of 9.6 μF, an inductance of about 26 nH and a resistance of about 13 mΩ The exploding wire gap had coaxial symmetry; 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 a diameter of 70 mm. The wi(re could be mounted in the gap under vacuum by using a specially constructed manipulator, a procedure which reduced the interval between two successive shots to less than 5 min. The gap was evacuated by means of a two stage gas ballast rotary high vacuum pump with a displacement at normal speed of 9 m^3/h a oil diffusion pump with a capacity of 150 liter/sec. The ultimate vacuum of the gap was measured by means of an ionization gauge and was found to be about 5 x 10^{-5} torr. The voltage measuring circuit including the voltage divider, the cable connections and the oscilloscope had an aperiodic response to unit voltage step, a total rise time of about 20 n sec. and a voltage reading accuracy better than 5%. The condenser bank charging voltage was measured by an ammeter connected in series with a resistance of 300 M Ω $\pm$ 2%. The current measuring circuit consisting of a Rogowsky coil and a passive RC integrator, had a total rise time including the oscilloscope of 15 n sec. and a current reading accuracy better than 5%. For the current derivative, a probe with a rise time of about 2 n sec. was used. The rotating mirror streak camera which was synchronized with the voltage and current recordings had a maximum resolution of 2.6 mm/ μ sec. The Kerr-Cell shutter cameras had constant exposure time of 30 and 50 n sec. respectively. The times at which the exposures were taken were determined by means of simultaneous oscillographic recordings of the current and the signals from the monitors of the cameras and by taking into account the time delays introduced.

Vlastos had observed one important fact that thin tungsten wires due to their mechanical or electrical properties produce with comparatively slow condenser banks at already low voltages X-ray radiation of short duration.

Baker (1980) had studied simulation of the burst phase of exploding wires. Baker had used bursting of a 1.5 mm. dia. aluminium wire in both air and vacuum. An external circuit with $R = 77.0 \times 10^{-3}\Omega$ $L = 292.0 \times 10^{-19}$ henry and $C = 2.3 \times 10^{-6}F$ with the capacitor bank is charged to 13 KV. Baker had shown a good agreement between the observed and computed current and voltage traces, upto the time of burst for a number of different wire materials and diameters. After burst there are deviations which are attributed to two mechanisms. First the assumption that the plasma independent of the axial coordinate breaks down at this time and a two dimensional simulation might be necessary to proceed further. The model of resistivity may breakdown and a carrier-limited conduction regime might set in.

(E) HALL EFFECT IN AN ARC PLASMA

When a magnetic field is applied perpendicular to a conductor carrying current, a voltage is developed across the specimen in the direction perpendicular to both the current and the magnetic field. This phenomenon is called the Hall effect.

In an external electric field "E_0" along the axis of a specimen electrons will drift in the opposite direction. If we apply a magnetic field "H" perpendicular to thex axis of the specimen, the carrier will experience Lorentz force and tend to be deflected to one side. The surface charge then will give rise to transverse electric field "E_H" called the Hall field which causes a compensating drift such that the carriers remain within the specimen and in equilibrium. The force due to Hall field "E_A" on the electrons exactly balances the Lorentz force.

Let us consider an infinite specimen with total electric field "E_0". For a uniform steady state the Boltzmann equation in the relaxation time approximation can be written as

$$\frac{\partial f}{\partial P} F \frac{f - f_0}{T} = 0 \qquad (1.40)$$

because the derivative of distribution function 'f' with respect to position and with respect to time vanishes. The force "F" now includes a magnetic as well as an electric force and is given by

$$F = -eE_0 - \frac{e}{c}(v \times H) \tag{1.41}$$

The distribution function can be written to a first approximation

$$f = f_0(\bar{n}) + f_1 \tag{1.42}$$

where $f_0(\bar{n})$ is the equilibrium distribution function based on the average electron density (it is not function of position) and f_1 is the deviation from this equilibrium. Substituting (1.42) and (1.41) in (1.40) we have,

$$\frac{\partial f_0}{\partial E} v\left(-eE_0 - \frac{e}{c} v \times H\right) + \frac{\partial f_1}{\partial P}\left(-eE_0 - \frac{e}{c} v \times H\right) + \frac{f_1}{\tau} = 0 \tag{1.43}$$

The first term in magnetic field $v \cdot (v \times H)$ is zero and the term in electric field $eE_0 \frac{\partial f_1}{\partial P}$ is second order term hence may be dropped.

The equation (1.43) becomes

$$-e\frac{\partial f_0}{\partial E} V E_0 - \frac{e}{c}\frac{\partial f_1}{\partial P}(V \times H) + \frac{f_1}{\tau} = 0 \tag{1.44}$$

We cannot simply solve for the first order distribution function. One way to solve is to note that the effect of the magnetic field roughly speaking is to rotate the distribution. We therefore, try to form in analogy with that obtained in conductivity calculations but with electric field replaced by a general vector G which will be determined, i.e., we assume

$$f_1 = e\tau \frac{\partial f_0}{\partial E} V . G \tag{1.45}$$

Derivating f_1 with respect to P assuming P = mV

$$\frac{\partial f_1}{\partial P} = e\tau\left\{\frac{G}{m}\frac{\partial f_0}{\partial E} + \frac{\partial^2 f_0}{\partial E^2}(V.G)V\right\} \tag{1.46}$$

Substituting (1.46) in (1.44) we have

$$-e\frac{\partial f_0}{\partial E}(v.E_0) - \frac{e\tau}{c}\left\{\frac{G}{m}\frac{\partial f_0}{\partial E} + \frac{\partial^2 f_0}{\partial E^2}(v.G)v\right\}(v \times H)$$

$$+ e\frac{\partial f_0}{\partial E}(v.G) = 0$$

Since $v.(v \times H)$ is zero and cancelling the factor $\left(-e\frac{\partial f_0}{\partial E}\right)$ we have

$$v.E_0 + \frac{e\tau}{mc}G.(v \times H) - v.G = 0$$

or

$$v.\left\{E_0 + \frac{e\tau}{mc}(H \times G) - G\right\} = 0$$

As $G.(v \times H) = v.(H \times G)$

We note that this will be a solution for all values of V if and only if

$$E_0 = G - \frac{e\tau}{mc}(H \times G)$$

(1.47)

In absence of magnetic field the current density $I = \sigma E_0$ where σ is the electrical conductivity of the specimen. Thus we have

$$E_0 = G = I/\sigma$$

Thus we may write the electric field interms of the current in the form

$$E_0 = \frac{I}{\sigma} - \frac{e\tau}{mc\sigma}(H \times I)$$

(1.47A)

The second term is a component of the electric field which is transverse both to the applied magnetic field and to the current which is Hall field "E_H". Thus

$$E_H = -\frac{e\tau}{mc\sigma}(H \times I) \qquad (1.48)$$

The proportionality constant is called the Hall constant and its magnitude is given by

$$R = \frac{(-e)\tau}{m c \sigma} = \frac{1}{n(-e)c}$$

The study of Hall Effect was extended to positive column of glow discharge.

The effect of a transverse magnetic field on the positive column of a glow discharge has been studied by Beckmann (1948). It was shown that the magnetic field deflects the column towards the wall with the result that the total loss of electrons and ions increased. This causes an increase of electron temperature and in the axial field strength. Formulae relating the axial electric field, the magnetic field and the electron temperature was derived as well as equations describing the electron density distribution

$$N = N_o \ \exp. (-Cr \cos \phi / 2 D_a) J_0 (\eta_r / r_0)$$

The above equation describes the electron density distribution.

The positive column was uniformly deflected towards the wall along the whole length of the tube. The anode glow was also influenced by the magnetic field and it is possible that the observed change in axial field was partly due to variations in the anode fall. The general effects of the transverse magnetic field have been investigated by Mc Bee and Dow (1953) in an unconfined glow discharge in air, within the pressure range 0.3 - 10 torr discharge current 0.05 - 2.5 A with the magnetic field varying from zero to 7000 G. They found with probe measurements that the anode and cathode fall first decrease and then increase and the positive column and the anode region become more luminous.

Sen & Gupta (1971) had studied variation of discharge current in a transverse magnetic field in a glow discharge. The variation of discharge current in a transverse magnetic field (0 - 300 G) has been studied in the positive column of a glow discharge in air, carbon dioxide, hydrogen, helium and neon within the pressure range of 80 to 200 m torr. The current gradually rises with the increase of the magnetic field, then attains a maximum value at a particular value of the magnetic field which is same for all the gases and independent of pressure for the same initial discharge current then gradually decreases. The value of the magnetic field at which the discharge current is maximum is found to be proportional to the square root of the initial discharge current and the maximum value of the current is inversely proportional to pressure in all the gases; utilizing Beckman's expression for the axial electric field and the radial electron density distribution in a transverse magnetic field, a mathematical expression for the discharge current and its variation with magnetic field was deduced by Sen and Gupta (1970). The theoretical results are in qualitative agreement with experimental observations and the causes of discrepancy have been attributed to

(a) limitations of Beckman's expression for electron density distribution and axial electric field

(b) absence of data for fraction of energy loss in collision and that of the electron temperature at E/P values at which observations are made by Sen and Gupta (1971). Effect of transverse magnetic field on an arc discharge was first observed by Allen in the case of heavy current pulsed arc discharge in hydrogen and the voltage current characteristic showed a slight negative gradient over the range of 25 to 80 amperes with no magnetic field but became increasingly negative with increase of magnetic field.

Forrest and Franklin (1966) had developed a theoretical model for the behaviour of the positive column of a low pressure arc discharge in a magnetic field. The model is applicable to free fall conditions in which ions are assumed to fall freely from their point of generation under the influence of a radial electrostatic potential gradient.

For the case of a cylindrical plasma column predictions are made for the variation with magnetic field of radial electron number density profile, radial potential profile, number density, electron temperature and radial light emission profile. The constriction of a plasma column in a magnetic field is considered and predictions from the above model are compared with measured radial light emissions profile from a mercury discharge.

The Hall effect in gaseous plasmas has received little experimental attention upto 1962.

Klein (1962) has first measured Hall electromagnetic force in air. An experiment was reported in which an induced Hall electromagnetic force in air was measured in a shock tube. Agreement was found with theory for values of the product of the electron cyclotron frequency and the mean collision time for electrons over a gas temperature of 3000° to 4200°K. The theory is based upon a mean collision time for electrons that is determined solely by electron neutral particle collisions and an ohm's Law that is valid for slightly ionized gases. The induced Hall electromagnetic force is theoretically independent of the electron concentration of the shock heated air. The experiments thus provide a technique for determining the collision time that does not depend upon the establishment of equilibrium.

Klein (1962) had considered a shock tube geometry and had applied both an externally applied radial magnetic field and externally applied axial magnetic field since the gas velocity V is perpendicular to the radial magnetic field, there will be a current induced in the V X B on azimuthal direction. This current was referred as j_0 Hall electromagnetic force is theoretically a function of $\omega \tau_e$ i.e. the product of electron cyclotron frequency and the electron mean collision time.

When $\omega \tau_e$ is non zero, a potential known as the Hall potential is induced in the $j \times B$ direction. The following current equation was arrived

$$j + \omega \tau_e \frac{j \times B}{B Z} = \sigma (E + V \times B)$$

ω is the cyclotron frequency of the electrons based on the "Z" component of magnetic field and τ_e is the mean collision times for electrons with neutrals. The gas conductivity σ is given by

$$\sigma = n e^2 \tau_e / m_e$$

where n is the electron density

e is the electronic charge

m_e is the electron mass.

Due to the experimental geometry the only current that can flow is j_θ . There is no way for currents to close in the flow direction, except in the boundary layer and such currents were neglected by Klien. Considering the radial and azimuthal components

Radial
$$\omega \tau_e (1/BZ) j_\theta B_Z = \sigma E_r$$

Azimuthal
$$j_\theta = \sigma V_Z B_r$$
$$E_r = \omega \tau_e V_Z B_r.$$

The above equation says that the potential induced in the $j \times B$ direction the Hall potential per unit radial magnetic field will be directly proportional to the gas velocity V_Z and to $\omega \tau_e$. Therefore, by measuring E_r and the gas velocity for given magnetic fields one has a direct measure of $\omega \tau_e$ Since $\omega = e B_Z / m_e$ depends upon the constant e/m_e and the magnetic field B_Z the Hall potential measurement is a direct measurement of τ_e the free time between collisions of the electron in the slightly ionized gas mixture.

The above equation of Hall potential E_r predicts independent electron concentration, i.e., one ~~xx~~ can measure τ_e directly without waiting for thermodynamic equilibrium to be established in the gas.

Anderson (1964) had observed Hall effect in the plasma of the positive column established in the rare gases and nitrogen at gas pressures $\sim$ 1 torr. Anderson ignored magnetic resistance effect which is second order in B and also alternation of the mean electron temperature with increasing magnetic field was considered negligible. Redistribution of electron and ion density in the transverse cross section of the discharge column upon application of the magnetic field may not be disregarded however since this contributes markably to the net Hall potential which develope across the column.

Starting with the general Boltzmann equation for a gas of charged particles in much denser gas of neutral particles many simplifying assumptions were made which are consistant with the experimental conditions. Electron - electron and ion-ion collisions are ignored, the pressure tensor is determined for an isotropic velocity distribution in a frame of reference drifting with the charged particles, drift velocity is assumed small compared to random velocity and the gravitational potential is neglected. Charged particles are formed by gas ionization with their momentum randomly oriented and thus make no contribution to the Boltzmann collision integral in the momentum balanced equation. Finally in the stationary state, the time derivative of the drift velocity is assumed zero. The 'i' component of electron particle flow is found to be

$$\Gamma_i = \left(n/m\bar{\nu}_m\right)\langle F_i\rangle - \left(1/\bar{\nu}_m\right)\nabla_i \left(n\left\langle \frac{1}{3} v_r^2\right\rangle\right)$$

where

$$\Gamma_i = n\langle v_i\rangle = \int_{-\infty}^{+\infty} v_i f\, dv$$

and

$$\bar{\nu}_m = -\left(\int_{-\infty}^{+\infty} m v_i \left.\frac{\partial f}{\partial t}\right|_c dv\right)\left(\int_{-\infty}^{+\infty} m v_i\, dv\right)^{-1}$$

where $\bar{\nu}_m$ is the momentum transfer collision frequency, v_r is the random electron velocity, 'f' is the distribution function ~~and~~ and $(\partial f/\partial t)_c$

pertains to alteration of 'f' by collisions. Also the force term

$$n \langle F_i \rangle = e \int_{-\infty}^{+\infty} E_i f \, dv + e \int_{-\infty}^{+\infty} (v \times B)_i f \, dv$$

yields

$$e E_i + e \left[\langle v \rangle \times B \right]_i$$

Since B and E are independent velocity. The flow equation for one species of charged particle is then

$$\Gamma = - D \nabla n + n \mu \left(E + \langle v \rangle \times B \right)$$

D = diffusion coefficient = $\left(1/\bar{\nu}_m \right) \langle v_r^2/3 \rangle$

and the mobility $\mu = e/m \, \bar{\nu}_m$

as independent of position in the plasma. The subscripts e and p will be used to designate quantities describing electrons or ions respectively.

The immediate interest is a formulation of particle flow transverse to axis of the plasma column. For this case the transverse flows Γ_e and Γ_p must be equal if the discharge container walls are not conducting and

$$\nabla \cdot \Gamma_e = \nabla \cdot \Gamma_p = n_e \nu_i$$

where ν_i is the rate of ionizing collisions. Eliminating E for Γ_e and Γ_p and applications of divergence operator gives

$$\mu_e n \nu_i = -\left(D_p \mu_e + D_e \mu_p\right) \nabla^2 n - \mu_e \mu_p \nabla\left[n \langle v \rangle_e \times B\right]$$

The subscripts "e" and 'p' are not considered for "n" since quasi-neutrality, $n_e \cong n_p$ is assumed. Also $\mu_e \gg \mu_p$ and thus $\langle v_p \rangle \times B$ is neglected.

The drift velocity $\langle v_e \rangle$ and B are approximately independent of position in this experiment which allows

$$\nabla \cdot \left[n \langle v_e \rangle \times B \right] = \left[\langle v_e \rangle \times B \right] \cdot \nabla n$$

A general differential equation for charge density then becomes

$$\left[D_p + D_e (\mu_p / \mu_e) \right] \nabla^2 n + \mu_p \left(\langle v_e \rangle \times B \right) \cdot \nabla n + n \upsilon_i = 0$$

Proceeding to cylindrical coordinates (r, ϕ, z) and applying 'B' in the $r\phi = 90^\circ$ direction

$$\partial^2 n / \partial r^2 + (1/r + A \cos \phi)(\partial n / \partial r) + (1/r^2)(\partial^2 n / \partial \phi^2) - (A \sin \phi / r)(\partial n / \partial \phi) + C_n = 0$$

The discharge maintainance current density is $n_e \langle v_z \rangle$
The solution of above equation was found by Beckmann,

$$n = n_0 \exp\left(-\frac{1}{2} A r \cos\phi\right) R(r)$$

where

$$R(r) = J_0\left[\left(C - \frac{1}{4}A^2\right)^{1/2} r\right]$$

$$C = \mu_e v_i \left(\mu_e D_p + D_e \mu_p\right)^{-1}$$

and

$$A = \mu_p \langle v_z \rangle B \mu_e \left(\mu_e D_p + D_e \mu_p\right)^{-1}$$

Previous experiment had verified that the equation does very nearly describe the variation of electron density in a cross section of plasma column.

Various forces on electrons namely Lorentz magnetic force, the electron pressure gradient and the space charge fields to be in equilibrium for directions transverse to the column axis, since no net electron current flows in the external circuit. This balance of forces may be integrated to give potentials

$$-\frac{2}{3}\frac{\bar{U}_n}{e}\int \frac{\nabla n}{n} \cdot de = \int E \cdot dl + \int \left(\langle v_z \rangle \times B\right) \cdot dl$$

where $\bar{v}_c = \frac{1}{2} m \langle v_r^2 \rangle$

after integrating to $\pm r_0$, the column walls of the expression for Hall potential is found. It is valid only in that portion of the column where D and μ are essentially constant and does not strictly speaking apply in the wall sheath. However, Thompson invokes the Bohm criterion for sheath formation (wall directed ion energy at sheath edge is approximately one half the mean electron energy) to show that a nearly constant ratio exists between electron density at sheath edge and at the wall. Thus equal drops in potential across the sheath at each wall ($\pm r_0$) cancel, and the Hall voltage to be measured with wall probes is found from equation,

$$V_H = -\int E \cdot dl = 2 r_0 \cos\phi \left[\left(+ \langle v_z \rangle B - \frac{2}{3} \bar{\upsilon}_e / \bar{e} \right) \frac{1}{2} A \right.$$

If the thickness of the wall sheath is neglected then

$$V_H = 2 r_0 \cos\phi \langle \upsilon_z \rangle B \left[1 - \frac{2}{3} \left(\bar{\upsilon}_e / e \right) \left(\mu_p / 2 D_a \right) \right]$$

where

$$D_a = D_p + D_e \left(\mu_p / \mu_e \right)$$

Strictly there are small contribution by the magnetic field to the sheath potential. The above equation may be further simplified for the plasma of the positive column because $\overline{\upsilon}_e >> \overline{\upsilon}_p$. It is usual to relate to diffusion coefficient to the mobility by

$$D = \mu \left(\tfrac{2}{3} \overline{\upsilon} / e \right)$$

for both the electron and ion gases

$$D_a \cong D_p + D_e (\mu_p / \mu_e) \cdot \mu_p \tfrac{2}{3} (\overline{\upsilon}_e / e)$$

and finally equation of $\vec{\upsilon}_H$ becomes

$$| \upsilon_H | = 0.5 \langle \upsilon_z \rangle B \; 2 r_0 \cos \phi$$

$$(2 r_0 = d)$$

This simple result indicates that exactly one half of the Hall potential expected on the basis of the magnetic term of the Lorentz force is actually measured. The discrepancy is in fact due to an alternation of charge density of the column when the magnetic field is applied.

Thompson calculates the excepted Hall potential for the low pressure case where ion falls freely to the wall (planar discharge walls at $\pm r_0$) and obtains

$$|V_H| = +0.875 \langle v_z \rangle B 2r_0$$

Ecker and Kanne also calculated the low pressure case and found for the planar discharge

$$|V_H| = 0.175 \langle v_z \rangle B 2r_0$$

and for circular-cylindrical column

$$|V_H| = 0.22 \langle v_z \rangle B 2r_0$$

Ecker and Kanne claimed that discrepancy between two $|V_H|$ is due to numerical errors in the determination. They include a contribution by the magnetic field in the wall sheath which is not negligible in the low pressure case.

In the above the particle flow was obtained from the momentum balance equation. Another approach for solution of the Boltzmann equation is dependent upon the assumption that the ordered perturbation to the distribution function is destroyed in each particle collision and the net motion in the plasma is described according to diffusion coefficients and mobilities which apply to flow perpendicular, transverse or parallel to the applied magnetic field. The transverse flow becomes

$$\Gamma_T = -\mathrm{grad}_{\Gamma}\left(n D_{\Gamma}\right) - n\mu_{\Gamma} E_{\Gamma} - n\mu_{\Gamma} E_{axial}.$$

A similar expression is applicable for positive ions except that the magnetic field is neglected.

We follow the procedure previously outlined for determining the transverse distribution of charge density, finally the Hall voltage is obtained

$$V_H = 0{\cdot}5 \langle v_z \rangle \left(\mu_\perp / \mu_{\parallel}^{2}\right) 2 r_0$$

from the plane parallel case. The factor $\cos\phi$ is needed for the circular column.

At low charge densities, the axial column voltage gradient may increase appreciably due to failure of the quansineutrality condition. A constant ratio between ion and electron densities may be assumed and an approximate solution found in terms of an altered ambipolar diffusion coefficient.

In the experimental set up done up by Anderson, the axial voltage is a function of discharge current, decreasing for increasing current. This suggests failure of quasineutrality and possibly the Hall voltage may not be obtained from the deduced equation. However, an analysis of this case indicates that the principal influence of charge imbalance may be expressed in equation

$$\nabla . \left[n \langle v_e \rangle \times B \right] = \left[\langle v_e \rangle \times B \right] . \nabla$$

by redefining the rate of ionizing collisions ν_i so long as the condition, $\gamma \mu_p << \mu_e$ is yet realised $(n_p = \gamma n_e)$

Hence changes in the Hall voltage are not expected because R(r) remains symmetrical with respect to radius and during integration of the equation

$$- \frac{2}{3} \frac{\overline{v_e}}{3} \int \frac{\nabla n}{n} \cdot dl = \int E \cdot dl + \int (\langle v_z \rangle \times B) . dl$$

its contribution cancells.

Anderson has observed Hall potential for positive columns established at pressures near 1 torr in He, neon, argon and nitrogen. Simultaneous measurement of the density of electrons in the column by the microwave cavity technique has given an independent determination of the electron drift velocity. The proportionality factor α between the Hall field measured and the product of the drift velocity and applied magnetic field has been determined by Anderson. The factor α for the case of helium was 0.50 ± 0.07 which is in agreement with theory. For neon $\alpha \cong 0.60$ also in agreement with theory. The column established in argon or nitrogen was generally noisy but $\alpha \cong 0.5$ and showed a tendency to decrease with decreasing gas pressure as is also expected from the theory. Electron collision frequency for momentum transfer was determined by microwave methods and also from d.c. mobility.

Sanduloviciu and Toma in 1970 had worked on Hall voltage, measurement in a d.c. glow discharge. The superficial processes produced by the fast electrons in d.c. glow discharge might influence the values of the potential difference measured with the Hall probes.

In order to obtain a good agreement between calculated and measured Hall voltages it is necessary to exclude these superficial processes, specially the secondary electron emission at the surface of the Hall probes. In this paper the influence and the optimum work conditions for Hall probes measurements in a d.c. glow discharge were studied by the authors.

Zhilinsky (1980) had done an experimental investigation of the Hall effect in a toroidal discharge. The purpose of the work was to investigate Hall effect in a direct current toroidal discharge application.

SCOPE AND OBJECT OF THE PRESENT WORK

It is proposed to carry out the investigation on the physical properties of glow discharge and arc plasma along the following lines:-

A) Heat flow processes in the positive column of glow discharge.

There have been a large amount of theoretical work regarding the kinetic properties of partially and fully ionised gases and from these generalised theories it has been possible to deduce expressions for the thermal conductivity of an ionised gas. The direct experimental determination of thermal conductivity of an ionised gas has been little reported so far. A detailed experimental investigation for determining the different processes of heat flow in the positive column of a low pressure mercury arc has been performed by Ghosal, Nandi and Sen (1979) and it has been observed that the major part of the heat loss is due to diffusion and the loss due to conduction by electrons, ions and neutral atoms is comparatively small. To see whether similar processes of heat flow are maintained when we cross over from arc to glow transition it will be of interest to find the contribution of electrons to the total heat conductivity of a low pressure glow discharge. To study the mechanism of heat loss in a plasma it is assumed that Ellenbaas Heller heat balance equation [Elenbaas (1951)] holds good with the inclusion of a radiation term. Hence utilizing this equation experimental results will be analysed and the dominent processes responsible for heat flow can be identified. In the proposed section an indirect method of measuring the thermal conductivity of an ionised gas is presented and from the analysis of the results it is expected to find the processes responsible for the propagation of heat in a plasma of low electron density.

B) Evaluation of electron temperature in a glow discharge from measurement of diffusion voltage.

The standard method for the measurement of electron temperature in a plasma is the Langmuir single probe method. The radiation of microwave energy from a hot plasma has also been utilized for the evaluation of electron temperature by assuming that the plasma radiates like an ideal black body. A reliable method for the measurement of electron temperature is by spectroscopic method which also stipulates that the plasma must be in local thermal equilibrium. Each of these methods suffers from some limitations. The process of of diffusion of electrons and ions in a glow discharge is well known. It is proposed in this section to analyse the diffusion equations and device a method for the measurement of electron temperature T_e in an ionised gas from the measurement of diffusion voltage. The variation of T_e with (E/P) where (E/P) is the reduced field will also be investigated.

Further from a detailed mathematical analysis of the physical processes occuring in a magnetised plasma it has been deduced by Sen and Gupta (1971) that the electron temperature T_{eH} in a transverse magnetic field is given by

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

where $C_1 = \left(\frac{e}{m} \cdot \frac{L}{\vartheta_r} \right)^2$ where L is the mean free path of the electron in the gas at 1 torr and ϑ_r the random velocity of the electron. Though the above deduction has been utilized to explain satisfactorily the variation of discharge current and intensity of emission of spectral lines (Sen and Gupta, 1971; Sen, Das and Gupta (1972) in glow discharge in presence of transverse magnetic field field, it is desirable to verify the above deduction experimentally. It is therefore proposed to measure the electron temperature in an ionised gas to study its variation in a variable transverse magnetic field by the diffusion method introduced here.

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

It has been suggested by several authors that the study of acoustic wave propagation may lead to a diagonistic method for measurement of plasma parameters. In all the investigations carried out theoretically so far to find the interaction of sonic waves with an ionised gas it has been assumed that the medium is fully ionised and collision of electrons and ions with neutral gas molecules has been assumed to be absent. Ghosal and Sen (1976) have derived the general wave equation and dispersion relation using macroscopic variables of the plasma and have provided a uniform treatment of the subject for a non-isothermal plasma taking into consideration the collision of charged species with the neutral particles. Further it has been possible to obtain from general dispersion relation the attenuation constant of the plasma when a sonic wave propagates through it. The attenuation constant is given by

$$\alpha_p^2 = \frac{\left[1 + \frac{\nu_{pa}^2}{\omega^2}\right]^{1/2} - 1}{\frac{2\gamma K(T_e + T_i)}{m_i}}\,\omega^2$$

where γ is the adiabatic constant, K the Boltzman constant T_i the ion temperature, T_e the electron temperature, m_i the mass of the ion ν_{pa} the effective ion atom collision frequency and ω the frequency of the incident sound wave. It is proposed in this section to measure the attenuation constant of a propagating sound wave through an ionised gas launched from an external source of sound. From the equation (mentioned above) it is evident that if T_e the electron temperature is obtained from an independent measurement and we assume $T_i \approx T_g$ the gas temperature which is valid for discharge currents of the order of a few milliamperes (von Engle, 1965) then the collision frequency ν_{pa} can be obtained from the measured value of α_p. The results will be reported here for air and hydrogen. Electron temperature for a number of molecular gases has been measured in this laboratory for various (E/P) values by Sadhya et al (1979) by the Langmuir probe method. Consequently the collision cross section can be obtained for a range of (E/P) values. The data for ion atom collision cross section has been little reported so far specially for low values of (E/P). It is suggested that sonic probe can be an alternative method for measurement of collision cross section and the object is to test the validity and limitation of the method for determination of plasma parameters.

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

Discharge of a series of condensers charged to high voltages has been utilized to create a high density plasma in a rarefied Gas. The phenomena has been ascribed to the process of thermal ionization. Little work has however been reported when a bank of condensers 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 will be utilised for the measurement of intensity of the spectral lines in a glow discharge when a bank of condensers discharges through it. A quantitative measurement of electron density and electron temperature will be made in air and hydrogen glow raised to highly conducting condition by the discharge of a bank of condensers. As the charged particles are in an excited state in a glow discharge, it will be instructive to see how the particles will react when they receive the additional burst of energy due to discharge of the bank of condensers through the glow discharge. The results may have some relevance for the heating of the plasma.

E) Hall effect in an arc plasma.

The Hall effect is a standard diagonistic method for determining the charge particle mobility and density in a semiconductor and it has also been used for measurement of plasma parameters in a glow discharge. The effect of a transverse magnetic field on the positive column of a glow discharge has been investigated by Beckman (1948) and the variation of current in a variable transverse magnetic field has been studied by Sen and Gupta (1971) who provided a detailed mathematical analysis consistent with observed experimental data. Anderson (1964) investigated the Hall effect in the positive column in glow discharge in some rare gases and obtained the drift velocities of electrons for a range of (E/P) values. The voltage current characteristics and the power relation has been investigated in a mercury arc carrying current from 1.2 to 2 amp. in presence of a transverse magnetic field [Sen and Das, (1973)] . In contrast to semiconductors or metals it is to be noted that when an arc or glow plasma is placed in an external magnetic field the radial electron density distribution and discharge current are significantly altered and this effect has to be taken into consideration in calculating Hall coefficient in an arc plasma. It is proposed to measure the Hall coefficient in a mercury arc plasma and calculate the electron density and mobility taking into consideration the variation of main arc current in presence of the transverse magnetic field. The results will also indicate the limitation of the magnetic field upto which the expressions for current as deduced by Sen and Gupta (1971) are valid.

F) Outlines of a generalised theory of arc plasma

For the last few years electrical, optical and thermal properties of arc plasma have been investigated experimentally by Sen and his coworkers in this laboratory and theoretical analysis consistent with observed experimental results have been provided. In this section of the present work an attempt will be made to correlate the observed experimental results and present the outlines of a generalised theory regarding the occurance of an arc plasma. Two theories namely the thermionic emission and field emission of electrons from the electrodes of an arc have been advanced to explain some observed experimental results regarding cathode and anode fall in arcs. An attempt will be made here to present the outlines of a theory which can explain the recently observed experimental data in arcs.

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CHAPTER II

EXPERIMENTAL ARRANGEMENT

2.1. Apparatus Utilised

1. Discharge Tubes of various dimensions
2. Arc tube of various dimensions
3. High voltage transformer
4. Variac
5. Milliammeter, Microammeter.
6. High current Rheostats
7. V.T.V.M.
8. D.C. Power supply (Stabilized).
9. D.C. Generator
10. A double stage Rotary vacuum pump.
11. Pirani Gauge
12. Needle valve
13. Gauss meter
14. Audio frequency generator
15. A.C.Microvoltmeter
16. Oscilloscope
17. High voltage power supply
18. Spectrograph
19. Audio frequency generator
20. Loudspeaker and Microphone.

2.2. Discharge tubes

All the discharge tubes in which measurements were carried out were constructed of pyrex glass. For glow discharge measurements the tubes were fitted with brass (80% Cu 20% Zn) and stainless steel electrodes and for low pressure mercury arcs, the arcs were struck in between mercury pools. The arc tubes are fitted to simple traps through standard joints. In this way 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 joining rubber tubes and a mercury plug would be formed in the passage and hereby would disturb the vacuum system.

The discharge tubes were thoroughly cleaned by chromic acid, petroleum ether and distilled water and dried on the pump. Then the tubes were heat baked in an electric oven in the usual way. Finally the tubes were heated and pumped off by rotary pump for several days (and for several hours before each set of observations) to degas them. For removing the occluded gases from the electrodes, both the electrodes were used as cathodes alternatively by reversing the currents through the discharge. The tubes were then flushed with the desired gas for two or three days and then the gas was introduced through a microleak of a needle valve to a desired pressure. (Ref FIG 2.2.(1) & 2.2(2))

2.3. Preparation of gases

For measurements in dry air, the air was passed through two U - tubes containing phosphorous pentoxide Powder and caustic potash pellets to remove traces of water vapour, then it was introduced to the discharge tube through a needle valve.

Hydrogen and oxygen gases were prepared from electrolysis of a warm solution of pure barium hydroxides 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 was next passed through series of U-tubes containing phosphorous pentoxide powder and caustic potash pellets.

The oxygen gas evolved in the anode of the electrolysis tube was passed through a flask containing sulphuric acid.

The nitrogen gas was supplied by Indian Oxygen Ltd. and was passed through concentrated sulphuric acid

After purification has been done in the stated manners the gases were stored in a round bottom glass flask which is connected to the discharge tube.

For mercury arcs, triple distilled mercury was used. In course of experiments, occassionally the mercury in the tubes was replaced by fresh supply and the discharge tubes were cleaned and degassed.

2.4. Measurement of pressure

Pressure of the gas in the discharge tube was measured by a Mcleod gauge fitted with triple distilled mercury.

In some of the experiments the pressure in the discharge tubes could not be measured directly because the tube was placed in between the pole pieces of electromagnet, but a parallel line was used. 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 Mcleod gauge. Dushman and Lafterty (1962) have discussed that effective pumping speed, S_{eff} is given

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C}$$

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

$$C = 2{\cdot}84 \frac{a^4}{l} P_2 \text{ litre/Sec}$$

where 'a' and 'l' are the radius and length of the tubes and P_2 the upstream pressure. So the parallel tubes were identical as far as possible. The lines were made of rubber and polythene pressure tubes. For the same reason, the needle valve was placed in between the junction of identical lines and the pump. A pirani gauge was used in the discharge tube line and through it the pressure of air could be compared.

The pressure of mercury vapour was determined from standard tables (Hodgman 1956) after noting the inside wall temperature (T_W) of the discharge tube which is equal to the outside wall temperature increased by the temperature drop over the tube wall resulting from the energy which is dissipated in the tube and carried away via the tube wall (Verweij, 1960). The outside wall temperature was measured by a mercury in glass thermometer when the arc was in steady state. Generally the arcs were cooled by electric fans. So a steady state of an arc corresponded to a steady outer wall temperature. The temperature drop as calculated by Verweij can be estimated by assuming that the total energy dissipated $W = Ei$ per cm of tube length (E is the intensity of electric field, measured by noting the voltage across the arc minus standard cathode fall of 10 volts as determined by Lamar and Cromptor (1931), then divided by arc length and i is the arc current. This energy is carried away by thermal conduction through the surface area of 1 cm. of tube length, thus through $2\pi R$ cm^2 (R is the internal radius of the discharge tube), since the amount of energy which escapes as radiation through the tube wall is relatively small, the ultraviolet resonance radiation being absorbed within a very small penetration depth in pyrex glass wall. The temperature drop ΔT_ω is given by

$$W = 2\pi R K \frac{\Delta T_\omega}{d}$$

where d is the thickness of glass wall (0.14 cm) and K is the thermal conductivity of the glass (K pyrex = 11×10^{-3} Joule/cm/sec/^oC). For a typical operation of arc at a current of 2.5 amp., ΔT_ω amounted to 7 - 8^oC. Since number density of ground state mercury atoms 'n_g' is directly related with p_{Hg} by the relation

$$n_g = 3.3 \times 10^{16} \frac{p_{Hg}}{T_\omega} 273$$

In all the arc measurement, dry air was admixed with mercury vapour. The pressure of dry air was measured by Mcleod gauge.

2.5 MAGNET and power supplies

In some of the experiments electromagnets were used. Depending upon the diameter and length of the discharge tube, the diameter of the pole pieces (10 cm x 8 cm square and 5 cm diameter) and length between them were adjusted. For a specific experiment, the pole pieces were so chosen that the magnetic field was uniform and without any radial component at the location of discharge tube. For measurements in axial magnetic field, the total discharge tube was placed in between the pole pieces. Transverse Mag field is applied at only certain portion of the discharge tube. [Fig 2.5(i)]

The magnetic fields were measured by a calibrated differential gauss meter. The electromagnets were powered by a stabilized d.c. supply.

The power supply for generating glow discharges was a stabilized electronic d.c. supply (0 - 1200 volts in steps of 105 volts). The supply was connected to discharge tubes via a high wattage balast resistor.

For a.c. glow discharges 50 Hz common supply was used through a step up transformer whose input was connected to an auto transformer.

The mercury arcs were struck by a d.c. generator (200 - 240V) whose voltage output could be adjusted to a constant value by a variable external resistor. For glow discharges, the discharge current was varied between 8 to 30 mA and arc current was varied between 1.5 to 5 Amp. [Ref FIG 2.5(i)]

2.6. Diagnostics by spectroscopic method

Spectroscopic method was utilized to determine electron temperature. The radiation of the axial regions of the discharge tube after passing through a vertical slit was focussed by a double convex lens on the vertical slit of the collimator of the spectrograph. In the spectrograph there was a Pellin - Broca prism for 90 degree deflection of the spectrum. Such a mounting was appropriate as a monochromator with fixed slit. The exit slit was in a direction of 90 degree with the plasma source. The wavelength is changed by rotating the prisms with a mechanical arrangement fitted with an accurately calibrated drum. The wavelengths of the radiations were further checked from standard values given in International Critical Tables (1926). The slit width which could be varied with a micrometer arrangement was varied from 0.2 mm to 1 mm depending on the response of lines chosen to the photomultiplier. For a set of observation however the slit width was fixed.

The collimator was focussed by rack and pinion arrangements, the selected line was focussed on the cathode of the photomultiplier RCA 931 operated at 1425 V. The surface open type photomultiplier which has low mean radiation equivalence of dark current was placed in a darkened chamber behind the exit slit. The power source of photomultiplier was made in two sections; the first was 1200 V stabilised pack to supply the dynode voltage while the second was used to furnish some 225 V, between the final dynode and the anode. The last voltage source was also used to operate the vacuum tube voltmeter, which consisted of two 6J7 tubes operating with about 32 V, on the plates and about 1.3 V negative grid bias. The grids were connected to the two ends of the resistor R_1 (600 KΩ) which was in series with the plate of the photomultiplier tube. When current flowed through this resistor, a voltage drop occured and one of the 6J7 tubes drew less current producing an imbalance in the plate circuit. A 0 ~ 200 μA meter between the plates measured this imbalance.

When the signal approximated 3 V, the 6J7 reached cutoff and beyond this point there was no increase in the meter deflection. With no light on photomultiplier tube and a rough balance obtained with R_4, the meter was set to zero with R_2 (Fig.2.6.(1)). In this way the effect of photomultiplier dark current was eliminated completely. Then, with 3 V or more applied to resistor R_1, the meter was set to full scale deflection by means of control R_3. The micrometer at the output recorded the intensity of the spectral line. The slit was adjusted so that meter deflection corresponding to the line with strongest response to the photomultiplier was well within the range of full scale deflection.

The sensitivity of a photomultiplier depends on wavelength of incident radiation and on quantum efficiency of the cathode material (including the effect of photomultiplier's window material). Percentage Quantum efficiency was taken from Carl Zeiss brochure (reproduced in fig.2.6(2)).

From this plot the cathode radiant sensitivity S in amperes per watt corresponding to a radiation of wavelength λ A^o is calculated as

$$S = \frac{Q\lambda}{12395 \times 100}$$

here Q is the percentage quantum efficiency. From S the relative spectral sensitivity for two lines was calculated and the micro ammeter reading for total intensities of lines was corrected for relative spectral response of the photomultiplier. Moreover emission coefficient corresponding to a radiation with frequency

ν which is directly proportional to observed total intensity can be separated into a continuous and discrete part

$$\epsilon_\nu = \epsilon_{\nu c} + \epsilon_{\nu L}$$

$\epsilon_{\nu L}$ contains the desired spontaneously emitted energy within the line, $\epsilon_{\nu c}$ was eliminated by balancing the V.T.V.M. to the null of meter reading with resistors in the circuit when the continuum radiation at the near vicinity of the line was focussed on the photomultiplier tube cathode and the contribution for $\epsilon_{\nu c}$ was found to be negligible.

2.7. EXPERIMENTAL ARRANGEMENT

2.7.1. Heat Flow Process in the Positive Column of a Glow Discharge

Apparatus required: Discharge tube, High voltage transformer, Variac, Stabilised D.C. power supply, Pirani gauge, Needle valve, Microammeter, Separate arrangement for prep of H_2, O_2, N_2, Milliammeter, Oil Rotary pump.

Arrangement:- The discharge tube provided with four electrodes (A, B, C, D) (Fig. 2.7.1.(i)) of which the electrodes A and B connected to a source of high voltage are used to excite the discharge. The discharge tube was cleaned as per procedure mentioned in 2.2.

The pressure of the gas under investigation is measured with an accurately calibrated pirani gauge (Ref. 2.4).

An external variable voltage from a stabilized power supply is applied to the electfodes C & D. The plasma within the electrodes C & D acts as a conducting medium and with the plasma on, the current is measured in the microammeter (Fig.2.7.1(2)) for different values of applied voltage.

The investigations were carried out first in air, For measurements in dry air the procedures were followed which is explained in 2.3.

After air, hydrogen and oxygen is introduced in the discharge tube separately. Preparation of hydrogen and oxygen is explained in 2.3.

Then nitrogen was introduced in the discharge tube and similar procedure of applying external variable voltage from a power supply is applied to C and D.

A representative curve is shown in Fig. (3.4) for hydrogen Fig. (3.5) for nitrogen, Fig. (3.3). for oxygen, From the linear portion of the curve the resistence and hence the conductivity of the plasma has been calculated.

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

Apparatus required -

1. Discharge tube
2. High voltage Transformer
3. Variac
4. Milliammeter
5. Oil Rotary pump
6. Pirani Gauge
7. Needle valve
8. Magnet with power supply
9. V.T.V.M.

Arrangement:-

The discharge tube of length 10 cm in which the ionized gas under investigation was produced by a high voltage source. The pressure under investigation is measured by an accurately calibrated Pirani gauge The discharge tube was cleaned as per procedure mentioned in 2.2.

Two cylindrical probes of length 1 cm and diamter 0.01 cm. are placed parallel to one another, one along the axis $r = 0$ and other at a distance $r = 0.9$ cm. from the axis (Fig. 2.7.2.(i)). The radius of the discharge tube is 1.6 cm.

The output voltage at the two probes is measured by a V.T.V.M. having an internal impedance of 100 MΩ

A filter circuit (Low pass filter) was designed and is connected at the output of the probes to prevent oscillations generated in the plasma from reaching the V.T.V.M.

The output voltage has been measured for different (E/P) values in air, where E is the axial field i.e., the voltage per cm. length of the positive column and P is the pressure in torr. The axial field E is determined by measuring the voltage between the two extra probes at a distance 5 cm. placed in the positive column.

The variation of T_e with (E/P) has been plotted in (Fig. 4.1.).

After that a transverse magnetic field was applied to the discharge tube. The details of the electromagnet and power supply are already discussed in 2.5. The magnetic field was varied from 0 to 100 gauss for a constant discharge current of 2.8mA.

2.7.3. Hall Effect in an Arc Plasma:-

Arrangements:- The arc has been produced in an arc tube made of pyrex glass. Besides the two tungsten probes (immersed upto the axis of the tube) stuck in the positive column region with a separation of

26.4 cms., between them. Two horizontal metallic plates (2.5 cm x 1 cm) at a distance of 0.8 cm. are introduced within the arc tube for measuring the Hall voltage.

Analytical quality of triple distilled mercury has been used here to produce the mercury arc. A double stage rotary vacuum pump has been utilized to maintain the system at a desired vacuum mark and a needle valve has been used in the line to control the degree of vacuum. In case any quantity of mercury comes up and contaminates the pump fluid, precautions have been taken by using several glass traps in the vacuum line. A pirani gauge was kept always fitted with the system to relay the vacuum situation. The arc has been operated by a high current D.C. voltage generator.

To control the arc current several high current rheostats have been used in series with a D.C. ameter (range 0 - 5A).

Circuits constants:-

Radius of the tube = 1.32 cm.

Distance between mercury pool = 26.4 cm.

Horizontal metallic plates = 2.5 cm x 1 cm

Distance between two plates = 0.8 cm.

Experimental procedures:-

As a preparation to produce the mercury arc in the glass tube, the tube has been thoroughly washed with dilute chromic acid and then with NaOH solution. After these chemical baths the tube has been washed several times with distilled water and after that with dehydrated pure benzene and then dried throughly. After completing these operations, triple distilled mercury has been poured into the tube to the desired level. The tube is then connected to a double stage rotary vacuum pump. Time was allowed to pass till the system reaches a vacuum of the order of 0.2 torr. [Ref FIG 2·7·3 (1)]

Arc is then produced inside the tube by following the tilting process. A number of fans have been used for cooling the arc and maintain a steady temperature.

Two horizontal metallic plates (2.5 cm x 1 cm) at a distance of .8 cm are introduced within the arc tube for measuring the Hall voltage. [FIG 2·7·3 (2) 2·7·3 (3)]

The magnetic field which is at right angles to both to the direction of the flow of current and measuring electrodes has been provided by an electromagnet. The power to run the electromagnet has been supplied by a stabilised power supply. The magnetic field which has been varied from zero to 550 gauss has been measured by an accurately calibrated gauss meter (Model EC GH 867). The gauss meter operates on the principle of the Hall effect. The Hall probe is made of a highly pure indium arsenide crystal and is encapsulated in a non magnetic sheath of approximately 50(mm x 5 mm x 2 mm and is connected to a three feet cable. A transparent cap is provided for the protection of the probe. The accuracy of the readings is ± 2.5 percent upto 10 kilogauss.

The Hall voltage developed in the arc plasma has been measured by a V.T.V.M. (Simpson Model N 321 - 1). The valve tube voltmeter is a versatile instrument designed for accurate measurement of voltage (both a.c. and d.c.). The d.c. voltage upto 1500 volts can be measured in seven stages, input impedance is 35 megaohms in all the ranges and and the accuracy of reading is ± 3 percent.

2.7.4. <u>Determination of plasma parameters by sonic wave through an ionised gas</u>:-

Apparatus required:-

1. Discharge tube
2. High voltage transformer
3. Variac
4. Milliammeter
5. Loudspeaker
6. Microphone
7. Audio frequency generator

8. Rotary pump
9. Pirani gauge and Niddle valve
10. Oscilloscope.

Experimental arrangement:

The discharge tube is made of pyrex glass of length 90 cm and 5.4 cm. in diamter. The discharge tube was cleaned as per procedure mentioned in 2.2. The electrodes of outer diameter 1.5 cm. and made of hollow cylindrical brass tubes (E, E) (Fig.2.7.4.a) are connected to high voltage transformer.

The discharge tube is fitted at one end with a loudspeaker (L) which is energised with a Philips Audio frequency generator (GM 2308) and the loudspeaker acts as a source of sonic waves.

At the other end a Microphone is fitted to receive the audio signal. Both the loudspeaker and the Microphone are fixed to the wall of the discharge tube through a sponge like material in the form of foam which effectively dampens the propagation of sound, so that no propagation of sound is possible through the body of the discharge tube.

This has been further tested by evacuating the discharge tube to a high degree of vacuum when it was observed that even for high input audio voltage, the output at the receiver was too low to be detected.

The output from the microphone has been detected by an a.c. microvoltmeter and then connected to an oscilloscope.

Pure and dry air was passed through the discharge tube using the procedure mentioned in 2.3.

The pressure inside the tube measured by a vacuoscope and was kept constant by a regulating needle valve.

2.7.5 <u>Enhancement of electron temperature by Bank condenser discharge:-</u>

<u>Apparatus required:-</u>

1. Discharge tube
2. Pirani gauge
3. Milliameter
4. Needle valve
5. Rotary vacuum pump
6. High voltage transformer
7. D.C. high voltage stabilised power supply
8. Spectrograph
9. Power supply for photomultiplier tube
10. D.C.Microammeter.

Arrangement:

The discharge tube was provided with four electrodes A, A,& B,B (Fig. 2.7.5.(i)) of which the electrodes A and A are connected to a source of high voltage which is used to excite the discharge. The discharge tube was cleaned throughly as per procedures mentioned in 2.2.

The discharge tube was evacuated by a double stage rotary vacuum pump and pressure was maintained to desired level by a fine needle valve and monitored by Pirani gauge. Dry air was passed through the discharge tube as per procedure mentioned in 2.3.

The glow discharge was maintained between the electrodes A and A.

The spectrograph slit was set accurately at the level of the discharge tube and dark current was adjusted before the observations (as per procedures mentioned in 2.6).

Two Sets of different lines were selected and at same [See chapter VI] discharge current, photomultiplier current for each specific line was noted (pressure was kept constant at 0.2 torr).

A high voltage d.c. power supply was designed at this laboratory. A bank of condensers (Each condenser having capacitance 24 μF and 2500 V and Total '8' condensers were connected in parallel) were charged at different voltages 2250 V, 2000V, 1750V, 1500 V from the high voltage power supply (Fig.2.7.5.(i)).

A special type of switch was also designed in our laboratory which connects the bank of condensers to power supply first (Fig.2.7.5(i)).

After the charging of condensers (Keeping the glow between A and A) the switch now connects the bank of condensers across the electrodes B & B).

Immediately the condenser bank was discharged between the electrodes B and B in presence of glow when the condenser bank discharges immediately discharge current and photomultiplier tube current increases. The discharge current and photomultiplier currents were recorded with great accuracy and the each set of experiment was repeated several times.

For a specific line, bank current discharge was varied from 2.25 KV to 1.50 KV.

Two sets of lines were choosen and similar procedure was repeated for each set.
The experiment was repeated with Air & hydrogen gas. For details of experimental set up, please refer chapter VI

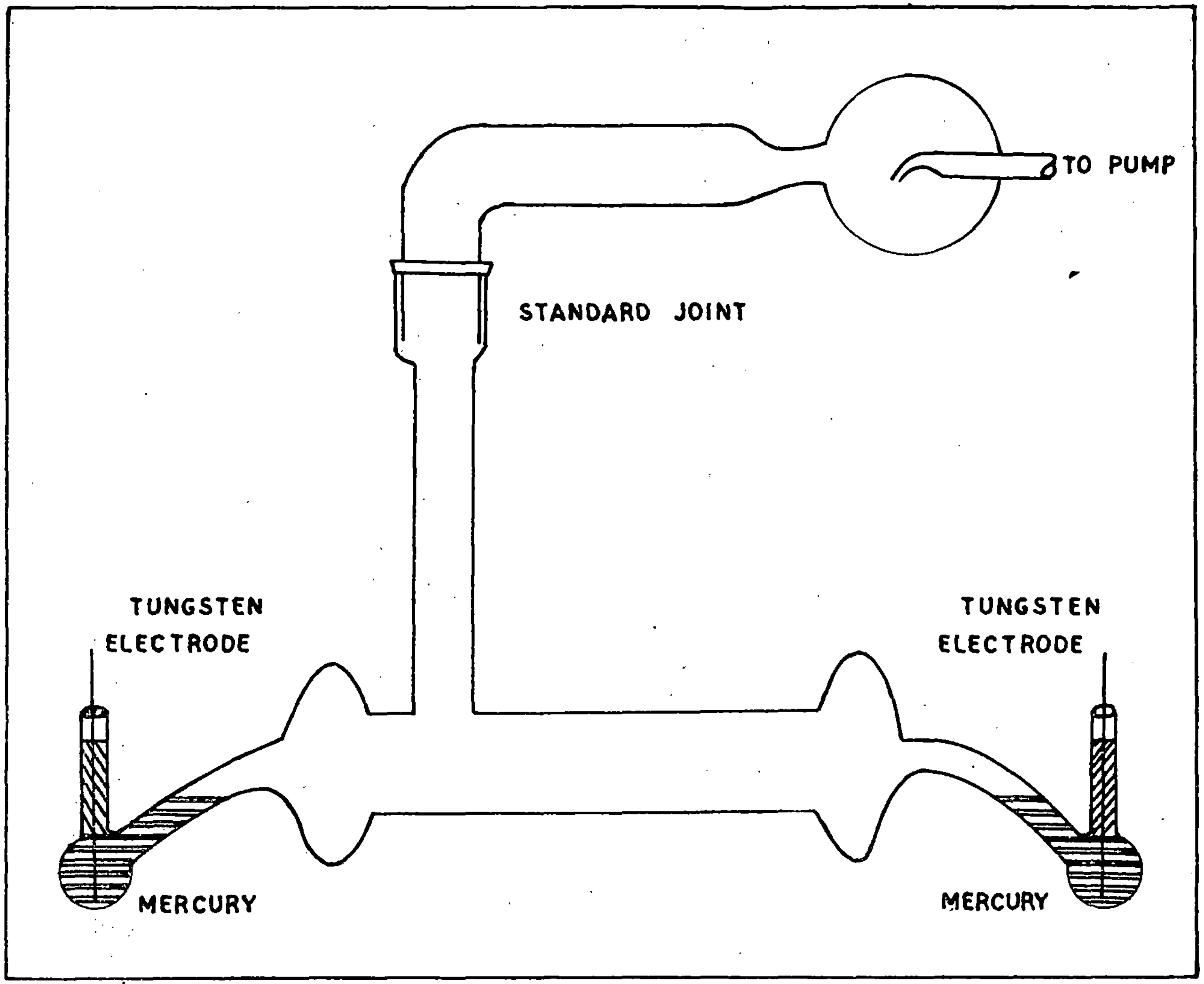

FIG. 2·2(1) DIAGRAM OF A MERCURY ARC TUBE

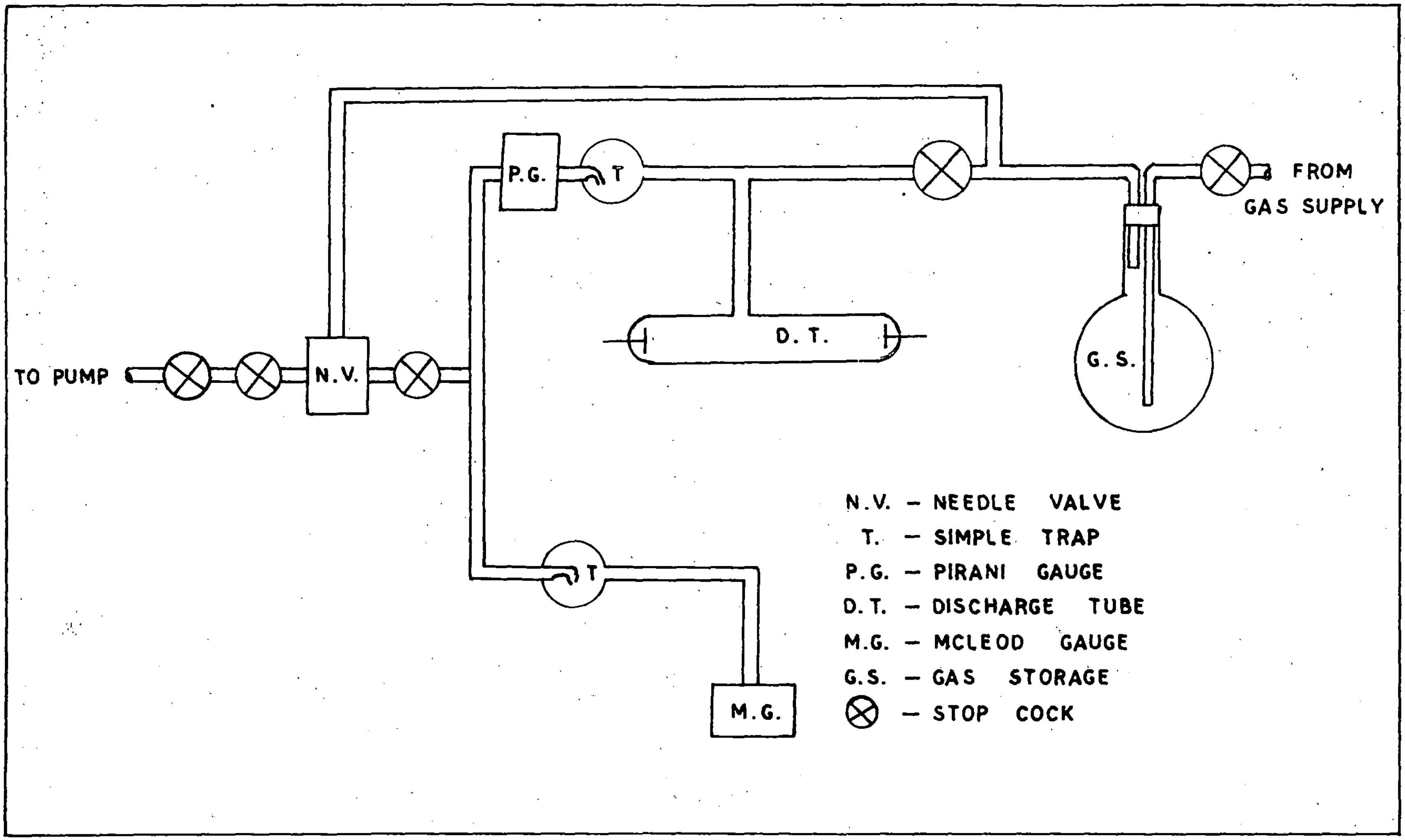

FIG. 2·2(2) DIAGRAM OF A GLOW DISCHARGE TUBE.

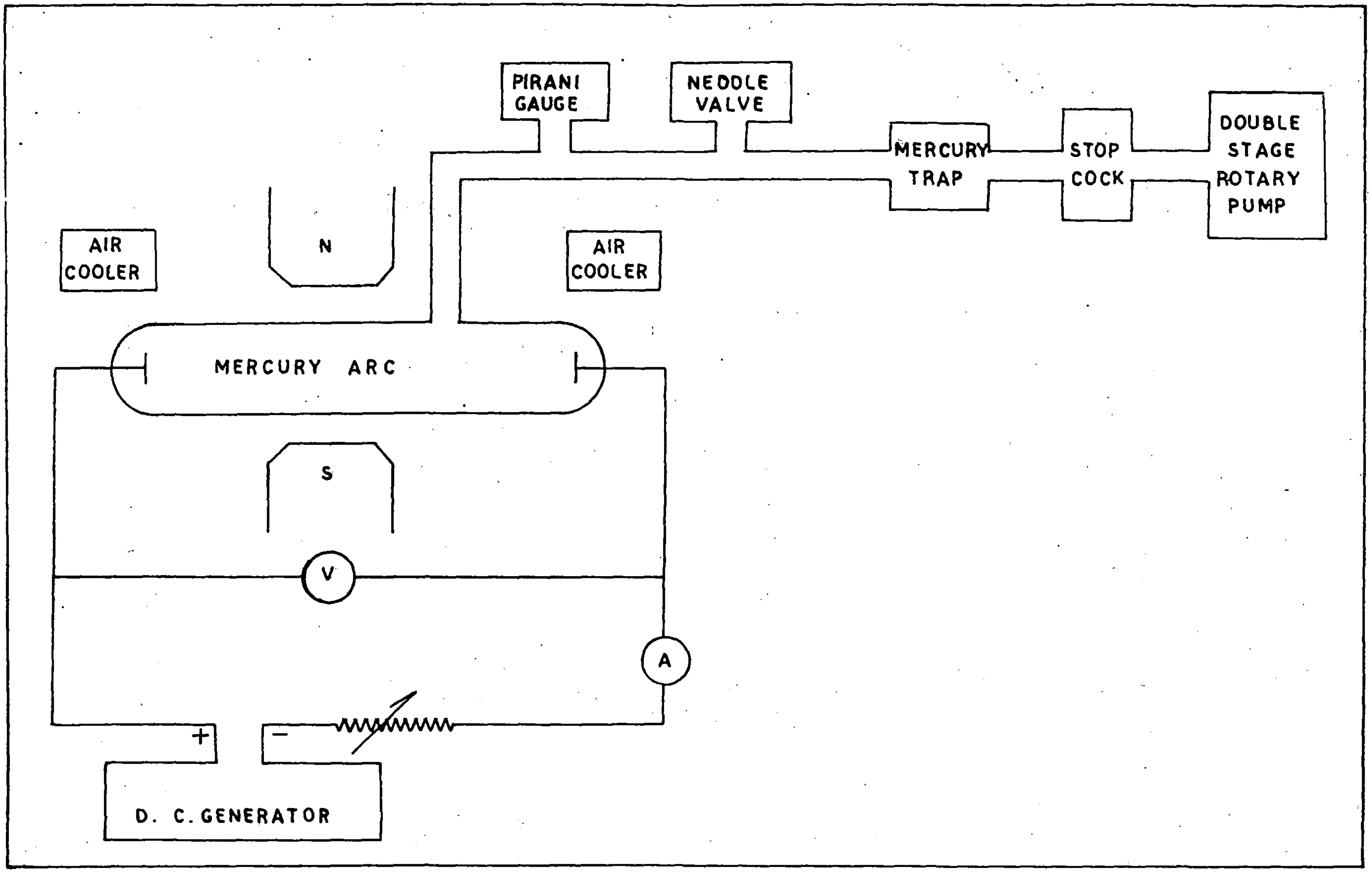

FIG. 2·5(i) SCHEMATIC DIAGRAM OF EXPERIMENTAL SET UP IN A TRANSVERSE MAGNETIC FIELD.

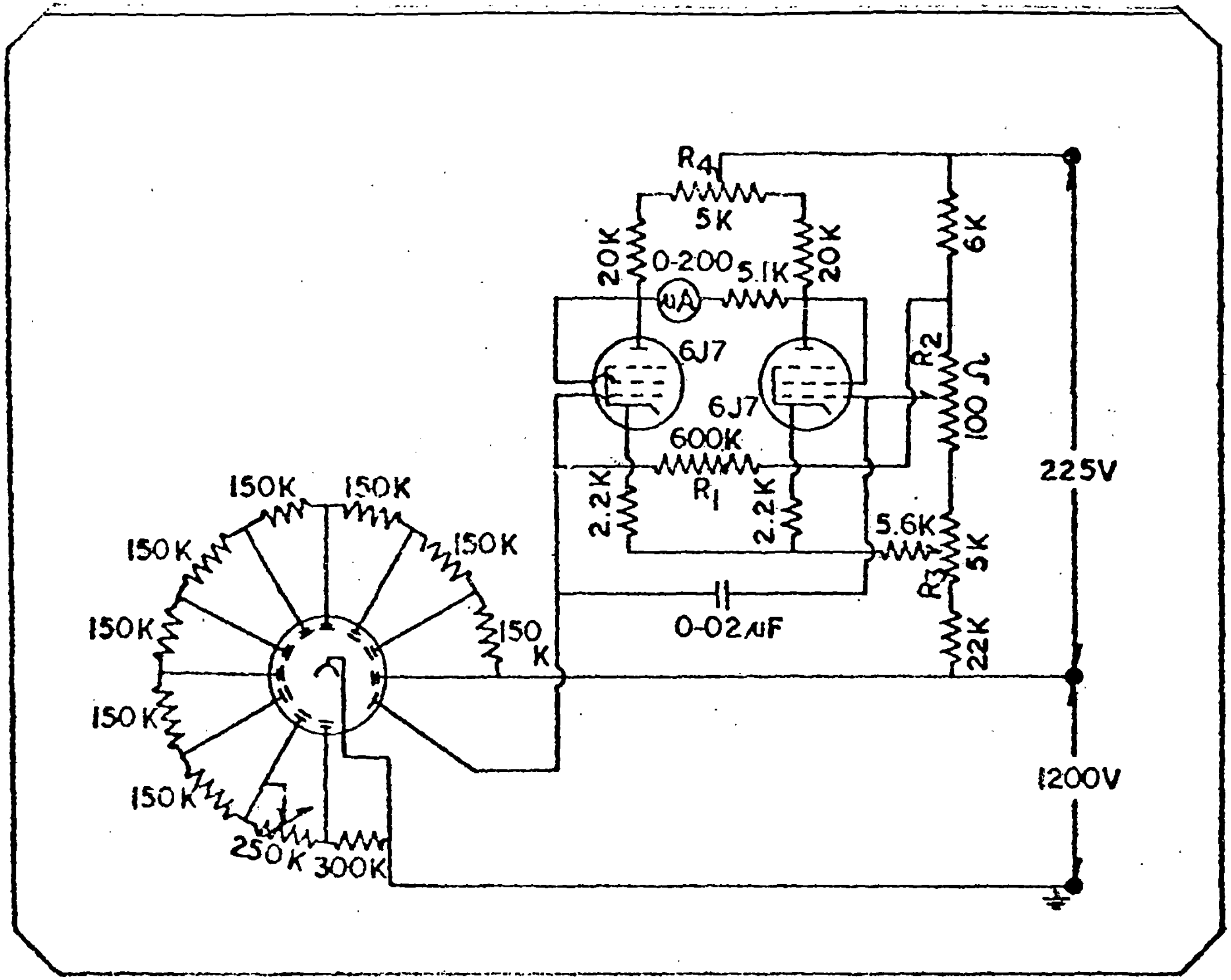

FIG. 2:6(1) PHOTOMULTIPLIER CIRCUIT.

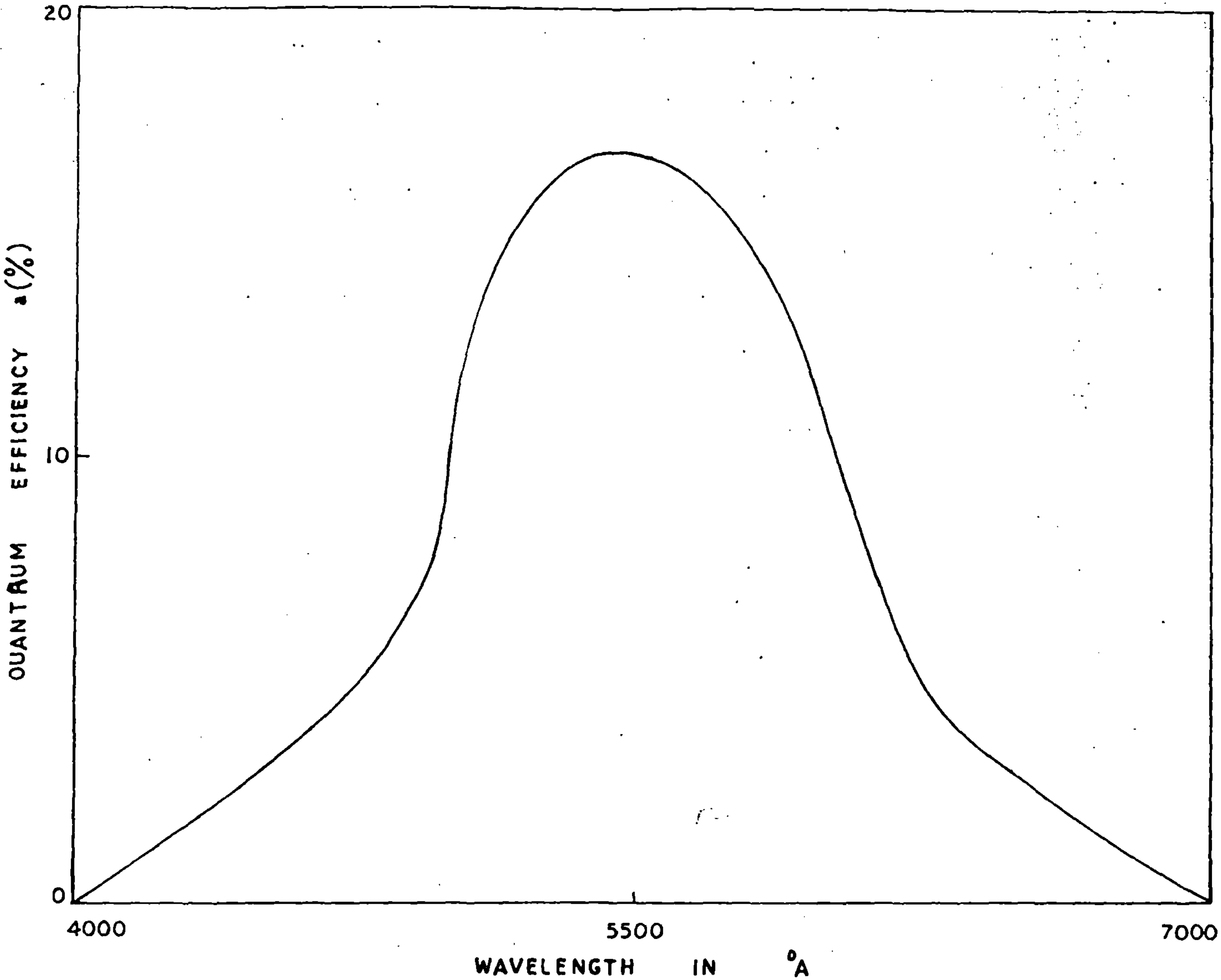

FIG. 2.6(2) QUANTUM EFFICIENCY IN % OF PHOTOMULTIPLIER M 10F 529 V_λ
(VEB CARLZEISS JENA BROCHURE NO. 40 – 637 – 2).

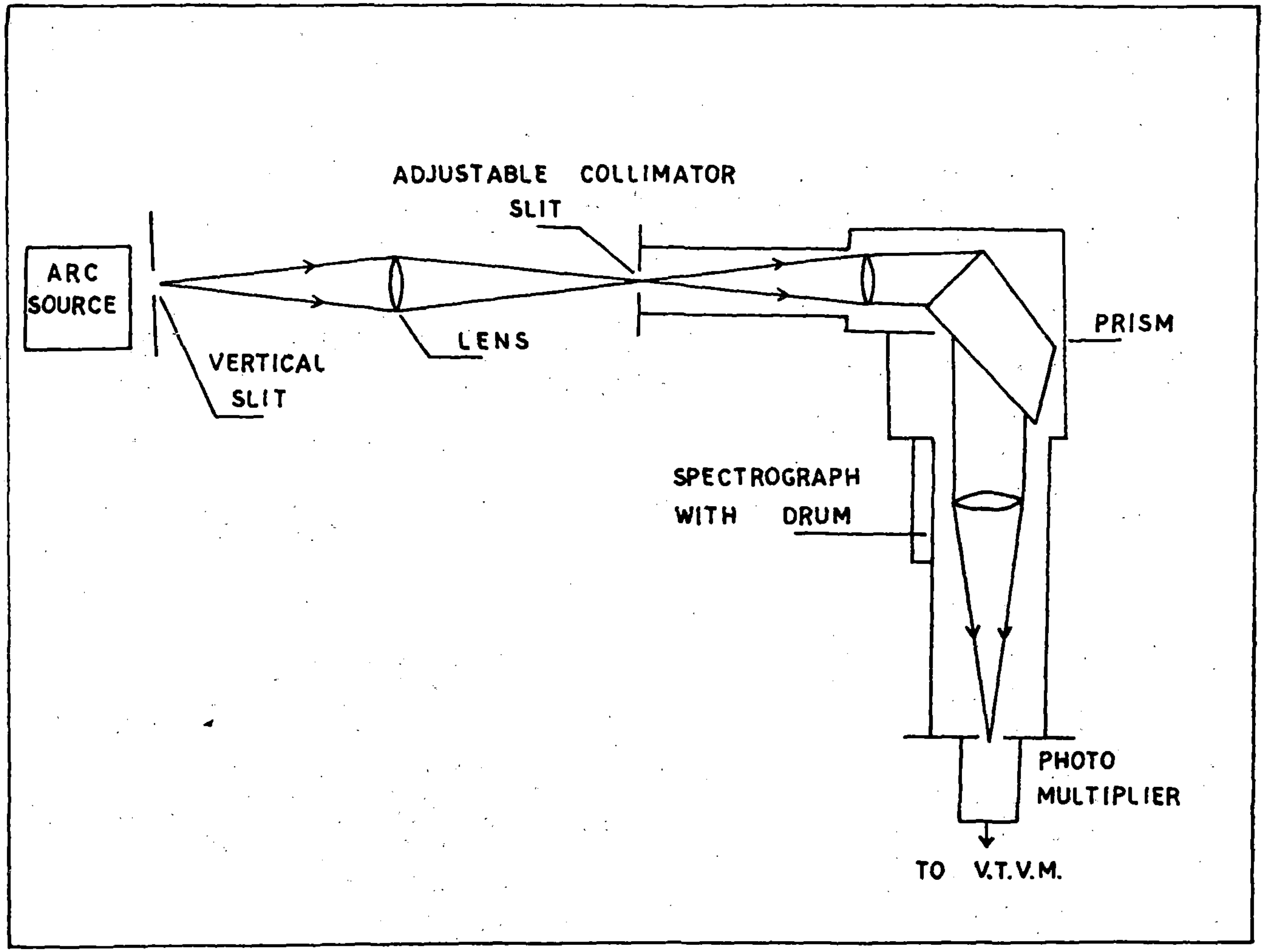

FIG. 2·6(3). EXPERIMENTAL SET UP FOR SPECTROSCOPIC MEASUREMENTS.

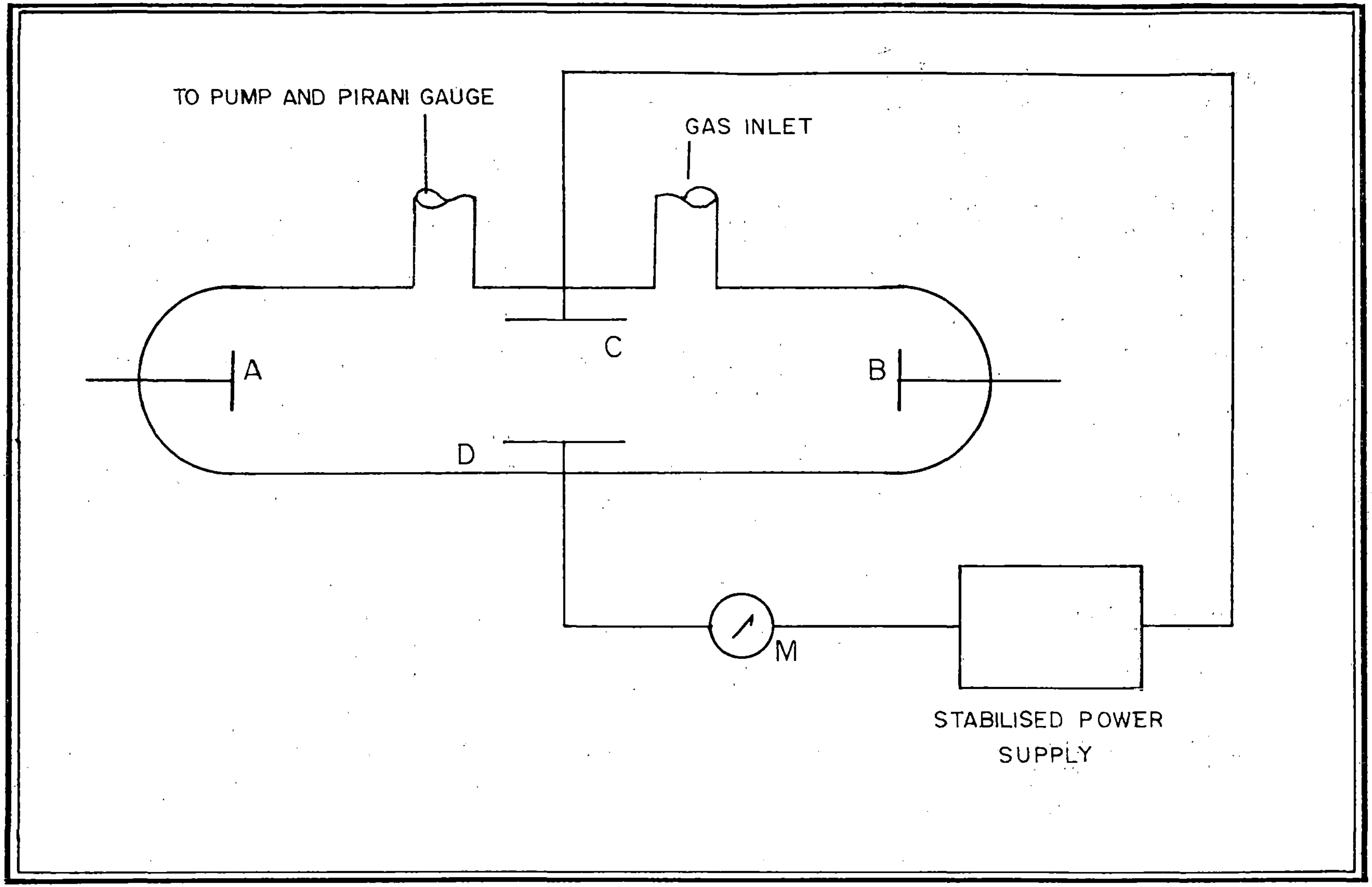

FIG 2.7.1.(1) EXPERIMENTAL SET UP

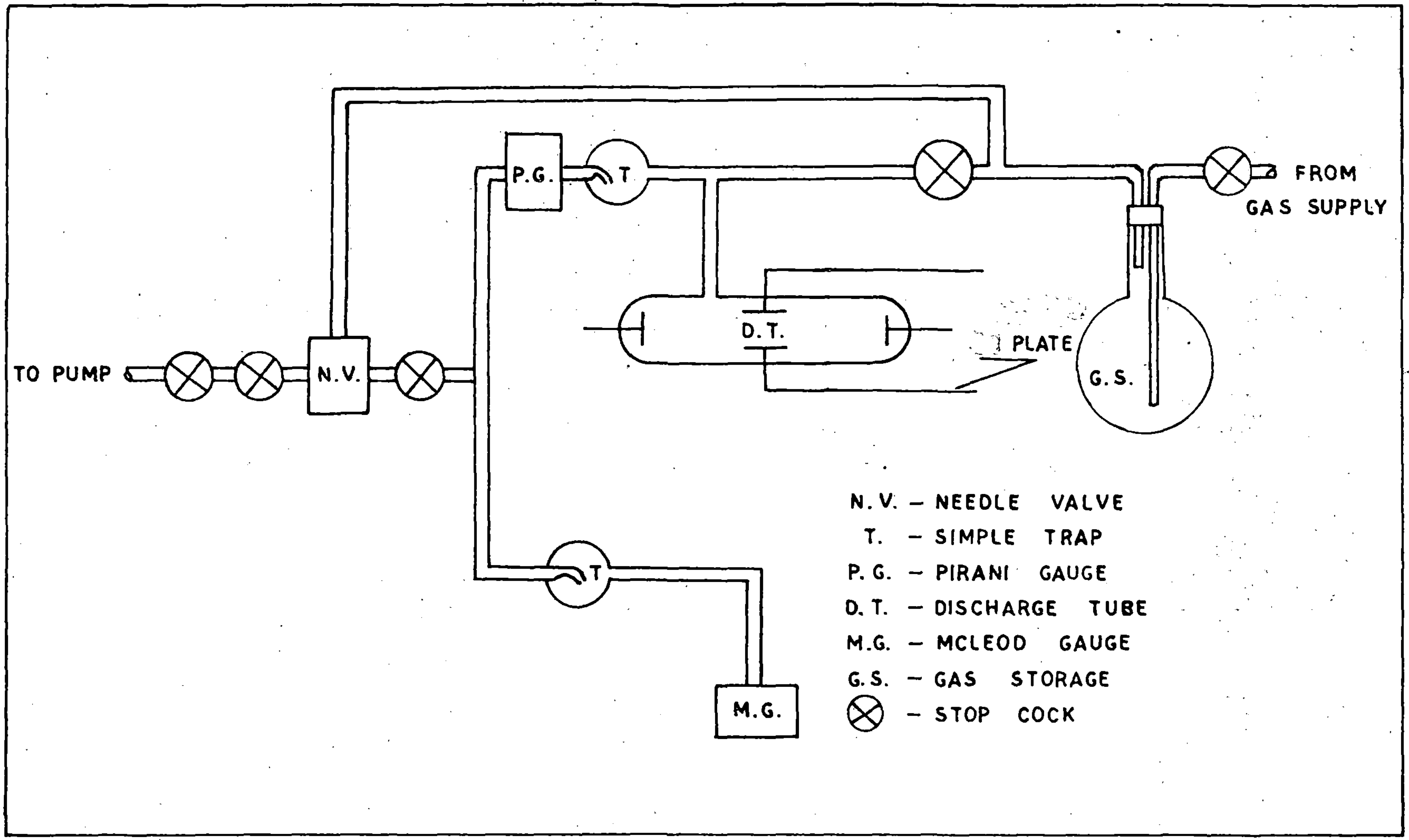

FIG. 2·7.1.(2). EXPERIMENTAL SET UP

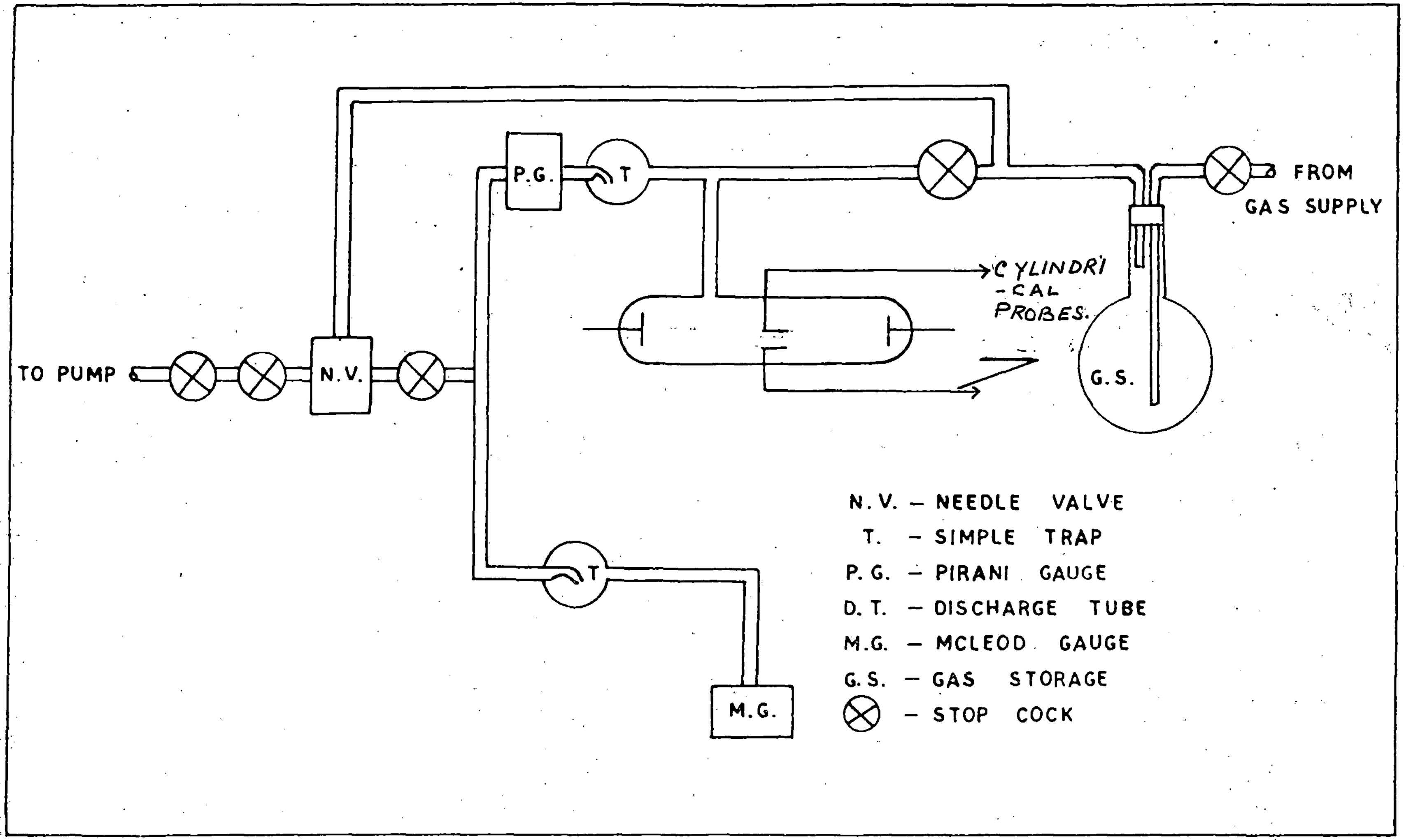

FIG (2.7.2(i)) EXPERIMENTAL ARRANGEMENT

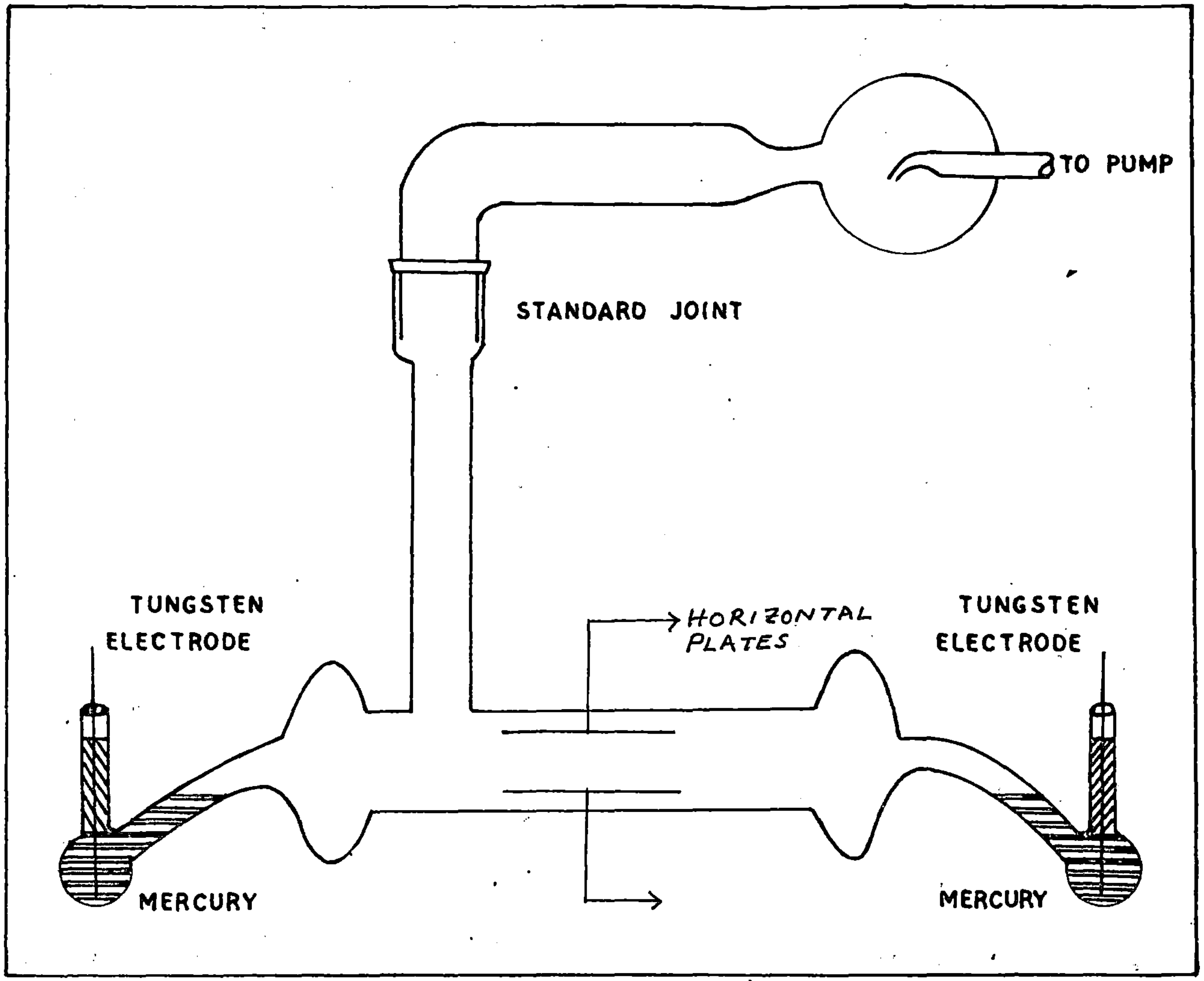

FIG 2.7.3.(1) DIAGRAM OF A MERCURY ARC TUBE

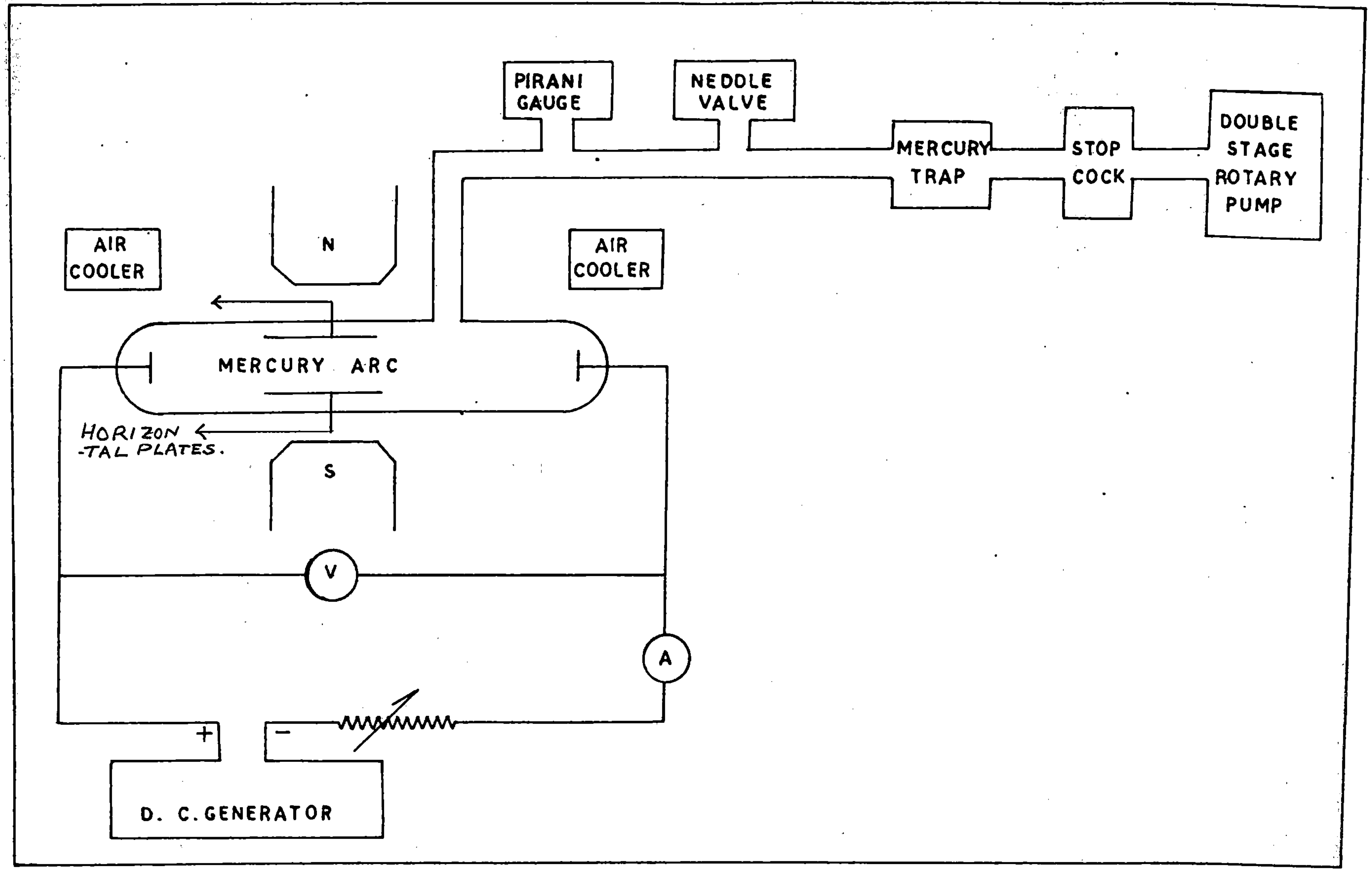

FIG. 2·7.3.(2) SCHEMATIC DIAGRAM OF EXPERIMENTAL SET UP IN A TRANSVERSE MAGNETIC FIELD.

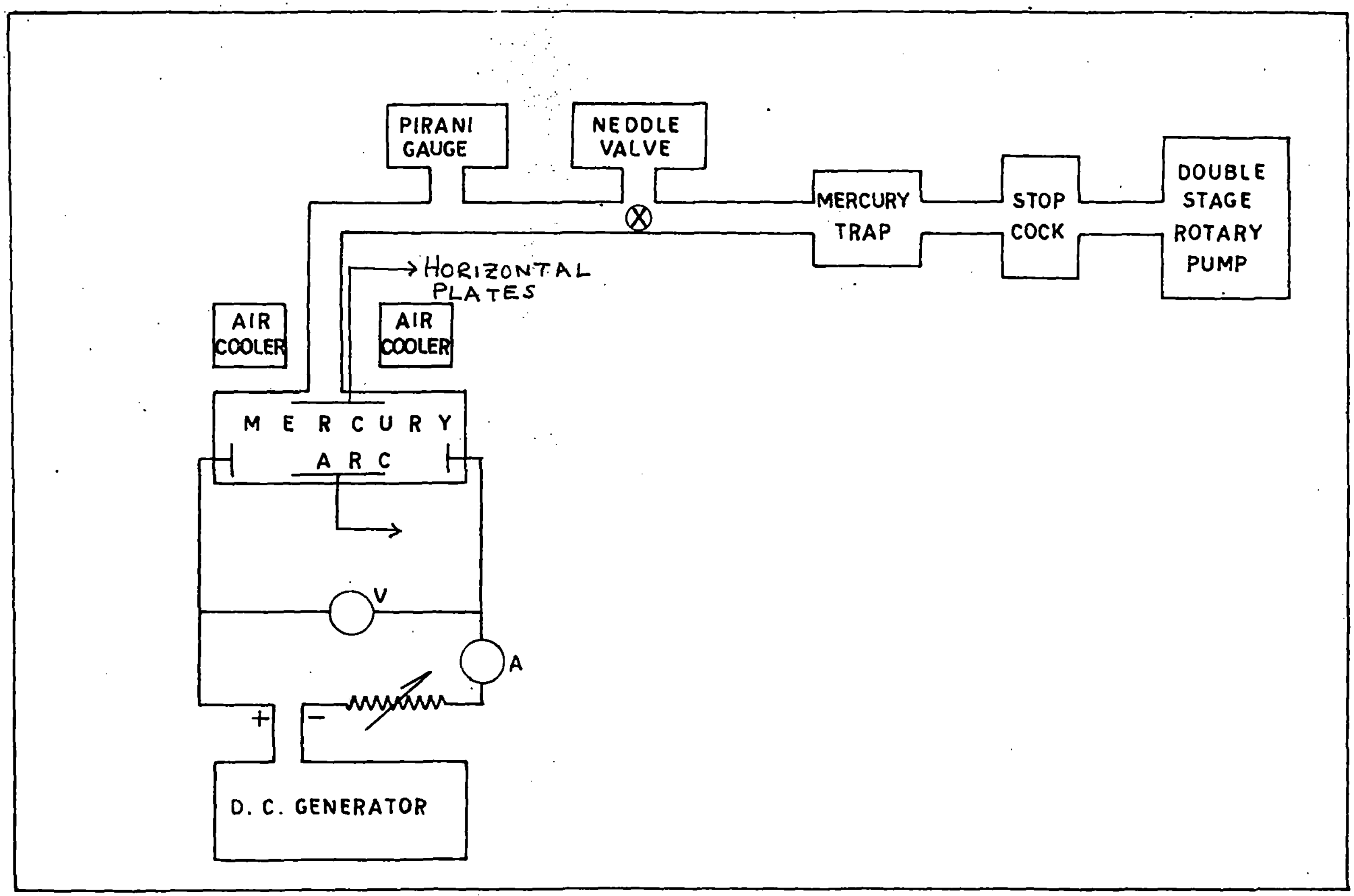

FIG. 2·7.3(3) SCHEMATIC DIAGRAM OF EXPERIMENTAL SET – UP

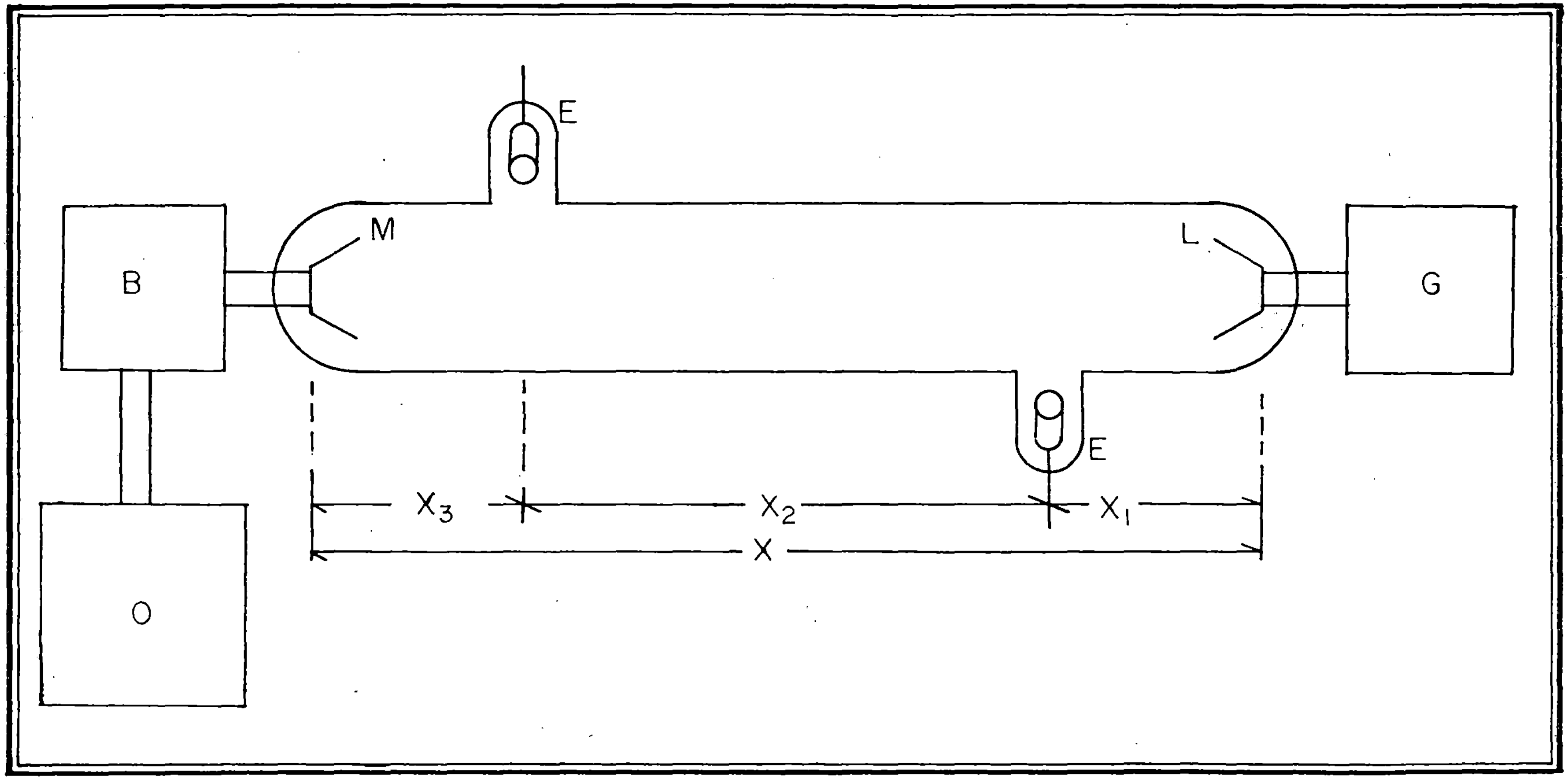

Fig 2·7.4(1) EXPERIMENTAL SET UP

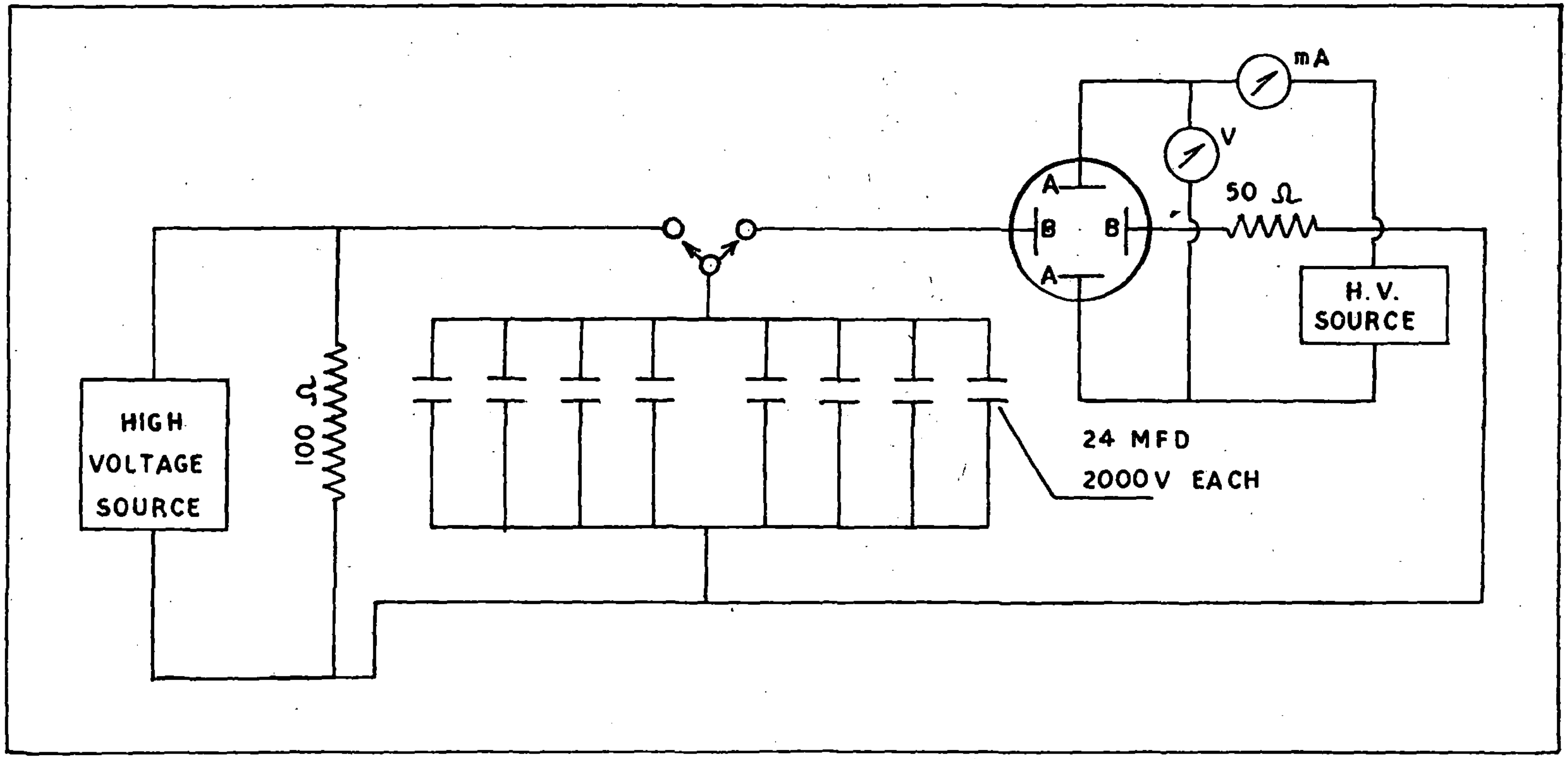

FIG. 2.7.5.(i) ENHANCEMENT OF SPECTRAL INTENSITY BY BANK CONDENSER DISCHARGE.

CHAPTER III

HEAT FLOW PROCESS IN THE POSITIVE COLUMN OF A GLOW DISCHARGE

INTRODUCTION

There have been a large amount of theoretical work regarding the kinetic properties of partially and fully ionised gases and from these generalised theories it has been possible to deduce expressions for the thermal conductivity of an ionised gas. The direct experimental determination of thermal conductivity of ionised gas has been little reported so far. The standard method of determining the thermal conductivity of a gas is not applicable in case of an ionised gas as the presence of central conducting wire perturbs the state of plasma and vitiates the results to a large extent.

An elegent experiment has however been done by Goldstein and Sekiguchi (1958) in which a microwave technique has been utilised to determine the thermal conductivity of a decaying glow discharge where the plasma constituents were also in thermal equilibrium. A detailed experimental investigation for determining the different process of heat flow in the positive column of a low pressure mercury arc has been recently performed by Ghosal et al (1979); it has been observed that the major part of the heat loss is due to diffusion and the loss due to conduction by electrons, ions and neutral particles is comparatively small. To see whether similar process of heat flow is maintained when we cross over from arc to glow transitions it will be of interest to find the contribution of electrons to total heat conductivity of a low pressure glow discharge.

To study the mechanism of heat loss in a plasma it is assumed that Elenbaas-Heller heat balance equation (Elenbaas, 1951) holds good with inclusion of a radiation terms. Hence analysing the experimental results the dominant process reponsible for heat flow can be identified. In the following section an indirect method of measuring the thermal conductivity of an ionised gas is presented and from the analysis of the results it is expected to find the process responsible for the propagation of heat in a plasma.

Theory of Measurement

In case of a partially ionised gas, it can readily be shown that the d.c. conductivity is given by

$$\sigma = \frac{n e^2}{m \nu_c}$$

where 'n' is the electron density, 'm' is the mass of the electron and ν_c is the collision frequency of the electrons with neutral atoms and molecules, as

$\nu_c = v_r/\lambda_e$ where v_r is the random velocity and

λ_e is the mean free path of the electrons

$$\sigma = \frac{n e^2 \lambda_e}{m v_r} \tag{3.1}$$

Further for a partially ionised gas it can be shown that if $\overline{K_e}$ is the thermal conductivity of the ionised gas taking the contribution of electrons only

$$\overline{K_e} = \frac{m v_r \lambda_e K}{2} \tag{3.2}$$

where v_r is the random velocity and λ_e the mean free path of the electron in the gas, K is the Boltzmann constant. Hence from eqn. (3.1) and (3.2) we get

$$\frac{\overline{K_e}}{\sigma} = \frac{m v_r^2}{2} \cdot \frac{K}{e^2}$$

If T_e is the electron temperature

$$\frac{1}{2} m \, v_r^2 = \frac{3}{2} K \, T_e$$

then

$$\frac{\overline{K_e}}{\sigma T_e} = \frac{3}{2} \left(\frac{K}{e}\right)^2 \tag{3.3}$$

a relation identical with Weidamann and Franz law which is known to be valid in case of metals. The principle of determination of $\overline{K_e}$ thus consists in measuring σ and then its value can be evaluated from (3.3).

Experimental Arrangement:- (The same has been given in Ch. II).

RESULTS AND DISCUSSION

The method that has been adopted here for the measurement of d.c. conductivity of the plasma is the standard method of measurement used in magnetohydrodynamics of plotting the current against the applied voltage. It is observed in all cases that except for a small region of applied voltage the curve is a straight line indicating the validity of Ohm's Law. The experiments have been carried out in air, hydrogen, oxygen and nitrogen for discharge current varying from 2 mA to 8 mA in case of air and from 2 mA to 6 mA in case of other gases. The measured value of the d.c. conductivity is shown in the fourth column in Table (3.1). Measurement of electron temperature in case of molecular gases such as air, hydrogen, oxygen and nitrogen has been carried out in this laboratory by a number of standard diagonistic methods such as radiofrequency probe method (Sen and Ghosh, 1966), single probe method (Sadhya, et al, 1979) and spectroscopic method (Sadhya & Sen, 1980a, 1980b). The values of electron temperature

Table (3.1)

Air P = 0.6 torr, T_e = 3870^oK.

Discharge current in mA	Specific Resistance ρ ohm/cm	Conductivity σ mhos/cm	$\overline{Ke}$ Cal.cm^{-1} sec^{-1} $^oK^{-1}$
2	0.971×10^6	1.029×10^{-6}	1.0603×10^{-4}
4	0.693×10^6	1.443×10^{-6}	1.4869×10^{-4}
6	0.647×10^6	1.545×10^{-6}	1.5921×10^{-4}
8	0.597×10^6	1.675×10^{-6}	1.7260×10^{-4}

$K_n = 5.4 \times 10^{-5}$ cal. cm^{-1} sec^{-1} $^oK^{-1}$ where K_n is the thermal conductivity of air.

Table (3.2)

Nitrogen P = 0.3 torr, T_e=1548^oK

Current in mA	ρ Ohm-cm	σ mho/cm	$\overline{Ke}$ Cal.cm^{-1} sec^{-1} deg.$^{-1}$ ^oC	Kn Cal.cm^{-1} deg^1 ^oC
2	$0.8137\times10^{+06}$	1.229×10^{-6}	5.0656×10^{-5}	
4	$0.5577\times10^{+06}$	1.7931×10^{-6}	7.3908×10^{-5}	5.6×10^{-5}
6	$0.4382\times10^{+06}$	3.2821×10^{-6}	9.4064×10^{-5}	

Table (3.3)

Oxygen P = 0.3 torr, T_e = 1560 °K

Current in mA	ρ ohms-cm	σ mho/cm	$\overline{Ke}$ Cal.cm^{-1} sec^{-1} deg.$^{-1}$ °C	Kn Cal.cm^{-1} sec^{-1} deg.$^{-1}$ °C
2	$0.8137 \times 10^{+6}$	1.229×10^{-6}	4.9086×10^{-4}	
4	$0.5726 \times 10^{+6}$	1.7464×10^{-6}	6.9750×10^{-4}	5.7×10^{-5}
6	$0.5663 \times 10^{+6}$	1.7658×10^{-6}	7.0526×10^{-4}	

Table (3.4)

Hydrogen P = 0.3 torr, T_e = 1000 °K

Current in mA	ρ ohm/cm	σ mho/cm	$\overline{Ke}$ K.cal.cm^{-1} sec^{-1} deg^{-1} °C	K_n Cal.cm^{-1} sec^{-1} deg^{-1} °C
2	$0.8924 \times 10^{+6}$	1.1206×10^{-6}	2.983×10^{-5}	
4	$0.4674 \times 10^{+6}$	2.1395×10^{-6}	5.6968×10^{-5}	39.6×10^{-5}
6	$0.3926 \times 10^{+6}$	2.5741×10^{-6}	2.7821×10^{-5}	

for air, hydrogen, nitrogen and oxygen have been obtained from these measurements for the particular value of (E/P) after taking into account cathode and anode fall. Further in a recent communication it has been shown by Sen and Ghosh (1984) that electron temperature practically remains constant for a wide range of discharge current. The results are quite consistent with the value given by von Engel (1964).

The results for nitrogen, oxygen and hydrogen have been entered in Table (3.2),(3.3),(3.4).

In case of an ionised gas if we make the general assumption that heat is conducted by electrons, ions, neutral atoms and molecules then leaving aside the contribution made by neutral atoms and molecules we note that if $\overline{K_e}$ and $\overline{K_i}$ are the contribution of electrons and ions then

$$\overline{K_e} = n_e\, v_{re}\, \lambda_e\, K/2$$

$$\overline{K_i} = n_i\, v_{ri}\, \lambda_i\, K/2$$

so that

$$\frac{\overline{K_e}}{\overline{K_i}} = \frac{n_e\, v_{re}\, \lambda_e}{n_i\, v_{ri}\, \lambda_i}$$

assuming $n_e = n_i$

$$\frac{\overline{K_e}}{\overline{K_i}} = \frac{v_{re} \; \lambda_e}{v_{ri} \; \lambda_i}$$

Since $\lambda_i = \frac{1}{n_i Q_{ia}}$ and $\lambda_e = \frac{1}{n_e Q_{ea}}$ where n_e and n_i are the electron and ion density and Q_{ea} and Q_{ia} are the respective collision cross sections and as $n_e = n_i$ and collision cross sections are of the same order of magnitude it can be assumed that $\lambda_e = \lambda_i$ or in terms of electron and ion temperatures

$$\frac{\overline{K_e}}{\overline{K_i}} = \sqrt{\frac{T_e \; m_i}{T_i \; m_e}}$$

Hence $$\frac{\overline{K_e}}{\overline{K_i}} \gg 1$$

and hence the contribution of electrons will be much greater than that of ions and the ionic contribution to heat conductivity can be neglected. Since the gas is partially ionised degree of ionization is low and density of neutral molecules will be large compared to electron and ion density.Hence neutral molecules contribute to heat conductivity.The ions due to their low density will contribute much less than that by neutrals, but electrons due to their high temperature will make significant contribution. Thus in general it can be concluded that in a partially ionised plasma the loss of heat by conduction can be attributed to electrons and neutral atoms only. It is however, well known that radial charge particle distribution in a gaseous discharge is not uniform which causes the phenomenon of ambipolar diffusion. Hence heat can be lost from the plasma by the process of diffusion as well.

Now considering one dimensional (Z) case and assuming that charged particles are undergoing ambipolar diffusion in the Z-direction of the plasma the steady state perturbed distribution function f_{e1} may be given by the relation

$$v_Z \frac{\partial f_{eo}(Z, v_x, v_y, v_z)}{\partial Z} + \frac{eE_Z}{m_e} \frac{\partial f_{eo}}{\partial v_Z} = -\nu_{me} f_{e1}$$

where f_{eo} and ν_{me} are the equilibrium distribution function and electron atom collision frequency respectively and E_Z is the field produced in the radial direction due to diffusion of charged particles. For the present case, equilibrium distribution function (Maxwellian) is given by

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

Assuming Bessalian radial distribution in a glow discharge after Schottky model

$$n(z) = n_0\, \phi(z) = n_0\, J_0\left(2{\cdot}405\, \frac{r}{R}\right)$$

The field E_Z which arrests the tendency of having unequal diffusion speeds for electrons and ions can be obtained as

$$E_z = -\frac{1}{\phi(z)}\,\frac{D_e - D_i}{\mu_e + \mu_i}\,\frac{d\,\phi(z)}{d\,z}.$$

assuming $(n_e = n_i)$ where D_e, μ_e, D_i and μ_i are the diffusion coefficients and mobilities of electrons and ions respectively.

The total distribution function $f_e = f_{e0} + f_{e1}$ for electrons undergoing diffusion may thus be obtained from eqns.

$$H_e = \iiint_{-\infty}^{+\infty} n_0 \left(\frac{1}{2} m_e v^2\right) v_z\, f_e\, dv_x\, dv_y\, dv_z$$

$$H_e = \iiint_{-\infty}^{+\infty} n_0 \left(\frac{1}{2} m_e v^2\right) v_z\, (f_{e0} + f_{e1})\, dv_x\, dv_y\, dv_z.$$

$$H_e = \iiint_{-\infty}^{+\infty} n_0 \left(\frac{1}{2} m_e v^2\right) v_z\, f_{e0}\, dv_x\, dv_y\, dv_z$$
$$+ \iiint^{+\infty} n_0 \left(\frac{1}{2} m_e v^2\right) v_z\, f_{e1}\, dv_x\, dv_y\, \partial v_z$$

[For Evaluation of Integral Please See Appendix I]

which is obtained as

$$H_e = -\frac{5}{2}\,\frac{n_o\,\phi(z)\,K^2}{m_e\sqrt{m_e}}\cdot T_e\,\frac{dT_e}{dz}$$
$$-\frac{5}{2}\,\frac{n_o}{m_e}\,\frac{K^2}{\sqrt{m_e}}\,T_e^2\,\frac{d\phi(z)}{dz}$$
$$+\frac{5}{2}\,n_o\,K\,T_e\,\mu_e\,\frac{D_e - D_i}{\mu_e + \mu_i}\,\frac{d\phi(z)}{dz}$$

or

$$H_e = -\overline{K_e}\,\frac{dT_e}{dz} - \frac{5}{2}\,D_e\,\frac{d\phi(z)}{dz}\,n_o\,K\,T_e$$
$$+\frac{5}{2}\,n_o\,K\,T_e\,\mu_e\,\frac{D_e - D_i}{\mu_e + \mu_i}\,\frac{d\phi(z)}{dz}$$

where

$$\overline{K_e} = \frac{5}{2}\,\frac{n_o\,\phi(z)\,K^2}{m_e\sqrt{m_e}}\,T_e$$

If we assume that $\phi(z) = 1$ i.e. there is no variation of radial electron density or the plasma is radily uniform

$$\overline{K_e} = \frac{5}{2}\,\frac{n\,K^2\,\lambda_e}{m_e\,v_r}\,T_e$$

where $n = n_0$, and $\nu_{me} = \dfrac{v_r}{\lambda_e}$ where v_r is the random velocity and λ_e the mean free path of the electron and as

$$\frac{1}{2} m v_r^2 = \frac{3}{2} K T_e$$

$$\overline{K_e} = n v_r \lambda_e K / 1.2 \quad \cdots 3.4$$

which differs from the value of $\overline{K_e}$ eqn.(3.4) only in a numerical factor and hence $\overline{K_e}$ can be identified as the electronic thermal conductivity

Further

$$-\frac{5}{2} D_e \frac{d\phi(z)}{dz} n_0 K T_e + \frac{5}{2} n_0 K T_e \mu_e \frac{D_e - D_i}{\mu_e + \mu_i} \frac{d\phi(z)}{dz}$$

$$= -\frac{5}{2} n_0 K T_e \left[D_e - \mu_e \frac{D_e - D_i}{\mu_e + \mu_i} \right] \frac{d\phi(z)}{dz}$$

$$= -\frac{5}{2} n_0 K T_e D_A \frac{d\phi(z)}{dz}$$

where D_A is the ambipolar diffusion coefficient as

$D_A = D_e \dfrac{\mu_i}{\mu_e}$ and the contribution of electrons to heat propagation by conductivity and diffusion is

$$H_e = -K_e \frac{dT_e}{dz} - \frac{5}{2} n_0 K T_e \frac{\mu_i}{\mu_e} D_e \frac{d\phi(z)}{dz}.$$

The total heat flux will contain other terms such as that due to ions and neutral particles but as has been shown here the contribution of ions can be neglected.

Hence the total heat flux can be written assuming cylindrical symmetry where Z can be replaced by the radial variable 'r' as

$$H = -\bar{K}_e \frac{dT}{dr} - \frac{5}{2} n_0 K T_e \frac{\mu_i}{\mu_e} D_e \frac{d\phi(r)}{dr} - K_n \frac{dT_n}{dr}$$

At this stage let us assume the Ellenbaas Heller heat balance equation as the model which can be written as an equation expressing the balance of the three terms, namely

1. heat transfer by Joule effect
2. heat transfer by thermal conduction and other process if any
3. heat transfer by radiation

It is however, known that radiation effect specially in case of gaseous discharge plasma is small and it is a few percent of the total loss and we shall neglect this heat loss for the present.

Hence we can write in the case of present investigation if 'J' is the discharge current density and ρ the specific resistance

$$J^2 \rho = \bar{K}_e \, \phi(r) \frac{dT_e}{dr} + K_n \frac{dT_n}{dr} + H_D$$

where H_D is the loss of heat due to ambipolar diffusion and

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

and $$\phi(r) = J_0\left(2.405 \frac{r}{R}\right)$$

If T_{n0} and T_{nw} denote the temperature at the axis and at the wall and T_{e0} and T_{ew} the corresponding electron temperature and if the longitudinal electric field of the plasma is assumed to be uniform throughout the cross section of the plasma the quantity T_e becomes a constant parameter within it. This is true since the electron temperature T_e in the constant collision approximation is related to neutral particles temperature T_n and the applied electric field as shown by Persson (1961)

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

where M and m are the mass of neutral gas particle and electron respectively and K is the Boltzmann constant. Thus it can be assumed that

$$T_{eo} - T_{no} = T_{e\omega} - T_{n\omega}$$

and we get

$$J^2 \rho = \left[\bar{K}_e \, \phi(r) + K_n \right] \frac{(T_{no} - T_{n\omega})}{R} + H_D$$

or

$$J^2 \rho = H_e + H_n + H_D$$

The value of $(T_{no} - T_{n\omega})$ has been calculated from an analytical expression given by Mewe (1970)

$$T_{no} - T_{n\omega} = 9.3 \times 10^3 \, I \cdot P \, \langle U_e \rangle \left(\frac{E}{P} \right)^{-1}$$

where I is the discharge current in amperes, $\langle U_e \rangle$ the mean energy of the electrons expressed in electron volts, E/P is in volt meter^{-1}torr^{-1} and P is ~~x~~ in torr. For the gases considered here ($T_{no} - T_{n\omega}$) varies between 5^o to 3.5^{o}K.

Assuming $\phi(r) = J_0\left(2\cdot405\,\frac{r}{R}\right)$ we can find $\overline{He}$ and Hn and hence H_D and the results for air, hydrogen, oxygen and nitrogen are entered in Table below.

Table (3.3)

J current density x 10^3	E volt/cm	J^2 P calories	H_e calories	H_n calories	H_D calories	σ_{ia} $cm^2 x 10^{+16}$
			Air			
2.4978	7	6.0583	.000382	.000270	6.0576	15.2
4.9956	13.5	17.2953	.000535	.000270	17.2945	5.32
7.4934	20	36.3313	.000572	.000270	36.3305	2.53
9.9913	22	59.5976	.000621	.000270	59.5967	1.55
			Nitrogen			
3.9809	57.5	12.8954	.000182	.000284	12.8949	1.17
7.9618	112.5	35.3534	.000265	.000284	35.3529	0.43
11.9427	160.0	61.6307	.000378	.000284	61.6300	0.25

Table contd......

Table 3.3 (Contd....)

			Oxygen			
3.9809	75	12.8954	.000176	.000285	12.8949	1.04
7.9618	105	36.2979	.000250	.000285	36.2974	0.37
11.9427	155	80.7718	.000253	.000285	80.7713	0.17
			Hydrogen			
3.9809	65.0	14.1426	.000107	.00198	14.1405	1.69
7.9618	102.5	29.6292	.000204	.00198	29.6207	0.81
11.9427	160.0	55.9968	.000244	.00198	55.9946	0.43

From the results it is evident that in case of all the gases the heat lost by conduction by electrons and neutral atoms is insignificant in comparison to that carried on by diffusion.

Major portion of heat loss is thus due to ambipolar diffusion which was also previously observed in case of mercury arc by Ghosal et al (1979).

Further

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

as $$\frac{\mu_e}{D_e} = \frac{e}{K T_e}$$

$$H_D = \frac{5}{2} n_0 K^2 T_e^2 \frac{\mu_i}{e} \frac{d\phi(r)}{dr}$$

$$= \frac{5}{2} n_0 \frac{K^2 T_e^2}{M \nu_{ia}} \cdot \frac{d\phi(r)}{dr}$$

$$= \frac{5}{2} n_0 \frac{K^2 T_e^2 \lambda_i}{M \bar{v}_{ia}} \frac{d\phi(r)}{dr}$$

as σ_{ia} the collision cross section for ions

$$\sigma_{ia} = \frac{1}{n_0 \lambda_i} \quad \text{and} \quad v_{ri} = \left(\frac{3KT_i}{M} \right)^{1/2}$$

where T_i is the ion temperature

$$H_D = \frac{5}{2} \frac{K^{3/2} T_e^{2}}{\sqrt{3}\, \sigma_{ia} (M T_i)^{1/2}} \frac{d\phi(r)}{dr}$$

from which expression σ_{ia} the collision cross section for ions can be calculated. It is known from measurements of ion and electron temperature (Brown 1959) that in case of glow discharge in molecular gases the ion temperature is of the same order as the gas temperature and hence T_i has been taken to be equal to gas temperature in the calculation of σ_{ia} from the above expression.

From Table (3.3) it is evident that the contribution to the heat propagation in the positive column of glow discharge due to heat conductivity of electrons and neutral atoms is extremely small and the major portion of heat is propagated due to diffusion of electrons. Similar results have been obtained previously in the positive column of a mercury arc Ghosal et al (1979).

The present investigation further provided us with a method for calculating the ion atom collision cross section. The results are plotted in Figs. (3.2, 3.3, 3.4 and 3.5) for air, nitrogen, oxygen and hydrogen. The results are consistent with the data reported earlier by Muschilitz and Simons (1952) and Muschlitz et al (1956). The ion atom collision cross section is a function of the mean free path of ions and as in the case of electrons the meanf free path is a function of the energy of ions which is dependent upon the voltage of discharge.

Appendix - 1

Evaluation of the integrals

Formula used

$$\int_0^\infty e^{-\beta U^2} U^{2K}\, dU = \frac{1\cdot 3 ---- 2(K-1)}{2^{K+1}} \sqrt{\frac{\pi}{\beta^{2K+1}}}$$

(i) Since f_{eo} is even function of V, $\left(\frac{1}{2} m_e v^2\right) v_z$ is the odd function of velocity

The integral

$$\iiint_{-\infty}^{+\infty} n_o \left(\frac{1}{2} m v^2\right) v_z f_{eo}\, dv_x\, dv_y\, dv_z$$

vanishes

(ii)

$$\iiint_{-\infty}^{+\infty} n_0 \left(\frac{1}{2} m_e v^2\right) v_z f_{e1}\, dv_x\, dv_y\, dv_z$$

$$= \frac{n_0 m_e}{2} \iiint_{-\infty}^{+\infty} (v_x^2 v_z + v_y^2 v_z + v_z^3) \left(\frac{-v_z}{\sqrt{m_e}}\right) \frac{\partial f_{eo}}{\partial z}\, dv_x\, dv_y\, dv_z.$$

$$= \frac{n_0 m_e}{2\sqrt{m_e}} \left(\frac{a}{T_e}\right)^{3/2} e^{-b/T_e} \frac{\partial \phi(z)}{\partial z} \iiint_{-\infty}^{+\infty} (v_x^2 v_z^2 + v_y^2 v_z^2 + v_z^4) e^{-\beta v^2}\, dv_x\, dv_y\, dv_z.$$

$$- \frac{n_0 m_e}{2\sqrt{m_e}} \phi(z) \iiint_{-\infty}^{+\infty} (v_x^2 v_z^2 + v_y^2 v_z^2 + v_z^4) \frac{\partial}{\partial T_e} \left(\frac{a}{T_e}\right)^{3/2} e^{-b/T_e} \frac{\partial T_e}{\partial z}\, dv_x\, dv_y\, dv_z.$$

The first part of the right hand side equation can be written as

$$= \text{Const} \left[\int v_x^2 v_z^2 e^{-\beta v^2} dv_x\, dv_y\, dv_z + \int v_y^2 v_z^2 e^{-\beta v^2} dv_x\, dv_y\, dv_z + \int v_z^4 e^{-\beta v^2} dv_x\, dv_y\, dv_z \right]$$

$$= \text{const} \left[\frac{1}{4} \frac{\pi^{3/2}}{\beta^{7/2}} + \frac{1}{4} \frac{\pi^{3/2}}{\beta^{7/2}} + \frac{3}{4} \frac{\pi^{3/2}}{\beta^{7/2}} \right]$$

$$= \text{const} \; \frac{5}{4} \frac{\pi^{3/2}}{\beta^{7/2}}$$

$$= -\frac{5}{2} \frac{n_0 K^2 Te^2}{\sqrt{me}\; me} \frac{d\phi(z)}{dz}.$$

Similarly the second part of equation can be obtained

$$-\frac{5}{2} \frac{n\,\phi(z) K^2}{me \sqrt{me}} Te \frac{dTe}{dz}.$$

and the third part of the equation

$$\frac{5}{2} n_o K T_e \mu_e \frac{D_e - D_i}{\mu_e + \mu_i} \frac{d\phi(z)}{dZ}.$$

can be obtained from

$$H = \iiint_{-\infty}^{+\infty} n_o \left(\frac{1}{2} m_e v^2\right) f_{e_1} \, dv_x \, dv_y \, dv_z$$

$$= \frac{e}{\nu_{me} m_e} \frac{D_e - D_i}{\mu_e + \mu_i} \frac{1}{\phi(z)} \frac{d\phi(z)}{dZ}$$

$$\iiint_{-\infty}^{+\infty} n_o \left(\frac{1}{2} m v^2\right) \frac{\partial f_{eo}}{\partial v_z} dv_x \, dv_y \, dv_z$$

$$= \text{Const} \iiint_{-\infty}^{+\infty} v^2 v_z^2 e^{-Bv^2} dv_x \, dv_y \, dv_z.$$

$$= \text{Const} \frac{5}{4} \frac{\pi^{3/2}}{B^{7/2}}$$

$$= \frac{5}{2} n_o K T_e \mu_e \frac{D_e - D_i}{\mu_e + \mu_i} \frac{d\phi(z)}{dZ}$$

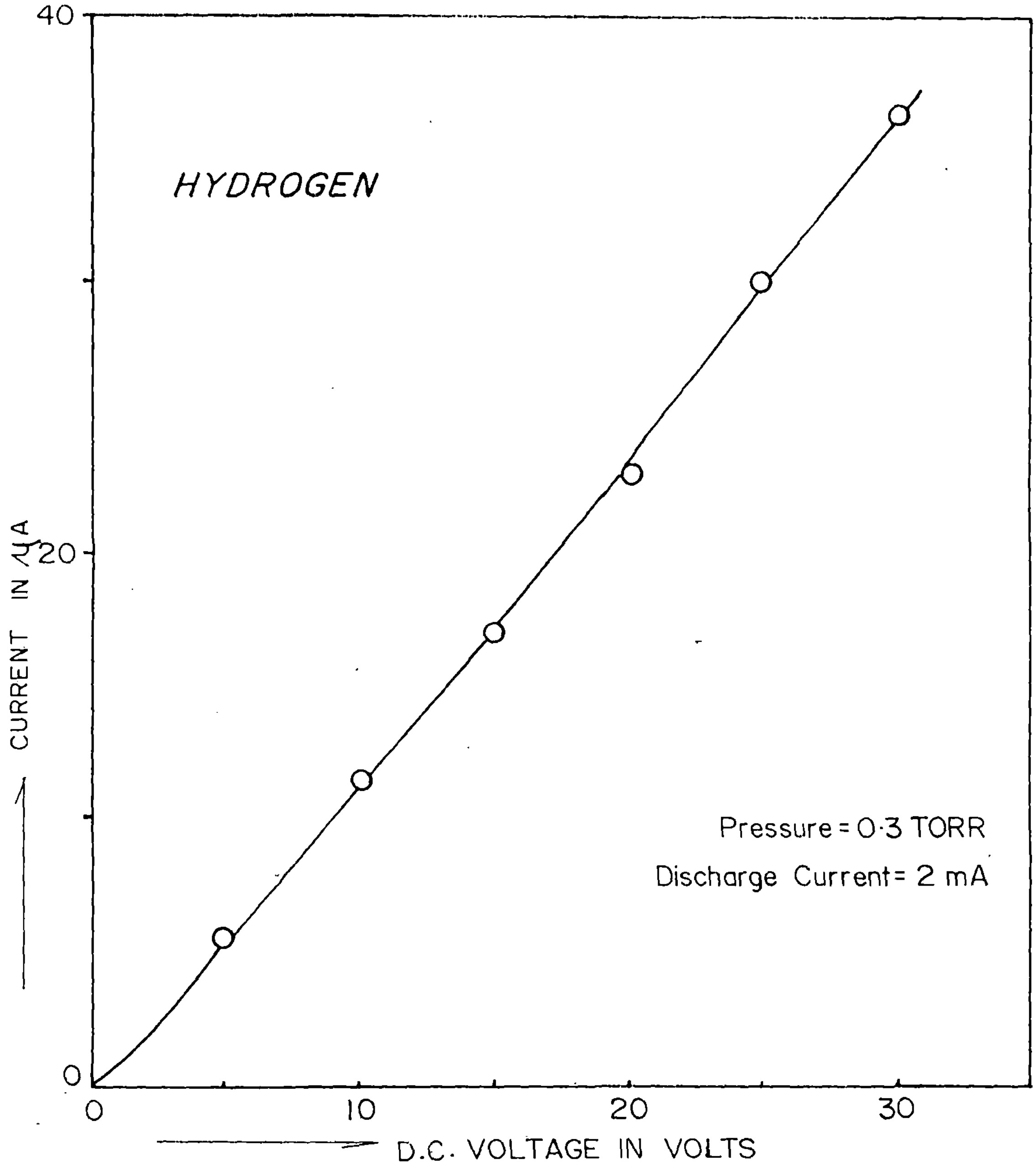

Fig. (3.1) Variation of current in Hydrogen plasma against applied external voltage.

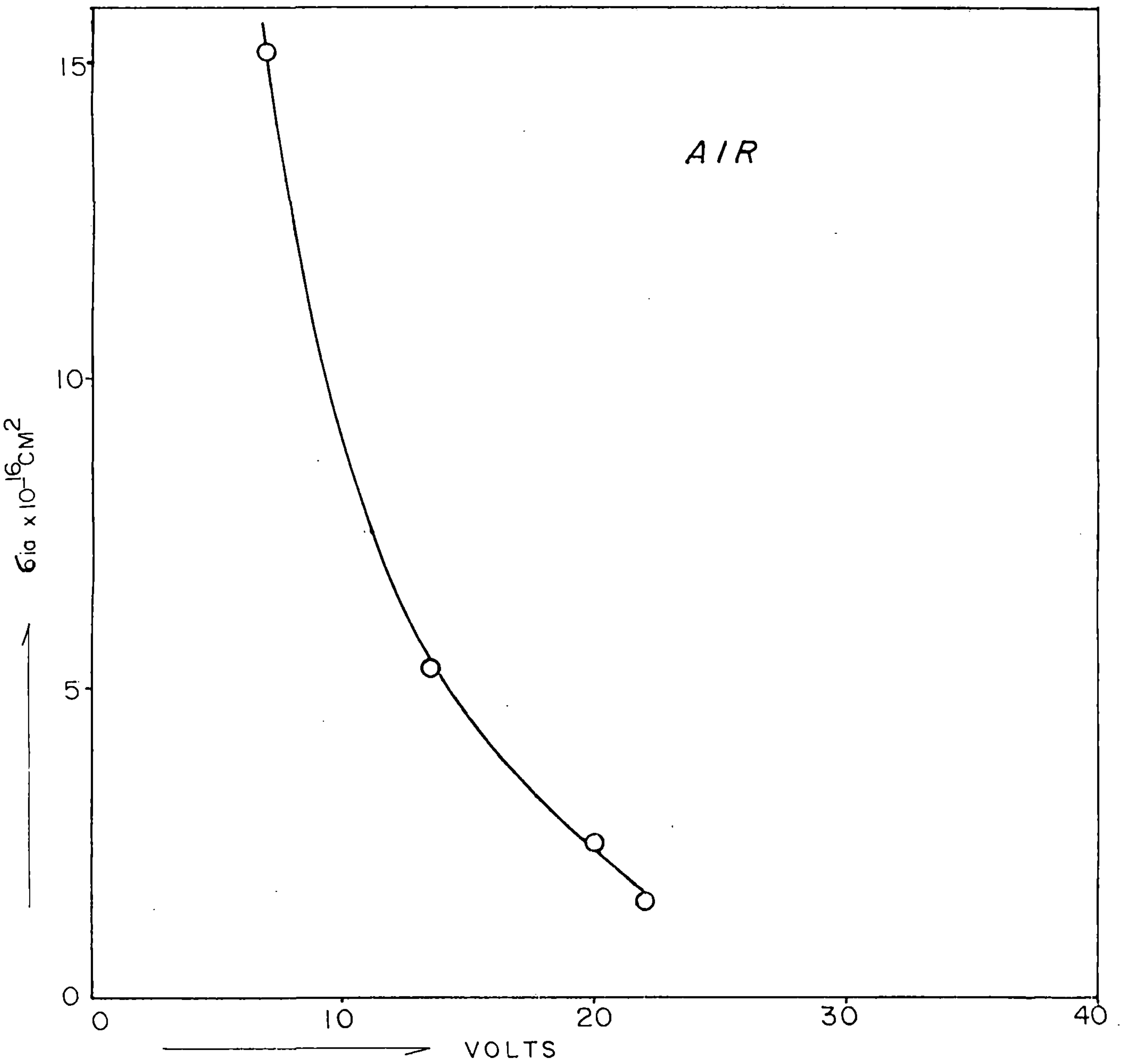

Fig. (3·2) Variation of ion atom collision cross section in air.

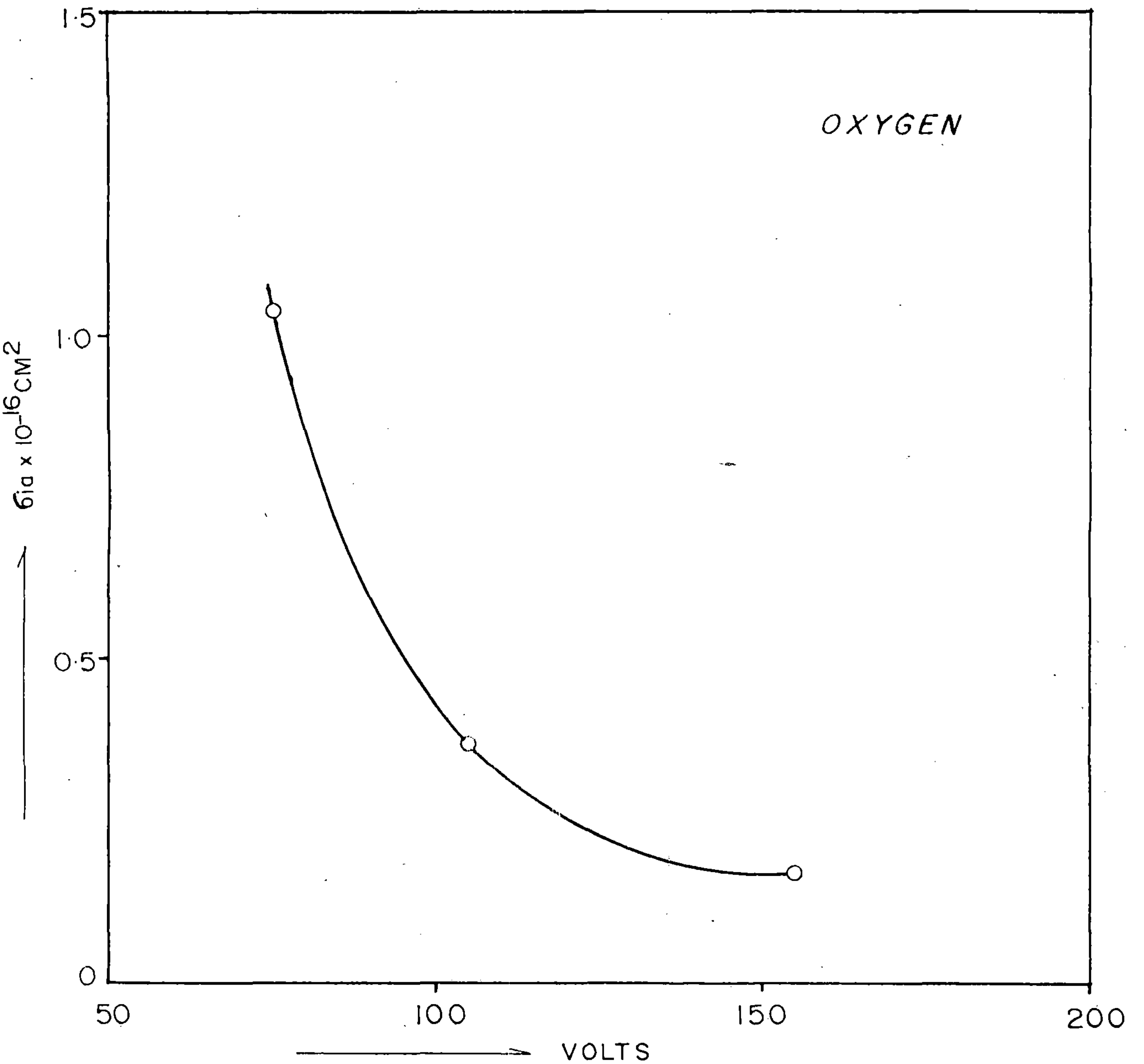

Fig. (3·3) Variation of ion atom collision cross section in Oxygen.

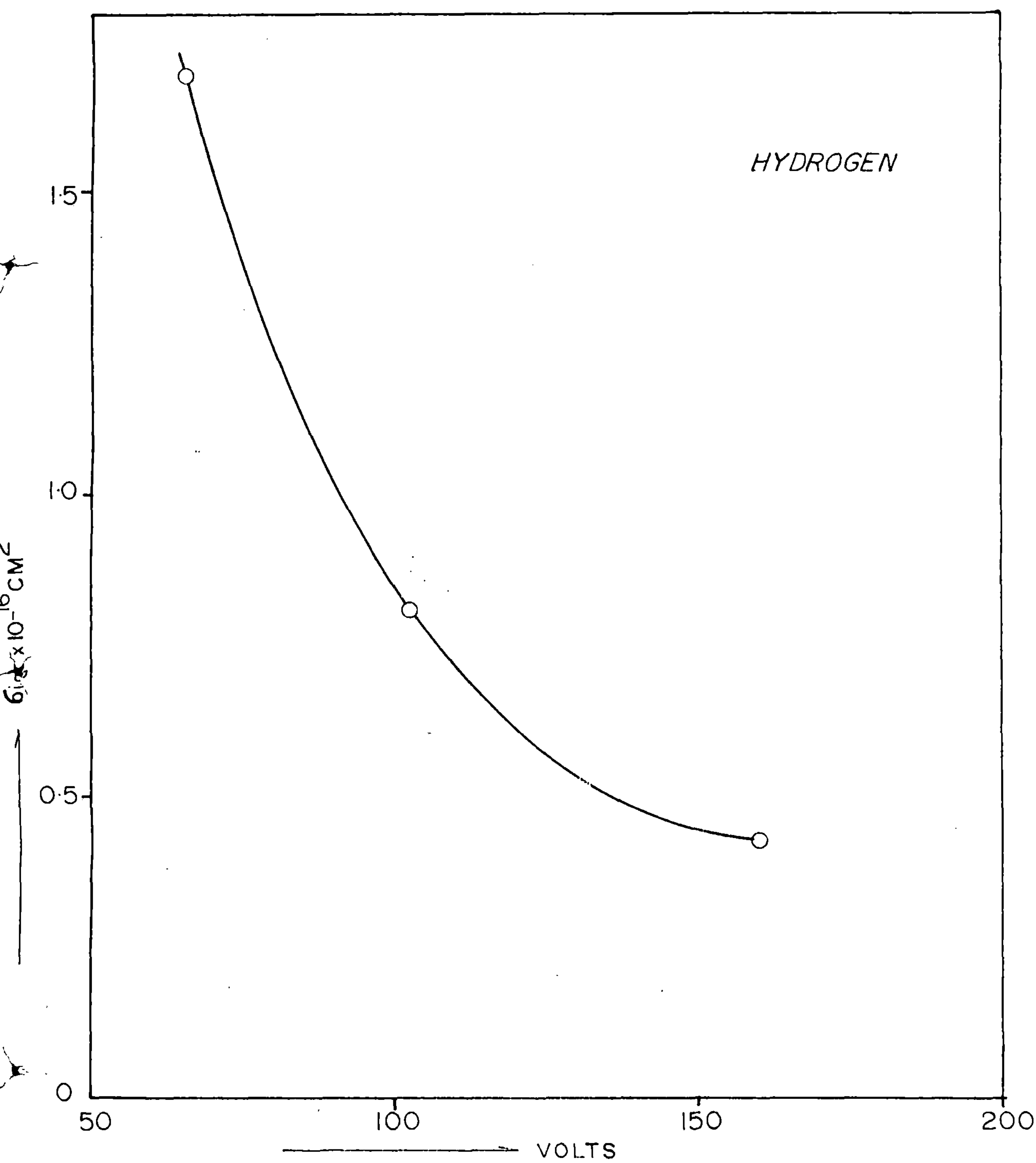

Fig. (3·4) Variation of ion atom collision cross section in Hydrogen.

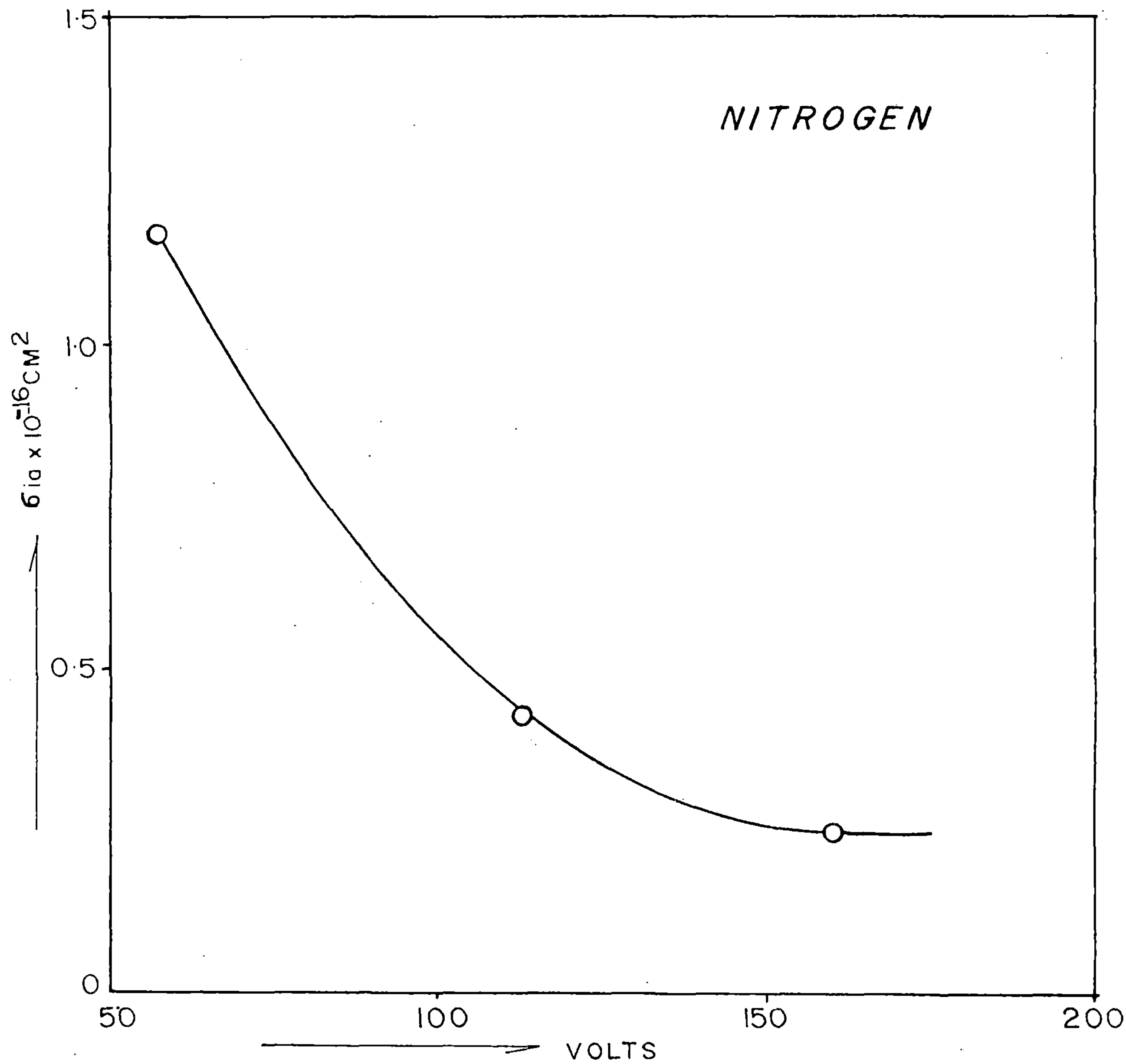

Fig. (3·5) Variation of ion atom collision cross section in Nitrogen.

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Printed in India.
Plasma Physics

HEAT FLOW PROCESSES IN THE POSITIVE COLUMN OF A GLOW DISCHARGE

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(*Received 28 July 1981*; *after revision 13 April 1982*)

The electronic thermal conductivity of ionised gases such as air, hydrogen, nitrogen and oxygen has been measured for discharge currents varying from 2 mA to 8 mA. The problem of heat flow processes in the positive column of the glow discharge has been investigated utilizing the first order perturbation technique to Boltzmann Transport equation incorporting the radial distribution of charged particles which is assumed to be Bessalian. The loss is due to heat conductivity of electrons, ions and neutral particles and also due to ambipolar diffusion of electrons. The experimental results enable us to calculate separately the contribution by different processes and it is observed that the major part of the heat loss is due to diffusion. Further from the experimental results it has been possible to calculate σ_{ia}, the ion atom collision cross section.

Keywords : Glow Discharge; Thermal Conductivity; Ambipolar Diffusion

INTRODUCTION

THERE have been a large amount of theoretical work regarding the kinetic properties of partially and fully ionised gases and from these generalised theories it has been possible to deduce expressions for the thermal conductivity of an ionised gas. The direct experimental determination of thermal conductivity of an ionised gas has been little reported so far. The standard method of determining the thermal conductivity of a gas is not applicable in case of an ionised gas as the presence of the central conducting wire perturbs the state of the plasma and vitiates the results to a large extent. An elegant experiment has however, been done by Goldstein and Sekiguchi (1958) in which a microwave technique has been utilized to determine the thermal conductivity of a decaying glow discharge where the plasma constituents were also in thermal equilibrium. A detailed experimental investigation for determining the different processes of heat flow in the positive column of a low pressure mercury arc has been recently performed by Ghosal, *et al.* (1979) and it has been observed that the major part of the heat loss is due to diffusion and the loss due to conduction by electrons, ions and neutral particles is compartively small. To see whether similar processes of heat flow are maintained when we cross over from arc to glow transition, it will be of interest to find the contribution of electrons to total heat conductivity of a low pressure glow discharge. To study the mechanism of heat loss in a plasma it is assumed that Elenbaas-Heller heat balance equation (Elenbaas, 1951) holds good with the inclusion of a radiation term. Hence utilizing this equation experimental results will be analysed and the dominant process responsible for heat flow can be identified. In the following section an indirect method of measuring the thermal conductivity of an ionised gas is presented and from the analysis of the results it is expected to find the processes responsible for the propagation of heat in a plasma.

THEORY OF MEASUREMENT

In case of a partially ionised gas, it can readily be shown that the d.c. conductivity is given by

$$\sigma = \frac{ne^2}{m\nu_e}$$

where n is the electron density, m the mass of the electron and ν_c is the collision frequency of the electrons with neutral atoms and molecules; as $\nu_c = \frac{\nu_r}{\lambda_e}$ where ν_r is the random velocity and λ_e the mean free path of the electron

$$\sigma = \frac{ne^2\lambda_e}{m\nu_r}. \qquad \text{...(1)}$$

Further also for a partially ionised gas it can be shown that if $\bar{K}_e$ is the thermal conductivity of the ionised gas taking the contribution of electrons only

$$\bar{K}_e = \frac{n\nu_r\lambda_e k}{2} \qquad \text{...(2)}$$

where ν_r is the random velocity and λ_e the mean free path of the electron in the gas K is the Boltzman constant. Hence from eqns. (1) and (2) we get

$$\frac{\bar{K}_e}{\sigma} = \frac{m\nu_r^2}{2} \cdot \frac{K}{e^2}$$

If T_e is the electron temperature

$$\tfrac{1}{2}\, m\nu_r^2 = \tfrac{3}{2}\, KT_e$$

then

$$\frac{\bar{K}_e}{\sigma T_e} = \tfrac{3}{2}\left(\frac{K}{e}\right)^2 \qquad \text{...(3)}$$

a relation identical with Weidamann and Franz law which is known to be valid in case of metals. The principle of determination of $\bar{K}_e$ thus consists in measuring σ and then its value can be evaluated from eqn. (3).

EXPERIMENTAL SET UP

The block diagram of the experimental arrangement is shown in Fig. 1. The discharge tube is provided with four electrodes A, B, C and D of which the electrodes

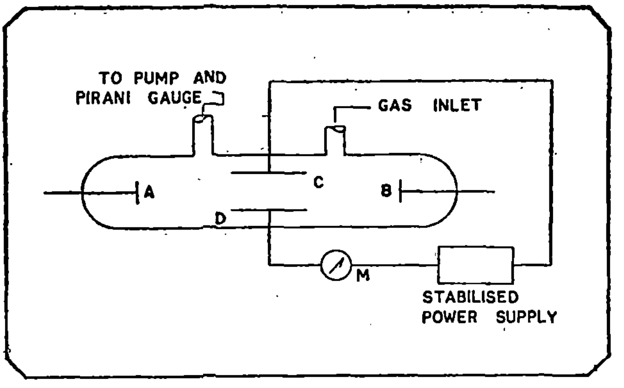

FIG. 1 Experimental set up.

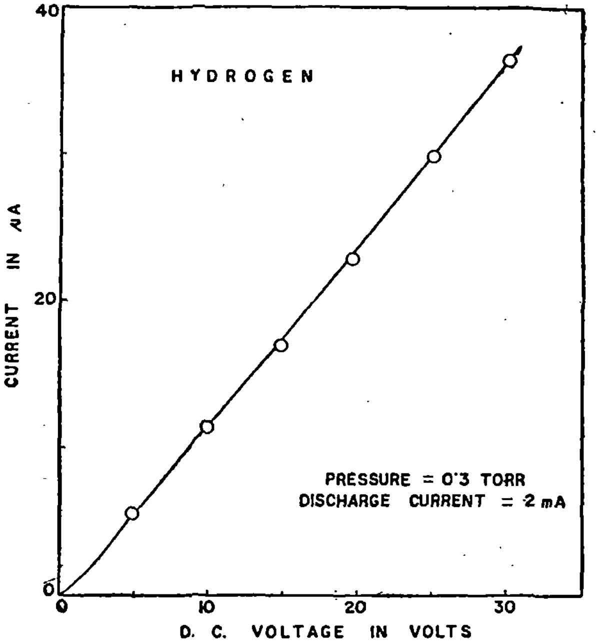

FIG. 2. Variation of current in hydrogen plasma against applied external voltage.

A and *B* connected to a source of high voltage are used to excite the discharge, the pressure of the gas under investigation is measured with an accurately calibrated pirani gauge. An external variable voltage from a stabilized power supply is applied to the electrodes *C* and *D*. The plasma within the electrodes *C* and *D* acts as a conducting medium and with the plasma on, the current is measured in the microammeter *M* for different values of the applied voltages; a representative curve is shown in Fig. 2 for hydrogen and the nature of the curve is the same for all the gases investigated. From the linear portion of the curve the resistance and hence the conductivity of the plasma has been calculated. The electron temperature of the gases has been measured previously by Sadhya *et al.* (1979) for all the gases under identical conditions, using Langmuir probe method.

Results and Discussion

The method that has been adopted here for the measurement of d.c. conductivity of the plasma is the standard method of measurement used in Magnetohydrodynamics of plotting the current against the applied voltage. It is observed in all cases that except for a small region of applied voltage the curve is a straight line indicating the validity of ohm's law. A single representative curve is shown in Fig. 2. The experiment has been carried out in air, hydrogen, oxygen and nitrogen for discharge current varying from 2 mA to 8 mA in case of air and from 2 mA to 6 mA in case of other gases. The measured values of the d.c. conductivity is shown in the fourth column in Table I.

TABLE I

Air $P=0.6$ *torr*, $T_e = 3870\ ^\circ K$

Discharge current mA	Specific resistance ρ Ohms. cm.	Conductivity σ mhos/cm	$\bar{K}_e$ Cal. cm^{-1} sec^{-1} $^\circ K^{-1}$
2	0.971×10^6	1.029×10^{-6}	1.0603×10^{-4}
4	0.693×10^6	1.443×10^{-6}	1.4869×10^{-4}
6	0.647×10^6	1.545×10^{-6}	1.5921×10^{-4}
8	0.597×10^6	1.675×10^{-6}	1.7260×10^{-4}

$K_n = 5.4 \times 10^{-5}$ Cal. cm^{-1} sec^{-1} $^\circ K^{-1}$ where K_n is the thermal condutivity of air.

Measurement of electron temperature in case of molecular gases such as air, hydrogen, oxygen and nitrogen has been carried out in this laboratory by a number of standard diagonistic methods such as radio frequency probe method (Sen & Ghosh, 1966), single probe method (Sadhya, *et al.*, 1979) and spectroscopic method (Sadhya & Sen, 1980*a*; 1980*b*). The values of electron temperature for air, hydrogen, nitrogen and oxygen have been obtained from these measurements for the particular value of (E/P) after taking into account the cathode and anode fall. Further, in a recent communication it has been shown by Sen and Ghosh (1981) that electron temperature practically remains constant for a wide range of discharge current. The results are quite consistent with the value given by von-Engel (1964).

The results for nitrogen, oxygen and hydrogen have been entered in Table II.

In case of an ionised gas if we make the general assumption that heat is conducted by electrons, ions, neutral atoms and molecules then leaving aside the contribution made by the neutral atoms and molecules we note that if $\bar{K}_e$ and $\bar{K}_i$ are the contributions of electrons and ions then

TABLE II

Nitrogen $P = 0.3$ *torr*, $T_e = 1548°K$

Current in mA	ρ ohms. cm	σ mho/cm	$\overline{K_e}$ Cal. cm^{-1} sec^{-8} degree^{-1} °C	K_n Cal. cm^{-1} sec^{-1} degree^{-1} °C
2	$0.8137 \times 10^{+6}$	1.229×10^{-6}	5.0656×10^{-5}	
4	$0.5577 \times 10^{+6}$	1.7931×10^{-6}	7.3908×10^{-5}	5.6×10^{-5}
6	$0.4382 \times 10^{+6}$	3.2821×10^{-6}	9.4064×10^{-5}	

Oxygen $P = 0.3$ *torr*, $T_e = 1560°K$

Current in mA	ρ ohms. cm	σ mho/cm	$\overline{K_e}$ Cal. cm^{-1} sec^{-1} degree^{-1} °C	K_n Cal. cm^{-1} sec^{-1} degree^{-1} °C
2	$0.8137 \times 10^{+6}$	1.229×10^{-6}	4.9086×10^{-4}	
4	$0.5726 \times 10^{+6}$	1.7464×10^{-6}	6.9750×10^{-4}	5.7×10^{-5}
6	$0.5663 \times 10^{+6}$	1.7658×10^{-6}	7.0526×10^{-4}	

Hydrogen $P = 0.3$ *torr* $T_e = 1000°K$

Current in mA	ρ ohms/cm	σ mho/cm	$\overline{K_e}$ K Cal. cm^{-1} sec^{-1} degree^{-1} °C	K_n Cal. cm^{-1} sec^{-1} degree^{-1} °C
2	$0.8924 \times 10^{+6}$	1.1206×10^{-6}	2.983×10^{-5}	
4	$0.4674 \times 10^{+6}$	2.1395×10^{-6}	5.6968×10^{-5}	39.6×10^{-5}
6	$0.3926 \times 10^{+6}$	2.5741×10^{-6}	2.7821×10^{-5}	

$$\overline{K_e} = n_e v_{re} \lambda_e k/2.$$

$$\overline{K_i} = n_i v_{ri} \lambda_i k/2.$$

So that

$$\frac{\overline{K_e}}{\overline{K_i}} = \frac{n_e v_{re} \lambda_e}{n_i v_{ri} \lambda_i}$$

assuming

$$n_e = n_i, \quad \frac{\overline{K_e}}{\overline{K_i}} = \frac{v_{re}\lambda_e}{v_{ri}\lambda_i}$$

Since $\lambda_i = \dfrac{1}{n_i Q_{ia}}$ and $\lambda_e = \dfrac{1}{n_e Q_{ea}}$ where n_e and n_i are the electron and ion density and Q_{ea} and Q_{ia} are the respective collision cross sections and as $n_e = n_i$

and collision cross sections are of the same order of magnitude it can be assumed that $\lambda_e \simeq \lambda_i$ or in terms of electron and ion temperatures

$$\frac{\overline{K}_e}{\overline{K}_i} = \sqrt{\frac{T_e}{T_i}\frac{m_i}{m_e}}.$$

Hence

$$\frac{\overline{K}_e}{\overline{K}_i} \gg 1.$$

and hence the contribution of electrons will be much greater than that of ions and the ionic contribution to heat conductivity can be neglected. Since the gas is partially ionised degree of ionization is low and density of neutral molecules will be large compared to electron and ion density. Hence neutral molecules contribute to heat conductivity. The ions due to their low density will contribute much less than that by neutrals, but electrons due to their high temperature will make significant contribution. Thus in general it can be concluded that in a partially ionised plasma the loss of heat by conduction can be attributed, to electrons and neutral atoms only. It is however, well known that radial charge particle distribution in a gaseous discharge is not uniform which causes the phenomena of ambipolar diffusion. Hence heat can be lost from the plasma by the process of diffusion as well.

Now considering one dimensional (Z) case and assuming that charged particles are undergoing ambipolar diffusion in the Z-direction of the plasma, the steady state perturbed distribution function f_{e1} may be given by the relation

$$v_z \frac{\partial f_{eo}(Z, v_x v_y v_z)}{\partial Z} + \frac{eE_z}{m_e} \cdot \frac{\partial f_{eo}}{\partial v_z} = - \nu_{me} f_{e1}. \qquad \text{...(4)}$$

where f_{eo} and ν_{me} are the equilibrium distribution function and electron atom collision frequency respectively and E_z is the field produced in the radial direction due to diffusion of charged particles. For the present case, equilibrium distribution function (Maxwellian) is given by

$$f_{eo}(Z, v_x v_y v_z) = \varphi(z) \left(\frac{m_e}{2\pi K T_e}\right)^{3/2} \exp\left(-\frac{m_e^2}{2KT_e}\right) \qquad \text{...(5)}$$

Assuming Bessalian radial distribution in a glow discharge after Schottky model

$$n(z) = n_0 \varphi(z) = n_0 J_0 \left(2.405 \frac{r}{R}\right) \qquad \text{...(6)}$$

The field E_z which arrests the tendency of having unequal diffusion speeds for electrons and ions can be obtained as

$$E_z = - \frac{1}{\varphi(z)} \frac{D_e - D_i}{\mu_e + \mu_i} \frac{d\varphi(z)}{dz} \qquad \text{...(7)}$$

assuming ($n_e = n_i$) where D_e , μ_e , D_i and μ_i are the diffusion coefficients and mobilities of electrons and ions respectively.

The total distribution function $f_e = f_{e0} + f_{e1}$ for electrons undergoing diffusion may thus be obtained from eqns. (4), (5) and (7). Thus one finds the electronic contribution to heat flux by using the relation

$$H_e = \iiint_{-\infty}^{\infty} n_0 \left(\tfrac{1}{2} m_e v^2\right) v_z f_e dv_x dv_y dv_z.$$

which is obtained as

$$H_e = -\tfrac{5}{2}. \frac{n_0 \varphi(z) K^2}{m_e \nu_{me}}. T_e \frac{dTe}{dz} - \tfrac{5}{2} \frac{n_0}{m_e} \frac{K^2}{\nu m_e}. T_e^2 \frac{d\varphi(z)}{dz}$$
$$+ \tfrac{5}{2} n_0 K T_e \mu_e \frac{D_e - D_i}{\mu_e + \mu_i} \frac{d\varphi(z)}{dZ}.$$

or

$$H_e = -\bar{K}_e \frac{dT_e}{dz} - \tfrac{5}{2} D_e \frac{d\varphi(z)}{dz} n_0 K T_e + \tfrac{5}{2} n_0 K T_e \mu_e \frac{D_e - D_i}{\mu_e + \mu_i} \frac{d\varphi(z)}{dz}$$

where

$$\bar{K}_e = \tfrac{5}{2} \cdot \frac{n_0 \varphi(z) K^2}{m_e \nu_{me}} T_e.$$

If we assume that $\varphi(z) = 1$ i.e. there is no variation of radial electron density or the plasma is redially uniform

$$\bar{K}_e = \tfrac{5}{2}. \frac{nk^2 \lambda_e}{m_e v_r}.$$

where $n = n_0$ and $\nu_{me} = \dfrac{v_r}{\lambda_e}$ where v_r is the random velocity and λ_e the mean free path of the electron and as

$$\tfrac{1}{2} m v_r^2 = \tfrac{3}{2} K T_e$$

$$\bar{K}_e = n v_r \lambda_e K / 1.2.$$

which differs from the value of $\bar{K}_e$ eqn. (2) only in a numerical factor and hence $\bar{K}_e$ can be identified as the electronic thermal conductivity.

Further

$$-\tfrac{5}{2}. D_e \frac{d\varphi(z)}{dZ} n_0 K T_e + \tfrac{5}{2} n_0 K T_e \mu_e \frac{D_e - D_i}{\mu_e + \mu_i} \frac{d\varphi(z)}{dZ}$$

$$= -\tfrac{5}{2} n_0 K T_e \left[D_e - \mu_e \frac{D_e - D_i}{\mu_e + \mu_i} \right] \frac{d\varphi(z)}{dz}.$$

$$= -\tfrac{5}{2} n_0 K T_e D_A \frac{d\varphi(z)}{dZ}.$$

where D_A is the ambipolar diffusion coefficient

as $$D_A = D_e \frac{\mu_i}{\mu_e}.$$

the contribution of electrons to heat propagation by conductivity and diffusion is

$$H_e = -K_e \frac{dT_e}{dz} - \tfrac{5}{2}\, n_0\, KT_e \frac{\mu_i}{\mu_e} D_e \frac{d\varphi(z)}{dZ}$$

The total heat flux will contain other terms such as that due to ions and neutral particles but as has been shown here the contribution of ions can be neglected.

Hence the total heat flux can be written assuming cylindrical symmetry where Z can be replaced by the radial variable r as

$$H = -\bar{K}_e \frac{dT}{dr} - \tfrac{5}{2}\, n_0 KT_e \frac{\mu_i}{\mu_e} D_e \frac{d\varphi(r)}{dr} - K_n \frac{dT_n}{dr}.$$

As this stage let us assume the Ellenbaas Heller heat balance equation and the model as it has been treated rests upon as an equation expressing the balance of the three terms; namely,

(1) heat generation by Joule effect,
(2) heat transfer by thermal conduction and other processes if any,
(3) heat transfer by radiation.

It is however, known that radiation effect specially in case of gaseous discharge plasma is small and it is a few percent of the total loss and we shall neglect this heat loss for the present.

Hence we can write in the case of present investigation if J is the discharge current density and ρ the specific resistance

$$J^2\rho = \bar{K}_e \varphi(r) \frac{dT_e}{dr} + K_n \frac{dT_n}{dr} + H_D$$

where H_D is the loss of heat due to ambipolar diffusion and

$$H_D = \tfrac{5}{2}.\, n_0\, KT_e \frac{\mu_i}{\mu_e} D_e \frac{d\varphi(r)}{dr}.$$

and

$$\varphi(r) = J_0 \left(2.405 \frac{r}{R}\right).$$

If T_{no} and T_{nw} denote the temperature at the axis and at the wall and T_{eo} and T_{ew} the corresponding electron temperature and if the longitudinal electric field of the plasma is assumed to be uniform throughout the cross section of the plasma the quantity T_e becomes a constant parameter within it. This is true since the electron temperature T_e in the constant collision approximation is related to neutral particles temperature T_n and the applied electric field as shown by Persson (1961)

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

where M and m are the masses of neutral gas particle and electron respectively and K is the Boltzmann constant. Thus it can be assumed that

$$T_{eo} - T_{no} = T_{ew} - T_{nw}$$

and we get

$$J^2\rho = [\bar{K}_e\,\varphi(r) + K_n]\frac{(T_{no} - T_{nw})}{R} + H_D = H_e + H_n + H_D$$

The value of $(T_{no} - T_{nw})$ has been calculated from an analytical expression given by Mewe (1970)

$$T_{no} - T_{nw} = 9.3 \times 10^3\ I.P. \langle U_e \rangle \left(\frac{E}{P}\right)^{-1}.$$

where I is the discharge current in amperes $\langle U \rangle$ the mean energy of the electrons expressed in electron volts, E/P is in volt meter^{-1} torr^{-1} and P is in torr. For the gases considered here $(T_{no} - T_{nw})$ varies between 5° to 3.5°K.

Assuming $\varphi(\gamma) = J_o\left(2.405\frac{\gamma}{R}\right)$ we can find $\bar{H}_e$ and H_n and hence H_D and the results for air, hydrogen, oxygen and nitrogen are entered in Table III; from the

TABLE III

J Current density $\times 10^3$	E volts/cm	J^2P Calories	H_e Calories	H_n Calories	H_D Calories	σ_{ia} cm^2 $\times 10^{16}$
			Air			
2.4978	7	6.0583	.000382	.000270	6.0576	15.2
4.9956	13.5	17.2953	.000535	.000270	17.2945	5.32
7.4934	20	36.3313	.000572	.000270	36.3305	2.53
9.9913	22	59.5976	.000621	.000270	59.5967	1.55
			Nitrogen			
3.9809	57.5	12.8954	.000182	.000284	12.8949	1.17
7.9618	112.5	35.3534	.000265	.000284	35.3529	.43
11.9427	160.0	61.6307	.000378	.000284	61.6300	.25
			Oxygen			
3.9809	75	12.8954	.000176	.000285	12.8949	1.04
7.9618	105	36.2979	.000250	.000285	36.2974	.37
11.9427	155	80.7718	.000253	.000285	80.7713	.17
			Hydrogen			
3.9809	65.0	14.1426	.000107	.00198	14.1405	1.69
7.9618	102.5	29.6292	.000204	.00198	29.6270	.81
11.9427	160.0	55.9968	.000244	.00198	55.9946	.43

results it is evident that in case of all the gases the heat lost by conduction by electrons and neutral atoms is insignificant in comparison to that carried on by diffusion. Major portion of heat loss is thus due to ambipolar diffusion which was also previously observed in case of mercury arc by Ghosal *et al.* (1979).

Further

$$H_D = \tfrac{5}{2}.\ n_0\, KT_e \frac{\mu_i}{\mu_e}.\ D_e \frac{d\varphi(r)}{dr}$$

as

$$\frac{\mu_e}{D_e} = \frac{e}{KT_e}$$

$$H_D = \tfrac{5}{2}\, n_0\, K^2 T_e^2 \frac{\mu_i}{e} \frac{d\varphi(r)}{dr}$$

$$= \tfrac{5}{2}\, n_0 \frac{K^2 T_e^2}{M\nu_{ia}}. \frac{d\varphi(r)}{dr}$$

$$= \tfrac{5}{2}\, n_0 \frac{K^2 T_e^2 \lambda_i}{M v_{ia}} \frac{d\varphi(r)}{d_r}.$$

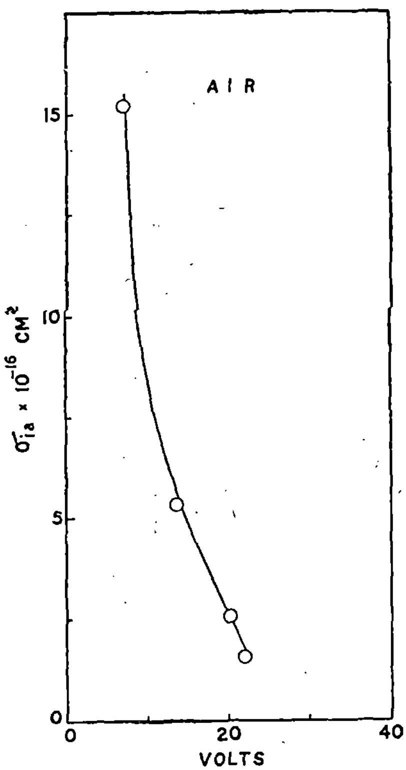

FIG. 3. Variation of ion atom collision cross section in air.

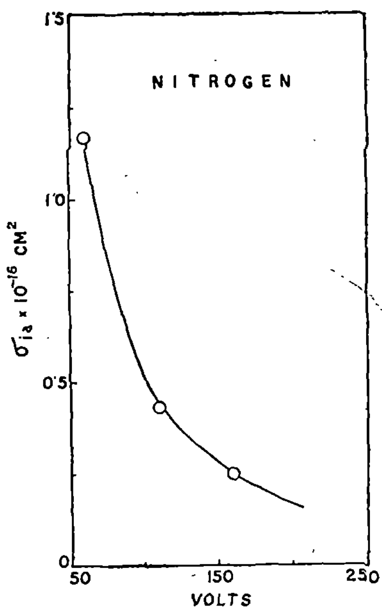

FIG. 4. Variation of ion atom collision cross section in nitrogen.

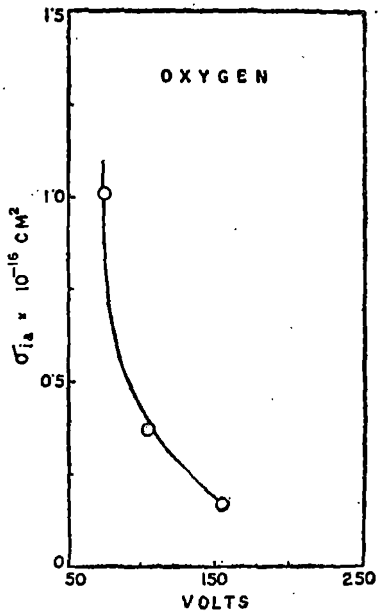

FIG. 5. Variation of ion atom collision cross section in oxygen.

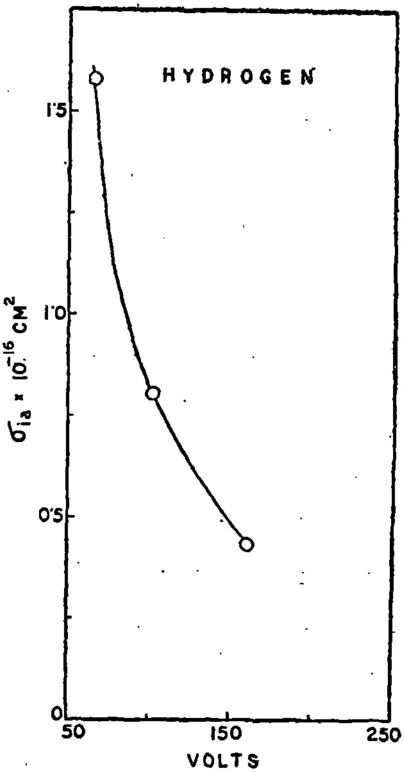

FIG. 6. Variation of ion atom collision cross section in hydrogen.

as σ_{ia} the collision cross section for ions

$$\sigma_{ia} = \frac{1}{n_0 \lambda_i} \text{ and } v_{ri} = \left(\frac{3KT_i}{M}\right)^{1/2}$$

where T_i is the ion temperature

$$H_D = \tfrac{5}{2} \cdot \frac{K^{3/2} T_e^2}{\sqrt{3}\ \sigma_{ia}(MT_i)^{1/2}} \cdot \frac{d\varphi(r)}{dr}.$$

from which expression σ_{ia} the collision cross section for ions can be calculated. It is known from measurements of ion and electron temperature (Brown, 1959) that in case of glow discharge in molecular gases the ion temperature is of the same order as the gas temperature and hence T_i has been taken to be equal to gas temperature in the calculation of σ_{ia} from the above expression.

From Table III, it is evident that the contribution to the heat propagation in the positive column of glow discharge due to heat conductivity of electrons and neutral atoms is extremely small and the major portion of heat is propagated due to diffusion of electrons. Similar results have been obtained previously in the positive column of a mercury arc (Ghosal *et al.*, 1979).

The present investigation further provides us with a method for calculating the ion atom collision cross section. The results are plotted in Figs. (3, 4, 5 and 6) for air, nitrogen, oxygen and hydrogen. The results are consistent with the data reported earlier by Muschlitz and Simons (1952) and Muschlitz, *et al.* (1956). The ion atom collision cross section is a function of the mean free path of the ions and as in the case of electrons the mean free path is a function of the energy of the ions which is dependent upon the voltage of the discharge.

Acknowledgement

The work forms part of the programme of the University Grants Commission scheme entitled "MHD power generation utilizing liquid fuel and seeded plasma". One of the authors (B.G.) is thankful to U.G.C. for the award of a Fellowship.

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CHAPTER IV

EVALUATION OF ELECTRON TEMPERATURE IN GLOW DISCHARGE FROM MEASUREMENT OF DIFFUSION VOLTAGE

It is well known that if D_e and D_i represent the electronic and ionic diffusion coefficients of electrons and ions in a partially ionised gas, then

$$D_e = \frac{1}{3} \lambda_e v_e \quad \text{and} \quad D_i = \frac{1}{3} \lambda_i v_i$$

where λ_e is the mean free path for electron neutral atom collision and λ_i is the mean free path for ion neutral atom collision and v_e and v_i are the random velocities for electron and ion respectively. As a general rule these two mean free paths are almost equal but at a given temperature, $v_e \gg v_i$ and hence electrons will diffuse more quickly than the ions. As a result a charge separation will take place and a space charge electric field will be established which will retard the diffusion of electrons and accelerate that of the ions so that ambipolar losses are equalised. If it is assumed that due to charge separation an electric field E is established and as the major part of diffusion is along the azimuthal direction, the field is radial then the ion current due to diffusion along the radial direction

$$I_i = -e D_i \frac{\partial n_i}{\partial r} + e \mu_i E_r n_i$$

$$e n_i v_i = -e D_i \frac{\partial n_i}{\partial r} + e \mu_i E_r n_i$$

$$v_i = -\frac{D_i}{n_i} \frac{\partial n_i}{\partial r} + \mu_i E_r.$$

In the same way for the electrons we get

$$v_e = -\frac{D_e}{n_e} \frac{\partial n_e}{\partial r} - \mu_e E_r.$$

Then $v_e - v_i = -E(\mu_e - \mu_i) - \frac{D_e}{n_e} \frac{\partial n_e}{\partial r} + \frac{D_i}{n_i} \frac{\partial n_i}{\partial r}.$

The effect of space charge electric field is to equalise the velocity so that $v_e = v_i$ then we get

$$E_r(\mu_e - \mu_i) = -\frac{D_e}{n_e} \frac{\partial n_e}{\partial r} + \frac{D_i}{n_i} \frac{\partial n_i}{\partial r}.$$

Due to charge neutrality $n_e = n_i = n$.

$$E_r(\mu_e - \mu_i) = -\frac{1}{n}\frac{\partial n}{\partial r}(D_e - D_i)$$

$$E_r\left(\frac{D_e e}{KT_e} - \frac{D_i e}{KT_i}\right) = -\frac{1}{n}\frac{\partial n}{\partial r}(D_e - D_i)$$

As in the case of ambipolar diffusion if we assume

$$T_e = T_i$$

$$\frac{E_r e}{KT_e}(D_e - D_i) = -\frac{1}{n}\frac{\partial n}{\partial r}(D_e - D_i)$$

$$E_r = -\frac{1}{n}\frac{\partial n}{\partial r}\frac{KT_e}{e} \tag{4.1}$$

Equation (4.1) shows that if T_e is constant then the radial electric field is a function of r. Since it is known that the field is varying, the equation cannot be~~x~~ used for the measurement of T_e. If however, voltage V_R between the axis and some point at a distance r away is measured then

$$V_R = \int E_r\,dr = -\int \frac{dn}{n}\frac{KT_e}{e} \tag{4.2}$$

In the case of an uniformly positive column of a glow discharge the distribution is

$$n = n_0 J_0 (2.405\, r/R)$$ Besselian where R is the radius of the discharge tube, so that

$$\frac{K T_e}{e} = \frac{V_R}{\log J_0 (2.405\, r/R)} \qquad (4.3)$$

It is thus evident that if V_R can be measured then the electron temperature can be obtained from eqn.(4.3)

Experimental Arrangement

The experimental arrangement has been given in ChapterII

Results and Discussion

The results are consistent with the literature value (von Engel, 1958). When a transverse magnetic field B is present, the plasma is compressed towards the wall and the radial distribution of charged particles chamges.

Sen & Gupta (1971) have shown that, at a distance 'r' from the axis, if n_B and n represent the electron densities in presence of and in absence of magnetic field respectively, then

$$n_B = n \exp(-aB)$$

where $$a = \frac{eE\, C_1^{1/2}\, r}{2kTe\, P}$$

where the symbols have their usual significance and

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

where L being the mean free path of the electron at a pressure of 1 torr and v_r is the random velocity of the electron so that C_1 is the square of mobility of the electron at 1 torr.

when r = 0, a = 0, $n_{0B} = n_0$

then as before, integrating we get

$$\frac{K\,Te_B}{e} = \frac{V_{RB}}{\log\left[J_0(2.405\, r/R)\exp(-aB)\right]}$$

The value of 'a' has been calculated from the known values of T_e as obtained here and the calculated value of 'a' is 0.0126.

Hence by placing the discharge tube in transverse magnetic field, the electron temperature has been measured by utilizing the above equation for magnetic field varying from 0 to 100 Gauss for a constant discharge current of 2.8 mA.

It has been reported by Sadhya and Sen that a theoretical expression

$$\left[\frac{T_{eB}^{2}}{T_e^{2}} - 1 \right] = C_1 \frac{B^2}{P^2}$$

is valid for low values of magnetic field in case of hydrogen and helium.

Table 4.1

Variation of $\left(T_{eB}^2 / T_e^2 - 1 \right)$ with $\left(B^2/P^2 \right) \times 10^{-3}$

$B^2/P^2 \times 10^{-3}$ $G^2/Torr^2$	$\left(T_{eB}^2 / T_e^2 - 1 \right)$
16	1.9
36	4.2
64	7.1
100	10.35
143.5	14.05

Table 4.1 shows the variation of ($T_{eB}^2 / T_e^2 - 1$) against B^2/P^2 in air. The agreement between the theory and experiment is quite good for low values of magnetic field and the curve is a straight line from which the value of $C_1 = 1.67 \times 10^{-4}$.

The quantity C_1 is the square of the mobility of the electron at 1 torr and its calculated value is in agreement (at least in order of magnitude) with the value given by Brown for the value of (E/P) reported here.

This is a straightforward and simple method and the only quantity to be measured accurately is the voltage between the central probe ($r = 0$) and a parallel probe placed at a convenient distance.

No further calculations are necessary and hence this method is more advantageous and accurate than the probe method. The error in the measurement of T_e is thus considerably minimized.

Further the proposed method can be utilised for measurement of electron temperature in a magnetic field, specially for low values of (B/P). At high values of magnetic fields the equation $\left[\frac{Te_{B}^{2}}{Te^{2}} - 1\right] = C_1 \frac{B^2}{P^2}$

becomes invalid because the simplied assumption of Beckman from which the formula is derived no longer holds good.

Thus it is evident from this chapter that the electron temperature in the positive column of a glow discharge can be calculated by measuring the radial d.c. voltage that developes between the probes due to the charge separation of electrons and ions subject to ambipolar diffusion and the method of measurement can be extended in presence of magnetic field as well. The method is simple and straightforward and the possibility of error is minimised.

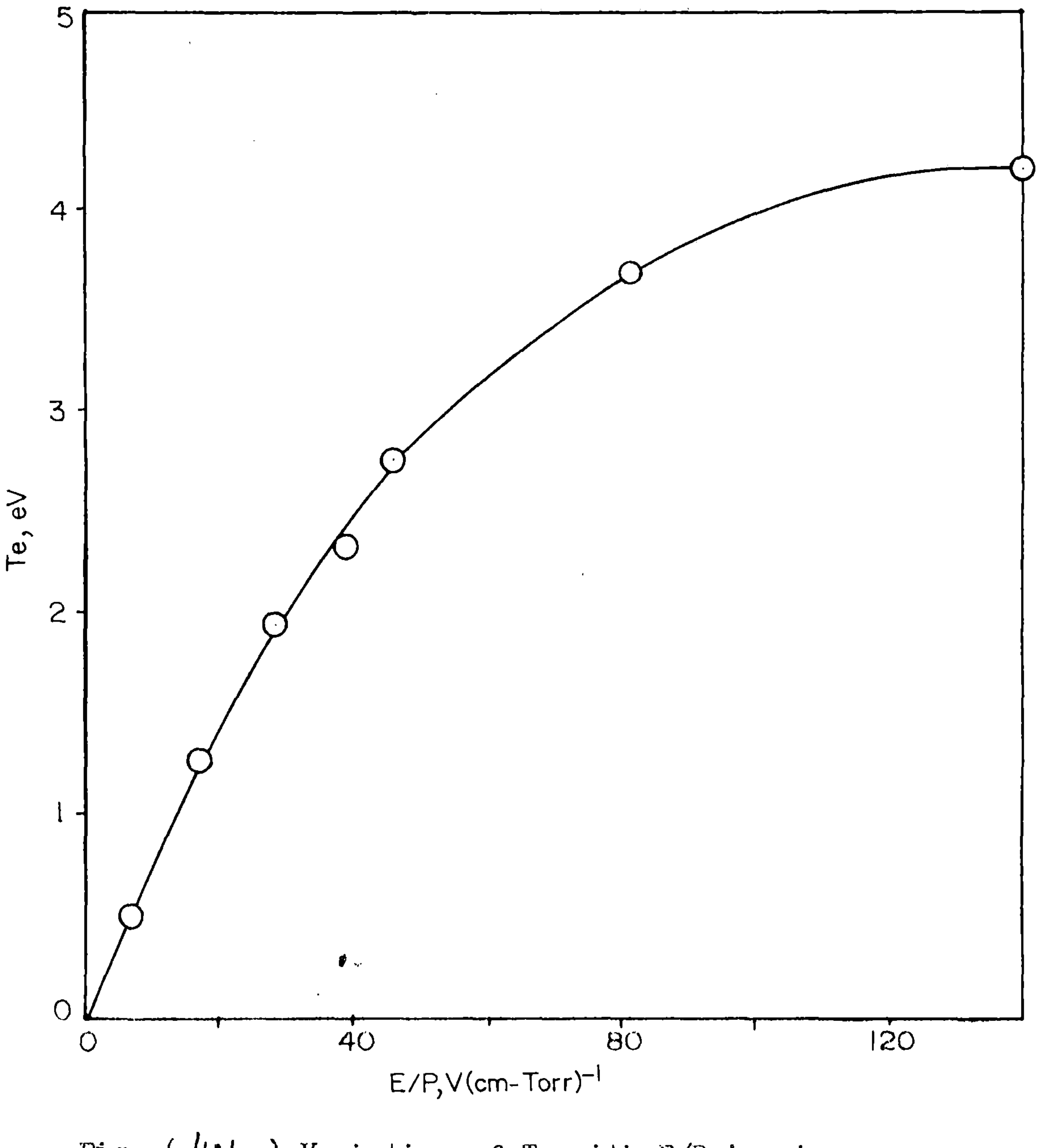

Fig. (4·1) Variation of T_e with E/P in air

P = 1 torr

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Indian Journal of Pure & Applied Physics
Vol. 21, October 1983, pp. 613-614

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

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Received 30 *September* 1982; *revised received* 11 *March* 1983

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

It is well known that in the positive column of a glow discharge due to different rates of diffusion of electrons and ions, an electric field develops as a result of charge separation and this field is effective in equalizing the diffusion rates and the phenomenon of ambipolar diffusion results. As the major part of diffusion is along the azimuthal direction, the field is radial. The radial field E_r is given by

$$E_r = -\frac{1}{n}\cdot\frac{dn}{dr}\cdot\frac{KT_e}{e} \quad \text{... (1)}$$

where n is the charged particle density and other symbols have their usual significance. Eq (1) shows that if T_e is constant then the radial electric field is a function of r. Since it is known that the field is varying, the equation cannot be used for the measurement of T_e. If however, the voltage V_R between the axis and some point at a distance r away is measured then,

$$V_R = \int E_r dr = -\int \frac{dn}{n}\cdot\frac{KT_e}{e}$$

In the case of a uniformly positive column of a glow discharge, the distribution is Besselian

$$n = n_0 J_0(2.405\, r/R)$$

where R is the radius of the discharge tube so that

$$\frac{KT_e}{e} = \frac{V_R}{\log J_0(2.405\, r/R)} \quad \text{... (2)}$$

It is thus evident that if V_R can be measured then the electron temperature can be obtained from Eq. (2).

The experimental assembly consists of a discharge tube of length 10 cm in which the ionized gas under investigation is produced, and the pressure is measured by an accurately calibrated Pirani gauge. Two cylindrical probes of length 1 cm and diameter 0.01 cm are placed parallel to one another, one along the axis $r = 0$ and the other at a distance $r = 0.9$ cm from the axis; the radius of the discharge tube being 1.6 cm.

The output voltage at the two probes is measured by a VTVM having an internal impedance of 100 MΩ. A filter circuit is provided at the output of the probes to prevent oscillations generated in the plasma from reaching the VTVM. The output voltage has been measured for different (E/P) values in air, where E is the axial filed, i.e. the voltage per cm length of the positive column and P is the pressure in Torr. The axial field E is determined by measuring the voltage between the two extra probes at a distance of 5 cm placed in the positive column. The variation of T_e with (E/P) has been presented in Fig. 1. The results are consistent with literature values (von-Engel[1]).

When a transverse magnetic field B is present, the plasma is compressed towards the wall and the radial distribution of charged particles changes. Sen and Gupta[2] have shown that, at a distance r from the axis, if n_B and n represent the electron densities in presence of and in absence of magnetic field respectively, then

$$n_B = n \exp(-aB)$$

$$\text{where} \quad a = \frac{eEC_1^{1/2} r}{2KT_e P}$$

where the symbols have their usual significance and $C_1 = (e/m \,.\, L/v_r)^2$, L being the mean free path of the electron at a pressure of 1 Torr and v_r is the random velocity of the electron, so that C_1 is the square of mobility of the electron at 1 Torr. When $r = 0$, $a = 0$, $n_{0B} = n_0$, then as before, integrating we get,

$$\frac{KT_{eB}}{e} = \frac{V_{RB}}{\log[J_0(2.405\, r/R)\exp(-aB)]} \quad \text{... (3)}$$

The value of a has been calculated from the known values of T_e as obtained here and the calculated value of a is 0.0126.

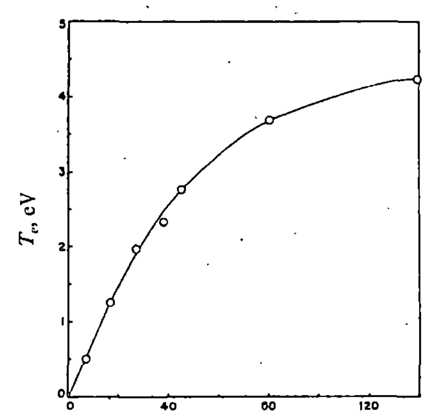

Fig. 1—Variation of T_e with E/P in air [$P = 1$ Torr]

Hence by placing the discharge tube in a transverse magnetic field, the electron temperature has been measured utilizing Eq. (3) for magnetic fielas varying from 0 to 100 Gauss for a constant discharge current of 2.8 mA. It has been reported by Sadhya and Sen[3] that the theoretical experession:

$$\left[\frac{T_{eB}^2}{T_e^2} - 1\right] = C_1 \frac{B^2}{P^2} \qquad \ldots (4)$$

is valid for low values of magnetic field in case of hydrogen and helium. Table 1 shows the variation of $(T_{eB}^2/T_e^2 - 1)$ against B^2/P^2 in air. The agreement between theory and experiment is quite good for low values of magnetic field and the curve is a straight line from which the value of $C_1 = 1.67 \times 10^{-4}$. The quantity C_1 is the square of the mobility of the electron at 1 Torr and its calculated value is in agreement (at least in order of magnitude) with the value given by Brown[4] for the value of (E/P) reported here. This is a straightforward and simple method and the only quantity to be measured accurately is the voltage between the central probe ($r=0$) and a parallel probe placed at a convenient distance. No further calculations are necessary and hence this method is more advantageous and accurate than the probe method. The error in the measurement of T_e is thus considerably minimized.

Further, the proposed method can be utilized for measurement of electron temperature in a magnetic field, specially for low values of (B/P). At high values of magnetic field Eq. (4) becomes invalid because the simplified assumptions of Beckman[5] from which the formula is derived no longer holds good.

Table 1—Variation of $(T_{eB}^2/T_e^2 - 1)$ With $(B^2/P^2) \times 10^{-3}$

$B^2/P^2 \times 10^{-3}$ G^2/Torr^2	$(T_{eB}^2/T_e^2 - 1)$
16	1.9
36	4.2
64	7.1
100	10.35
143.5	14.05

The purpose of this note is thus to show that the electron temperature in the positive column of a glow discharge can be calculated by measuring the radial dc voltage that develops between the probes due to the charge separation of electrons and ions subject to ambipolar diffusion, and the method of measurement can be extended in presence of magnetic field as well. The method is simple and straightforward and the possibility of error is minimized.

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CHAPTER V

DETERMINATION OF PLASMA PARAMETERS BY PROPAGATION OF SONIC WAVE THROUGH AN IONISED GAS

Introduction

Various diagonistic methods (Huddles tone and Leonard, 1964, Herald and Wharton, 1965, Griem, 1964) have been introduced for measurement of plasma parameters and these are now part of standard literature in plasma physics research. The object of this investigation is to see whether the propagation characteristics of an acoustic wave through a plasma can be utilised for measurement of plasma parameters. In all the investigations carried out theoretically so far to find the interaction of sonic waves with an ionised gas it has been assumed that medium is fully ionised and collision of electrons and ions with neutral gas molecules has been assumed to be absent.

Ghosal & Sen (1976) have derived the general wave equation and dispersion relation using macroscopic variables of the plasma and have provided a uniform treatment of the subject for a non isothermal plasma taking the effect of collision of charged species with the neutral particles. Further it has been possible to obtain from the general dispersion relation the attenuation constant of the plasma when a sonic wave propagates through it. The attenuation constant is given by

$$\alpha_p^2 = \frac{\left[1 + \frac{\nu_{pa}^2}{\omega^2}\right]^{1/2} - 1}{\frac{2\gamma K\,(T_e + T_i)}{m_i}}\,\omega^2 \tag{5.1}$$

where γ is the adiabatic gas constant K is the Boltzmann constant, T_i the ion temperature 'T_e' the electron temperature, m_i the massof ion, ν_{pa} the effective ion atom collision frequency and ω the frequency of incident sound wave. It has been suggested by several authors that the study of acoustic wave propagation may lead to a diagonistic method for measurement of plasma parameters. As a preliminary report we propose to measure the attenuation constant of a propagating sound wave through an ionised gas launched from an external source of sound. From eqn. (5.1) it is evident that if T_e the electron temperature is obtained from an independent measurement and we assume T_i to be equal to gas temperature which is valid in case of a gas discharge carrying small currents of the order of a few milliamperes (von Engel, 1965), then the collision frequency ν_{pa} can be obtained from the measured value of α_p. As a preliminary report we have measured the attenuation constant of a propagatory sound wave in a low density gas discharge in air, hydrogen and oxygen, Electron temperature T_e for some molecular gases for various (E/P) values has been measured in this laboratory (Sadhya et al,1979) by the Langmuir probe method. Consequently the effective collision frequency and hence the collision cross section have been obtained for the values of (E/P) used here. The data for ion atom collision cross section has been little reported, so far specially for low values of (E/P). There are various standard methods for the measurement of electron temperature and electron density but the only depend[illegible] method for the measurement of electron temperature and electron density is the microwave transmission method. It is suggested that sonic probe can be an alternative method for such measurement and it is proposed to study the usefulness and reliability of the method for plasma diagonistic measurement. Further the object is also to verify the deduction of eqn. (5.1) regarding the dependence of attenuation constant on the frequency of incident sonic wave for various values of discharge currents.

Experimental arrangement:-

The experimental arrangement is mentioned in Chapter II)

Theory of Measurements and Results

It will be evident from fig. (2.7.4.(i)) that the discharge does not extend throughout the length of the tube, but is confined between the electrodes. There are air gaps between the loudspeaker and one edge of the discharge column and the microphone. It is well known that when a progressive plane acoustic wave travels in a medium, reflection occurs if there is any discontinuity in the acoustic impedance of the medium. Several authors (Bhatnagar, 1964, Saxena and Gour, 1969, Gour and Saxena, 1970) have suggested that in a lossless plasma the attenuation is solely due to this reflection but when we consider the collision of plasma constituents (electrons and ions) with neutral molecules (Ghosh and Sen, 1976) the plasma becomes lossy and as a first approximation the contribution of reflection on damping on the acoustic wave can be neglected.

After evacuation to a pressure of 0.2 torr before exciting the discharge if I_0 and I denote respectively the initial amplitude and amplitude of the sound wave after traversing a distance $x = x_1 + x_2 + x_3$ where x_1, x_2 and x_3 are shown in the fig.(2.7.4(i)) then

then

$$I = I_0 e^{-\alpha_a x}$$

$$I = I_0 e^{-\alpha_a (x_1 + x_2 + x_3)}$$

(5.3)

where α_a is the attenuation constant for air at a pressure of 0.2 torr. When the plasma is present if I_p is the amplitude of the output signal with I_0 as initial input we get

$$I_p = I_0 e^{-\alpha_a x_1} e^{-\alpha_p x_2} e^{-\alpha_a x_3}$$

or

$$I_p = I_0 e^{-\alpha_a (x_1 + x_3)} e^{-\alpha_p x_2}$$

or

$$\frac{I_p}{I_0} = e^{-\alpha_a (x_1 + x_3) - \alpha_p x_2} \qquad (5.4)$$

where α_p is the attenuation constant for the plasma.

From equation (5.3) and (5.4) we get

$$\log_e (I/I_P) = (\alpha_P - \alpha_a) x_2$$

or

$$\alpha_P = \frac{\log_e (I/I_P)}{x_2} + \alpha_a$$

(5.5)

Now it is found that when the tube is evacuated to a pressure (0.2 torr) but no discharge has been excited the input voltage at the loudspeaker supplied from the output of the audio frequency generator and the output voltage at the microphone are measured by the microvoltmeter. Let the voltage recorded be E_0 and E respectively. It has been shown by Kinslar and Frey (1962) that when an alternating voltage $E_0 \cos \omega t$ is applied to the terminals of a voice coil the acoustic power radiated in watt is given by

$$W = \frac{\phi^2 R_r E_0^2}{Z_m^2 \; Z_1^2}$$

where ϕ, R_r, Z_m and Z_1 are typical characteristics of the mechanical and electrical properties of the voice coil.

Hence the amplitude I_0 of the emitted sound wave from the loudspeaker can be written as

$$I_0 = R_1 \left\{ \frac{\Phi \; R_r}{Z_m^2 \; Z_1^2} \right\}^{1/2} E_0 \qquad (5.6)$$

where R_1 is constant of proportionality. When the pressure wave is incident on the microphone, the sound waves on the diapharm cause the coil to move in the radial field of the permanent magnet thus generating an emf,

$$E = B.\ell.\vartheta$$

where B is the flux density of the magnetic field, 'ℓ' is the length of the wire in the coil and ϑ is its velocity. Evidently ϑ will be equal to $R_2 I\omega$ and $E = R_2 B \ell I \omega$

so that

$$I\omega = \frac{E}{R_2 B \ell} \qquad (5.7)$$

Then

$$\frac{I_0}{I} = \omega R_2 \left\{ \frac{\Phi^2 R_r}{Z_m^2 \; Z_1^2} \right\} B \ell \frac{E_0}{E}$$

then from eqn. (5.3)

$$\alpha_a = \frac{1}{x} \log \frac{I_0}{I}$$

$$= \frac{1}{x} \left\{ \log \omega + \log A + \log \frac{E_0}{E} \right\} \qquad (5.8)$$

where

$$A = R \left\{ \frac{\phi^2 R_r}{Z_m^2 Z_1^2} \right\}^{1/2} B.\,l.$$

The results of measurements in case of air, oxygen, at 0.2 torr and for hydrogen 0.35 torr without exciting the discharge is shown in table 5.1 at two frequencies.

Neglecting the contribution due to term log A in equation (5.8) whose magnitude is extremely difficult to obtain accurately we calculated α_a from experimental results and obtained α_a to be 0.1915 where frequency is 360 cycle/sec and 0.2051 when the frequency in 460 cycles/sec. Comparing this with the standard literature value of α_a = 0.1910 neper per/cm as given by Kinsler and Frey (1962) for air at a pressure of 0.2 torr, it can be assumed that

Table 5.1

System	Frequency C/S	Input voltage Eo(volt)	Output voltage E (microvolt)	α_a ne per/cm	α_a literature value neper/cm
Air	360	2.7	260	.1915	.1920
	460	2.7	160	.2051	.2048
Hydrogen	360	2.1	360	.1821	
	460	4	120	.2008	
Oxygen	360	2.4	330	.1844	
	460	2.35	375	.1855	

log A = 0.00005. Hence in our calculation the contribution of log A has been neglected.

The experiment has been performed at a pressure of 0.2 torr in case of air and oxygen and 0.35 torr in case of Hydrogen. In each case the discharge current has been varied from 1 mA to 8 mA. It has been noticed that even in the absence of any incident sonic wave there is a noise voltage in the output of the microphone when the discharge is excited and this noise voltage increases with the increase of discharge current. In calculating the actual output voltage when the sonic wave is incident the effect of this noise voltage has been taken care of. The experimental result for an incident sound wave of frequency 360 cycles/sec is entered in table 5.2 and that for 460 cycles/sec in table 5.3 and the values of α_a have been calculated from eqn. 5.5.

Since $\nu_{ps} = \frac{eE}{m_i \vartheta_d}$, the drift velocity ϑ_d and mobility μ of ions have been calculated and entered in table 5.5 which are in close agreement with literature values (Massey 1971). Further since Q the collision cross section is $Q = \frac{\nu_{pa}}{\vartheta_d \cdot n}$ where ϑ_d is the random velocity of the ions and n the number of molecules per unit volume at a pressure P, the collision cross section of nitrogen ions with air molecules can be calculated for different (E/P) values and the results are entered in table (5.5).

Calculation of ν_{pa}

From equation (5.1) it is evident that as α_p has been measured ν_{pa} can be calculated if T_e the electron temperature can be obtained from experimental values published in literature. The total voltage drop across the discharge tube for a current of 1 mA is 710 volts. As the cathode and anode fall in air at a pressure of 0.2 torr is 650 volts the voltage drop across the positive column is 60 volts so that $E/P = 60/50, \times 0.2 = 6$ volts/cm. torr. In the same way (E/P) for other discharge currents has been obtained. The values of electron temperature in air for various values of (E/P) have been obtained from the measurements of Sadhya et al (1979) in this laboratory and the results are entered in table (5.4).

Table 5.2.

Frequency 360 C/S

System	Discharge current in mA	0	1	2	3	4	5	6	7	8
	Output voltage in volts	260	255	253	251	249	247	246	245	244
	Noise in μ volts	0	10	15	19	23	25	27	30	33
Air Pressure = 0.2 torr.	Actual voltage in μ volts	260	245	238	232	226	222	219	215	211
	α_p in neper/cm		.1927	.1933	.1938	.1943	.1947	.1949	.1953	.1956
	α_p^2 in neper^2/cm^2		.0372	.0375	.0376	.0378	.0379	.0380	.0381	.0383

Table ~~x2~~ 5.2 (contd...)

Frequency 360 C/S.

System	Discharge current in mA	0	1	2	3	4	5	6	7	8
Hydrogen Pressure = 0.35 torr	Output voltage in μ volts	360	357.5	357	356	355	354	354	354	354
	Noise in μ volts	0	11	13	15	17	19	21	23	25
	Actual voltage in μ volts	360	346.5	344	341	338	335	333	327	326
	α_p in neper/cm		.224479	.224506	.224537	.224575	.224614	.224637	.224693	.224725
	α_p^2 in neper^2/cm^2		.05039	.05040	.05042	.05043	.05045	.05046	.05049	.05050

Table 5.2 (Contd.)

Frequency 360 C/S

System	Discharge current in mA	0	1	2	3	4	5	6	7	8
	Output μ voltage in volt	330	328	326	324.5	323	322	321	319	318
	Noise in μvolts	0	13	21	28	32	35	38	41	43
	Actual voltage in μ volts	330	315	305	396.5	391	387	383	378	375
Oxygen Pressure = 0.2 torr	α_p in neper/cm	–	.224546	.226888	.227010	.227099	.227153	.227214	.227294	.227344
	α_p^2 in neper^2/cm^2		.05042	.05148	.05153	.05157	.05163	.05166	.05166	.05168

Frequency 460 C/S.

System	Discharge current in mA	0	1	2	3	4	5	6	7	8
	Output voltage in μ volts	160	158	156	154	153	152	151	150	150
	Noise in μvolts	0	10	15	19	23	25	27	30	33
Air Pressure = 0.2 torr	Actual output volt in μvolt	160	148	141	135	130	127	124	120	117
	α_p in neper/cm		.2063	.2073	.2082	.2089	.2094	.2099	.2106	.2111
	α_p^2 in neper^2/cm^2		.0426	.0430	.0433	.0436	.0439	.0441	.0443	.0445

Table 5.3 (Contd.....)

<u>Frequency 460 C/S</u>

System	Discharge current in mA.	0	1	2	3	4	5	6	7	8
	Output voltage in μ volt	120	119	118	117	115.5	115	114.5	114	114
Hydrogen pressure = 0.35 torr	Noise in μvolt	0	7	12	16	19	22	25	27	29
	Actual output voltage in μ volt	120	112	106	101	96.5	93	89.5	87	85
	α_p		.24327	.24350	.243716	.243925	.244107	.244303	.24448	.244574
	α_p^2		.05918	.05929	.05939	.05950	.05959	.05968	.05975	.05982

Table 5.3 (Contd.....)

Frequency 460 C/S

System	Discharge current in mA	0	1	2	3	4	5	6	7	8
	Output voltage in μ volt	375	373.5	371	370	369	368.5	368	367.5	367
	Noise in μ volt	0	13	21	28	32	35	38	41	43
Oxygen Pressure = 0.2 torr	Actual output volt in μ volt	375	360.5	350	342	337	333.5	330	326.5	324
	α_p		.227797	.227824	.228012	.228077	.228123	.228165	.228211	.228246
	α_p^2		.05189	.05190	.05199	.05202	.05204	.05206	.05208	.05209

Table 5.4

System	Discharge current in mA	1	2	3	4	5	6	7	8
Air	E/P in volt/cm/torr	6	6.9	7.75	8.2	9	9.8	10.6	11.4
	T_e in eV	1.01	1.09	1.16	1.2	1.27	1.34	1.405	1.47
Hydrogen	E/P volt/cm/torr	4.76	5.33	5.71	6.19	6.67	7.14	7.62	8.09
	T_e in eV	.65	.78	.82	0.9	0.96	1.02	1.1	1.15
Oxygen	E/P in volt/cm/torr	6.05	6.67	7.27	7.88	8.41	8.94	9.47	16
	T_e in eV	1.98	2.10	2.19	2.27	2.32	2.37	2.43	2.44

Table 5.5

System	E/P in volts/cm/torr	6	6.9	7.75	8.2	9	9.8	10.6	11.4
	$V_{pa} \times 10^{-6}$ for frequency 360 C/S	2.724	2.949	3.149	3.274	3.470	3.66	3.854	3.940
	$V_{pa} \times 10^{-6}$ for frequency 460 C/S	2.445	2.657	2.845	2.862	3.143	3.327	3.505	3.681
Air	$V_d \times 10^{-5}$ in cm/sec.	3.147	3.341	3.515	3.578	3.705	3.858	3.929	4.029
	μ in $cm^2\ volt^{-1}\ cm^{-1}$	2.071	1.816	1.702	1.638	1.545	1.478	1.391	1.326
	$Q \times 10^{-16}\ cm^2$	48.87	52.94	56.63	58.76	62.30	65.82	69.18	70.74

Table 5.5 (contd...)

System	E/P in volt/cm/torr	4.76	5.33	5.71	6.19	6.67	7.14	7.62	8.09
	$V_{pa} x 10^{-6}$ for frequency 360 C/S	2.429	2.756	3.029	3.316	3.525	3.603	3.887	4.066
Hydrogen	$V_{pa} x 10^{-6}$ for frequency 460 C/S	2.233	2.537	2.794	3.062	3.259	3.336	3.602	3.769
	$V_d x 10^{-5}$ in cm/sec.	6.061	6.235	6.432	6.536	6.662	6.828	6.867	6.970
	μ in cm^2 $volt^{-1}$ sec^{-1}	1.65	1.603	1.555	1.529	1.501	1.463	1.456	1.435

Table 5.5 (Contd...)

System	E/P in volt/cm/torr	6.04	6.67	7.27	7.88	8.41	8.94	9.47	10.00
	$V_{pa} \times 10^{-6}$ for freq. 360 C/S	7.004	7.580	7.896	8.178	8.398	8.589	8.778	8.844
Oxygen	$V_{pa} \times 10^{-6}$ for freq. 460 C/S	5.680	5.860	6.098	6.311	6.477	6.621	6.761	6.810
	$V_d \times 10^{-5}$ in cm/Sec	1.311	1.558	1.638	1.709	1.758	1.843	1.915	2.006
	μ in cm^2 $volt^{-1}$ sec^{-1}	7.63	6.42	6.12	5.85	5.69	5.43	5.22	4.99

Discussion

It is thus seen from the values of ν_{pa} the ion-atom collision frequency obtained by the measurement of attenuation of sonic waves through the ionised gas, it is possible to obtain drift velocity, mobility and collision cross section of ions with neutral molecules. The values thus obtained and their variation with (E/P) are consistent with literature values. Since the ions are moving in their own gas, the charge transfer collisions are predominant. In such collisions the transfer of charge from ion to gas atoms produces an ion with very small kinetic energy.

Sena (1946) has shown that considering the collisions of ions with gas atoms as equivalent to that between two rigid spheres the drift velocity can be shown proportional to $(E/P)^{1/2}$. To verify the deduction the drift velocity of ions obtained in the present investigation has been plotted in Fig. (5.1) against $(E/P)^{1/2}$ and the curve is a straight line which shows that hard sphere collision model is appropriate in this case. To identify the nature of the ions a mass spectrographic analysis is necessary. As has been observed by Asundi, Schulz and Chantry (1967) at low pressure of the order of 0.1 torr which is of the same order of pressure used here (.2 torr) and close to the threshold energy value of 15 eV the ions are likely to be those of N_4^+. It has been further been suggested that formation of N_4^+ from N_2^+ is a three body reaction process.

Further from eqn. (5.1) it is noted that

$$\nu_{pa} >> \omega$$

$$\alpha_{pa}{}^2 = \frac{\nu_{pa}}{\frac{2\gamma K (T_e + T_i)}{m_i}} \omega$$

from which we get

$$\frac{\alpha_{p_1}{}^2}{\omega_1} = \frac{\alpha_{p_2}{}^2}{\omega_2}$$

where the a subscripts 1 and 2 refer to frequency 360 cycles/sec and 460 cycles/sec respectively.

Fig. (5·2) the ratio $\dfrac{\alpha_{p_1}{}^2/\omega_1}{\alpha_{p_2}{}^2/\omega_2}$ has been plotted against the discharge current and the curve is a straight line and the ratio has the value of 1.13 on the average. This justifies the assumption made in deducing eqn.(5.3) by Ghosal and Sen (1976).

It is thus observed that sonic probe method is a useful diagonostic tool in determining ion atom collision frequency from which it is possible to obtain drift velocity, mobility and ion-atom collision cross section. Since it is extremely difficult to measure experimentally the drift velocity of ions at low (E/P) values, the technique is partially useful to obtain drift velocity and mobility specially for low values of (E/P). The method is particularly applicable where the collision of plasma particles with neutral atoms and gas molecules has to be taken into consideration.

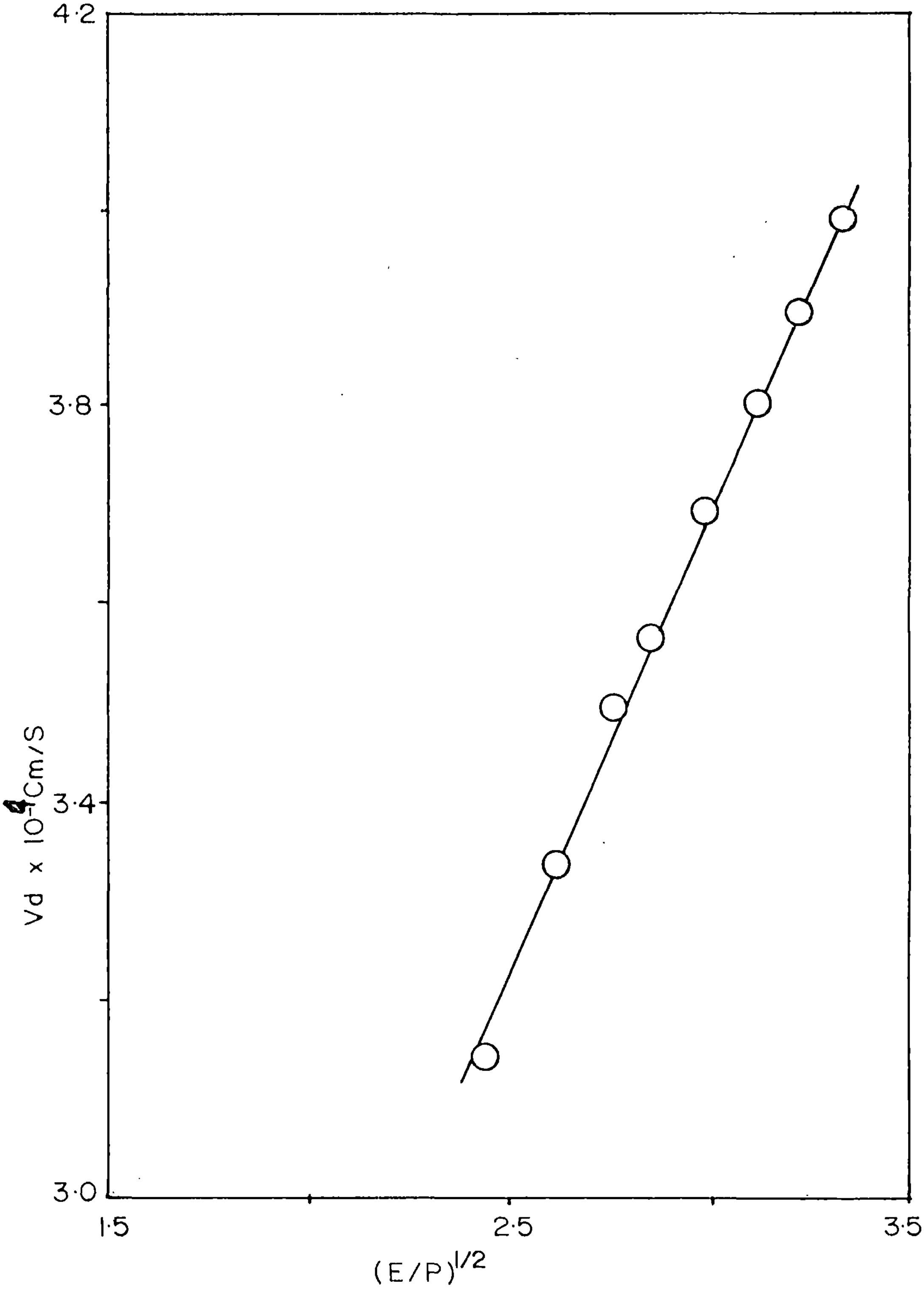

Fig. (5·1) Variation of drift velocity of ions with $(E/P)^{1/2}$.

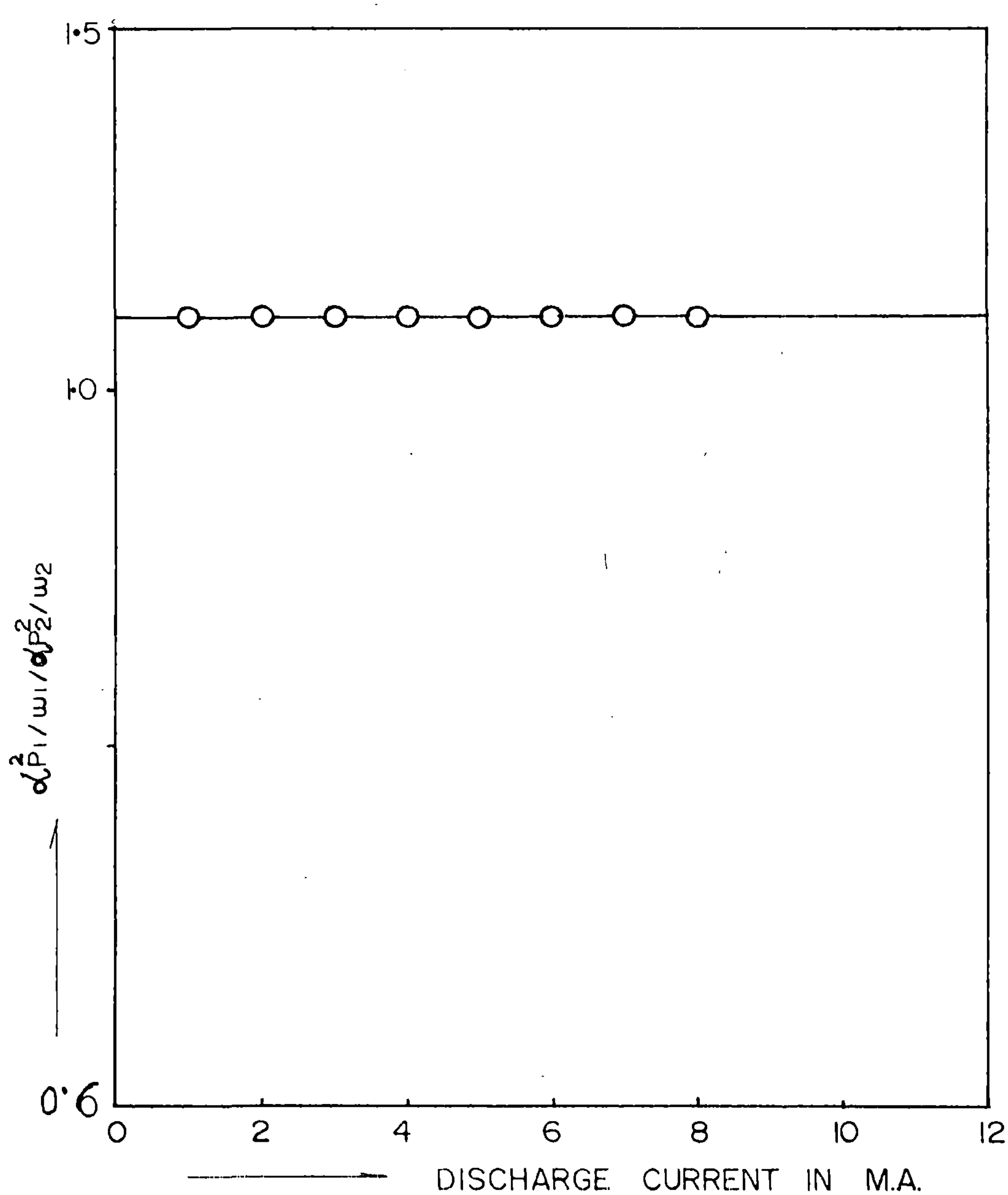

Fig. (5·2) Variation of $\alpha^2_{P_1}/\omega_2/\alpha^2_{P_2}/\omega_2$ with discharge current.

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CHAPTER VI.

EFFECT OF CAPACITOR BANK DISCHARGE ON LOW TEMPERATURE PLASMA:

: INVESTIGATION OF A GLOW DISCHARGE PLASMA SUBJECTED TO THE DISCHARGE OF A BANK OF CONDENSERS.

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. Nevodichanski 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 cumulative effect of converging shock waves. Showrouck 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 Aycoherry et al (1962). Emission of X-rays from exploding wires in a refefied gas has been investigated by

Vidovisky et al (1962) 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 Kerrcell shutter 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 x enable us to understand the interaction between an ionised gas and a high curfent pulsed discharge.

Experimental Arrangement

In this study a discharge tube of length 8 cm. and provided with four electrodes has been used. Fig. [2.75(b)]. 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 w has been kept constant by means of a needle valve and measured by a Mcleod gauge. The separation between the two electrodes to excite the discharge is 2.92 cm. and breakdown is done 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 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 (2.0). The above procedure is repeated when the bank of condensers is excited by 1500volts, 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 photomultiplier readings which are proportional to spectral line intensities, electron temperatures have been computed.

Results and Discussion

The measured experimental results are entered in table (6·1) before the discharge of condensers.

Table (6·1)

Gas	Pressure torr	Discharge current mA	Wavelength Å	Photomultiplier current μA
Air	0.2	10	4447 (1P - 1D°)	8
			4151 (4P - 4S°)	10
Hydrogen	0.7	10	4861 (2S - 4 P)	10
			4340 (2S - 5 P)	4

From the above data it is possible to calculate the electron temperature increased and electron density

Calculation of T_e

The electron temperature can be estimated from the equation

$$K T_e = \frac{E' - E}{\log(I E^3 \lambda^3 g' f' / I' E'^3 \lambda'^3 g f)} \quad (6.1)$$

I = Spectral line intensity for wavelength λ

g = Statistical weight (of the lower state of the line)

f = Absorption oscillator strength

E = Excitation energy

and the prime quantities denote the corresponding expressions for wavelength λ'

Calculation of T_e in case of air:

I' = photomultiplier current = 8 μA

E = 23.10 volts = 23.10 x 1.6 x 10^{-12} ergs.

λ' = 4447 x 10^{-8} cms.

$g' = 3$

$f' = 0.587$

I = Photomultiplier current = 10 μA

E = 13.26 volts = 13.26 x 1.6 x 10^{-12} ergs.

λ = 415.5 Å = 4151.5 x 10^{-8} cms.

g = 6

f = 0.00301

$$KT_e = \frac{(23.1 - 13.26) \times 1.6 \times 10^{-12}}{\log\left[\frac{10 \times (13.26)^3 (4151.5)^3 \times 3 \times 0.587}{8 \times (23.1)^3 (4447)^3 \times 6 \times .00301}\right]}$$

$$T_e = 3.92 \times 10^4 \ K^0$$

Calculation of n the electron density

Considering the distribution to be Bessalian,

$$\begin{aligned} i &= \mu e \ E_b \ n \ R \\ &= \mu e \ E_b \ 2\pi \int_0^R n(0) \ J_0\left(2.405 \frac{r}{R}\right) r . dr . \\ &= \mu e \ E_b \ 2\pi \ n(0) \times .597 \quad \text{at} \quad R = 1.15 \text{ cm.} \\ &= v_d \ e \ 2\pi \ n(0) \times .597 \end{aligned}$$

where v_d is the drift velocity of the electron μ. the mobility and E_b is the voltage drop per cm of the discharge tube.

n (average radially) = 0.597 $n(0)$

Breakdown voltage = 500 volts

Cathode fall = 375 volts

$$\frac{v_d}{u} = \left(\frac{1}{2} R\right)^{1/2} \qquad R = 2m/M$$

$$v_d = \left(\frac{m}{M}\right)^{1/2} u$$

$$= \left(\frac{9.1 \times 10^{-28}}{14 \times 1.67 \times 10^{-24}}\right)^{1/2} \times 3.86 \times 10^{8} \text{ cm/s}$$

$$= 2.408 \times 10^{6} \text{ cm/s}$$

$$u = \sqrt{\frac{2eE_{u}}{m}}$$

$$u = \sqrt{\frac{2 \times 4.8 \times 10^{-12} \times 125}{9.1 \times 10^{-28} \times 2.95 \times 300}}$$

$$u = 3.86 \times 10^{8} \text{ cm/s}$$

where $i = 10 \times 10^{-3}$ amp. (ammeter readings before discharge of condenser)

$$n(0) = \frac{10 \times 10^{-3}}{2.408 \times 10^{6} \times 1.6 \times 10^{-19} \times 2 \times 3.14 \times 0.597}$$

$$= .692 \times 10^{10}$$

$$n = 0.597\, n(0)$$

$$= .597 \times .692 \times 10^{10}$$

$$= .4131 \times 10^{10}/\text{cc}$$

Hydrogen

Calculation of T_e

$$K\,T_e = \frac{E' - E}{\log\left[I E^3 \lambda^3 g' f' / I' E'^3 \lambda'^3 g f\right]}$$

I = Photomultiplier current = 10

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 A

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

$$K\,T_e = \frac{(13\cdot05 - 12\cdot74) \times 1\cdot6 \times 10^{-12}}{\log\left[\dfrac{10 \times (12\cdot74)^3 \times (4861\cdot29)^3 \times 2 \times 0\cdot04193}{4 \times (13\cdot05)^3 \times (4340\cdot44)^3 \times 2 \times 0\cdot1028}\right]}$$

Te = 1.2599 x 10^{4} °K

Hydrogen

Breakdown voltage = 825 volts

Cathode fall = 214 volts

$$v_d = \left(\frac{1}{2} R\right)^{1/2} \qquad R = \frac{2m}{M} \qquad U = \sqrt{\frac{2 e E_0}{m}}$$

$$= 2.3343 \times 10^{-2} \times 8.534 \times 10^8, \quad = \sqrt{\frac{2 \times 4.8 \times 10^{-10} \times 611}{9.1 \times 10^{-28} \times 2.95 \times 300}}$$

v_d = 19.92 x 10^6 cm/S , U = 8.534 x 10^8 cm/S.

$$i = v_d \, e \, 2\pi \, n(0) \times 0.597$$

$$i = 10 \times 10^{-3} \text{ amp.}$$

$$n(0) = \frac{10 \times 10^{-3}}{19.92 \times 10^6 \times 1.6 \times 10^{-19} \times 2 \times 3.14 \times 0.597}$$

$$= .8368 \times 10^9 /cc$$

and n = 0.597 n (0)

$$n = 0.597 \times 0.8368 \times 10^9 = 0.499 \times 10^9/\text{c.c.}$$

The values of electron density and electron temperature are entered in Table (6.1)

Table (6.1)

Gas	Electron density per c.c.	Electron temperature ^{o}K
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 (6.2)

Table (6.2)

Gas	Pressure in torr	Wavelength in Å	Initial discharge current in mA	Initial Photomultiplier current in μA	Charging voltage in volts	Final discharge current in mA	Final photomultiplier current in μA
Air	0.2	4447	10	8	1500	22	57.5
		$(1P-1D^{o})$			1750	25	61.5
					2000	28	64.0
					2550	31	68.0
Hydrogen	0.7	4861.3	10	10	1750	65	80.0
					2000	75	92.0
		(2S - 4P)			2250	85	104.0

Calculation of n, the electron density when the bank of condensers is discharge through the glow discharge in case of air For 2250 volts. From (Table 6.2) the final discharge current is 31 mA

then $n = 0.597\ n(0)$

$$n(0) = \frac{31 \times 10^{-3}}{2.408 \times 10^{6} \times 1.6 \times 10^{-19} \times 2 \times 3.14 \times 0.597}$$

$$\doteq 2.1461 \times 10^{10}$$

$$n = .597 \times 2.1461 \times 10^{10} = 1.2812 \times 10^{10}$$

In the same way

n for 2000volts = 1.15×10^{10}

n for 1750 volts = 1.033×10^{10}

n for 1500 volts = $.909 \times 10^{10}$

Calculation of n the electron density when the bank of condensers is discharged, 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}

In calculating the 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

$$I_{ul} = \left\{ 1 - f_{lu} \lambda_{ul} P n_1(0) \right\} I_{ul}^{0}$$

where I_{ul}^{0} is the observed intensity and I_{ul} is the intensity without absorption f_{lu} is the partition function,

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

so that

$$I_{ul} = \left[1 - \alpha n_1(0) \right] I_{ul}^{0}$$

and

$$I_{ul}^{0} = n \frac{g_u}{Z_0} A_{ul} h \nu_{ul} \exp\left(-\frac{U}{KT_e}\right)$$

when

$$\alpha = f_{lu} \lambda_{ul} P$$

$$U = (E_U - E_l)$$

$$I_{Ul}^{0} = n \beta \exp\left(-\frac{U}{KT_e}\right), \quad \beta = \frac{g_u}{Z_0} A_{ul} h \nu_{ul}$$

$$I_{Ul} = \left[1 - \alpha n_1(0) \right] n \beta \exp\left(-\frac{U}{KT_e}\right)$$

when the condenser is discharged

$$I'_{ue} = \left[1 - \alpha\, n'_1(0)\right] n' \beta \exp\left(\frac{-U}{KT'_e}\right)$$

$$\frac{I'_{ue}}{I_{ue}} = \frac{\left[1 - \alpha\, n'_1(0)\right]}{\left[1 - \alpha\, n_1(0)\right]} \frac{n'}{n} \frac{\exp\left(\frac{-U}{KT'_e}\right)}{\exp\left(-\frac{U}{KT_e}\right)}$$

Putting the values of f_{eu}, λ_{ue}, r_0, C, M, K, T_g and R_0

$$\alpha = 2.52 \times 10^{-12}$$

So at 2250 volts, in case of air

$$\frac{I'_{ue}}{I_{ue}} = 8.5 = \frac{.945}{.982} \times 3.101 \exp\left[\frac{9.84 \times 1.6 \times 10^{-12}}{1.37 \times 10^{-16} \times 3.92 \times 10^{4}} - \frac{9.84 \times 1.6 \times 10^{-12}}{1.37 \times 10^{-16}\, T'_e}\right]$$

$$T'_e = 6.095 \times 10^{4} K$$

In the same way

T'_e for 2000 volts = 6.11×10^4 K

T'_e for 1750 volts = 6.2×10^4 K

T'_e for 1500 volts = 6.4×10^4 K

For hydrogen

T'_e for 2250 volts = $4.27 \times 10^4 K$

T'_e for 2000 volts = $4.39 \times 10^4 K$

T'_e for 1750 volts = $4.58 \times 10^4 K$

The values of electron density and electron temperature thus calculated are entered in table (6. 3)

Table (6.3)

gas	Voltage capacity	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	$.4996 \times 10^9$	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 fig. (61). 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 its 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 cumalative ionization. It has been shown by some workers that when a bank of condensers under high potential discharges through a gas 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 moleculas with increased energy, photo ionization, 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 ionizing processes which have been listed above electrons are involved in the augmentation of ionization process only through collision. It is evident that the increased ionization is mainly due to photo ionization, thermal ionization and ionization 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 microseeonds 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 photo ionization, thermal ionization and ionization by shock waves.

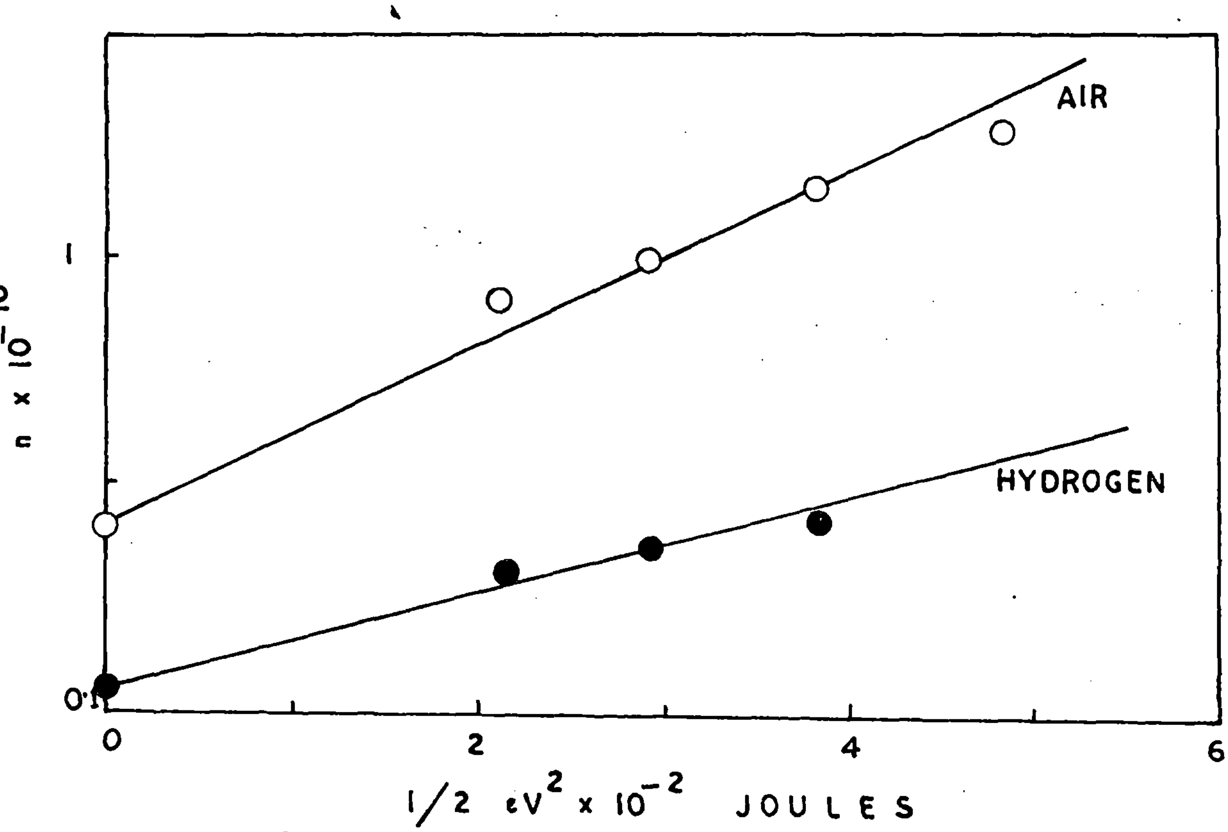

FIG. 6.1 .

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CHAPTER VII

HALL EFFECT IN AN ARC PLASMA.

Introduction

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

Theoretical Treatment

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

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

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

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

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

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

where

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

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

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

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

$$\omega^2 = (2 K T_e)/m .$$

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

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

where v_r is the random velocity

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

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

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

then

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

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

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

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

From eqn. (7.3)

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

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

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

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

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

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

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

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

$$n_e = n_0 J_0 \left(2 \cdot 405 \frac{\mu}{R} \right) \tag{7.6}$$

Then

$$\frac{n_H}{n_e} = \exp \left(- \frac{c \mu \cos \phi}{2 D a} \right) \tag{7.7}$$

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

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

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

where

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

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

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

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

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

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

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

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

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

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

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

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

$$\left(\frac{T_{eH}}{T_e}\right) \exp\left(\frac{e v_i}{K} \cdot \frac{T_{eH} - T_e}{T_e . T_{eH}}\right) = \frac{p}{p_H}$$

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

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

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

or

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

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

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

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

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

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

In this

$$a = \frac{e E C_1^{1/2} \mu}{2 K T_e P} \tag{7.12}$$

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

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

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

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

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

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

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

Experimental arrangement:- (MENTIONED in Chapter II)

Results and Discussion

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

Table 7.1

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

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

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

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

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

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

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

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

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

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Printed in India.

HALL EFFECT IN AN ARC PLASMA

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(*Received 1 June 1984*)

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

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

INTRODUCTION

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

THEORETICAL TREATMENT

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

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

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

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

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

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

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

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

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

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

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

Experimental Set up

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

Results and Discussion

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

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

TABLE I

Magnetic field in Gauss	Hall voltage volts/cm.	Value of n from the relation by $E_y = \frac{iH}{ne}$	$\left[1 + r \log \frac{1}{(1+C_1)\,(H^2/P^2)^{1/2}}\right]^{1/2}$	Value of n_0 from eqn. (4)
64	.34	3.599×10^{12}	.9910	3.631×10^{12}
112	.71	3.533×10^{12}	.9763	3.620×10^{12}
166	1.15	3.501×10^{12}	.9576	3.656×10^{12}
216	1.76	3.483×10^{12}	.9515	3.662×10^{12}
256	2.17	3.423×10^{12}	.9374	3.652×10^{12}
306	2.62	3.356×10^{12}	.9123	3.678×10^{12}
356	3.07	3.253×10^{12}	.8993	3.617×10^{12}
406	5.57	3.180×10^{12}	.8772	3.624×10^{12}
456	3.92	3.165×10^{12}	.8756	3.606×10^{12}
476	4.40	3.108×10^{12}	.8712	3.569×10^{12}
526	4.62	3.068×10^{12}	.8610	3.563×10^{12}

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

$$i = n_0 e v_d$$

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

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

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

Acknowledgement

The paper forms part of a work under the University Grants Commission scheme entitled "Development of MHD power generator using seeded plasma and liquid fuel" and one of the authors (B Ghosh) is thankful for the award of a fellowship under the scheme.

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CHAPTER VIII

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

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

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

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

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

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

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

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

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

$$a = eE\, C_1^{1/2}\, r / 2KT_eP \tag{8.2}$$

Further it has been deduced that

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

[Sen and Gupta 1969] (8.3)

Where

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

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

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

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

$$I = 5.76 \times 10^{-10} \frac{n_e \lambda}{\sqrt{T_e}} E \tag{8.5}$$

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

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

or

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

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

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

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

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

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

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

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

or

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

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

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

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

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

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

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

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

$$a = \frac{e E C_1^{1/2} r}{2 K T_e P} \tag{8.9}$$

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

Table 8.1

Values of a and C_1.

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

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

Table 8.2

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

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

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

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

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

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

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

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

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

$$\alpha = 0.2859.$$

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

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

From Beckman's expression (1948)

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

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

Hence as conductivity is proportional to electron density

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

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

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

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

Maximising we get

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

Putting α = 0.2859 and m = 0.2773

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

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

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

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

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

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

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

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

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

Theoretical consideration:

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

(I) Eddy current loss -

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

(II) Capacitative by pass -

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

$$R' = R_0 + \frac{R_2 C^2}{(C_0+C)^2+\omega^2 R_2^2 C^2 C_0^2} + \frac{\omega^2 M^2}{R_1^2+\omega^2 L_1^2} R_1 \tag{8.14}$$

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

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

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

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

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

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

To determine the azimuthal conductivity σ_S is given by

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

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

Derivation of the distribution function

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

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

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

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

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

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

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

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

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

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

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

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

Then from eqn. (8.14) and (8.15)

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

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

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

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

a) $\sigma(r)$ is cylindrically symmetric

b) It is a monotonically decreasing function

c) $\sigma(r) = 0$ at $r = R$.

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

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

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

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

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

Results and Discussion:

The values of "a" determined from the expression

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

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

Table (8.3)

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

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

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

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

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

Table 8.4

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

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

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

and after integration we get

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\sigma(r) = \sigma_0 \left[1 - \left(\frac{r}{R} \right)^2 \right]^n \qquad (8.23(a))$$

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

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

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

as σ is proportional to n we can write

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

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

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

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

Table 8.5

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

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

Table 8.6

Calculation of electronic mean free path at different pressure.

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

Table 8.7

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

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

Table 8.8

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

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

* from extrapolated value.

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

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

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

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

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

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

Ghosal, Nandi and Sen (1976)

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

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

From these equations it can be deduced that

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

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

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

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

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

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

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

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

In presence of magnetic field, (8.24) becomes

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

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

& $E_H = E(1 + mH)$ → (8.26)

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

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

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

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

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

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

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

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

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

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

Table (8.9)

Axial Magnetic Field.

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

Table (8.10)

Transverse magnetic field.

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

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

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

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

Theoretical Consideration:

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

$$J_z = \sigma_z E_z$$

and

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

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

Working formulae:

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

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

and

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

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

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

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

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

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

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

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

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

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

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

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

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

Writing

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

and

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

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

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

and from eqn. (8.29) and (8.33)

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

So from eqns. (8.35) and (8.36)

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

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

we get

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

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

We get from equation,

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

$$\nu_{ce} = \frac{\omega_{eB}}{\left[\frac{a'}{a_B'} - 1\right]^{1/2}} = \frac{1.76 \times 10^7 B}{\left[\frac{a'}{a_B'} - 1\right]^{1/2}} \qquad (8.39)$$

where B is expressed in gauss.

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

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

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

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

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

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

300

Table 8.10

Magnetic field in Gauss	P = 0.052 Torr E_B Volts/cm	$(\alpha'_B - 1)$	a'_B	$\sqrt{\frac{a'}{a'_B} - 1}$	ν_{ce}	P = 0.075 Torr E_B Volts/cm	$(\alpha'_B - 1)$	a'_B	$\sqrt{\frac{a'}{a'_B} - 1}$	ν_{ce}	P = 0.17 Torr E_B Volts/cm	$(\alpha'_B - 1)$	a'_B	$\sqrt{\frac{a'}{a'_B} - 1}$	ν_{ce}
Arc current 2 amp.															
0	0.587	0.5385	0.1580			0.6097	0.3857	0.1174			0.620	0.350	0.1080		
100	0.565	0.500	0.1413	0.340		0.587	0.3466	0.1076	0.265		0.609	0.335	0.1020	0.235	
150	0.554	0.470	0.1303	0.445	5.969 x	0.576	0.340	0.0979	0.395	6.714 x	0.598	0.320	0.957	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	x10^9
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	x10^9
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	0.6270	0.740	
Arc current 3 amp.															
0	0.348	0.7925	0.0919			0.446	0.590	0.0877			0.500	0.600	0.0833		
100	0.337	0.7857	0.0882	0.1950		0.439	0.5806	0.850	0.165		0.496	0.490	0.0810	0.150	
150	0.330	0.7650	0.0843	0.2850	9.308 x	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	x10^9
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		0.380	0.5230	0.0682	0.560		0.457	0.440	0.0670	0.510	
400	0.272	0.6750	0.0612	0.745		0.380	0.5077	0.0644	0.640		0.435	0.438	0.0635	0.590	

H. Hall effect in an arc plasma.

The Hall effect is a standard diagonistic method for determining the charged particle density and mobility in semi conductors and it has also been utilised for measurement of plasma parameters in a glow discharge. The voltage current characteristics have been investigated in a mercury arc carrying current from 1.3 to 2.0 A in presence of a transverse magnetic field upto 3000 gauss by Sen and Das (1973). The Hall effect in a toroidal discharge plasma has been investigated by Zhilinsky et al (1979) and Goldferb (1973) has presented some diagonistic techniques for the arc plasma. In contrast to semiconductors or metals it is to be noted that when an arc of glow plasma is placed in an external magnetic field the radial electron density distribution and discharge current are significantly altered and this effect has to be taken into consideration in calculating the Hall coefficient in a plasma. In the present investigation Sen and Ghosh (1985) results are reported on the measurement of Hall effect and calculation of axial density and drift velocity of electrons in a mercury arc plasma.

Theoretical treatment

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

$$E_y = \frac{iH}{ne} \tag{8.39}$$

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

$$\frac{i_H}{i} = \frac{\exp(-aH)}{\left[1 + r\log\left\{\frac{1}{(1+C_1H^2/P^2)^{1/2}}\right\}\right]^{1/2}} \tag{8.40}$$

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

$$n_H = n_0 \exp(-aH) \tag{8.41}$$

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

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

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

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

the drift velocity can be obtained.

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

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

Table(8.11)

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

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

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

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

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

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

$$V_A = V_C + V_P + V_a$$

V_C = cathode fall

V_P = fall of voltage at the positive column

V_c = annode fall.

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

Table (8.12)

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

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

Calculation of contact potential difference at the electrode.

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

Table 8.13

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

P_1 is the power loss when the electrodes are in contact

P_o Power drawn from the source .

P_R Power loss at the external resistance

R_r Calculated value of external resistance

V_{con} Contact potential difference

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

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

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

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

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

$$P_A = \frac{V_s^2}{\left(1 + \frac{R_r}{R_a}\right)^2 R_a} = \frac{V_s^2 \rho \frac{x}{s}}{\left(\rho \frac{x}{s} + R_r\right)^2}$$

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

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

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

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

TABLE - 8.14

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

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

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

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

(J) Spectroscopic Investigation of Plasma:-

(I) Mercucy arc plasma in axial magnetic field -

Introduction

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

(2) Experimental Measurements and Results.

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

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

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

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

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

Table 8.15

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

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

Table 8.16

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

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

CONCLUSION

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

Table (8.16)

Magnetic field in Gauss	$\frac{B^2}{P^2} \times 10^{-6}$		$\sqrt{\frac{T_e}{T_B}}$ (expt)		$\frac{i}{i_B}$ (expt)		$\sqrt{\frac{T_e}{T_{eB}}}$ $\frac{i}{i_B}$		C_1 from Fig. Ref [Sadhya & Sen (198	
	X	Y	X	Y	X	Y	X	Y	X	Y
0	0	0	1	1	1	1	1	1		
250	.44	.3	1.169	1.138	1.002	1.0014	1.17	1.14		
550	2.0	1.47	1.2218	1.2087	1.006	1.005	1.23	1.21	$.3\times10^{-7}$	.39x10
835	4.7	3.4	1.2564	1.2686	1.0117	1.011	1.27	1.28		
1050	7.5	5.3	1.2915	1.302	1.0156	1.017	1.32	1.33		

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

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

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

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

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

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

$$I_{ue} = (1 - A_S)\, I^0_{ue}$$

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

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

and $$A_S = f_{lu}\, \lambda_{ue}\, P\, n_1(0)$$

where f_{lu} is the absorption oscillator strength

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

then $$\frac{I_{ue}}{I_{2\cdot5}} = \left\{1 - f_{lu}\, \lambda_{ue} \frac{1}{3} \pi r_0 c \frac{M}{(2\pi K T_g)^{1/2}}\right\} \bar{c}$$

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

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

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

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

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

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

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

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

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

In case of magnetic field we have

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

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

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

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

where the symbols have their usual significance,

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

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

then

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

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

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

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

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

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

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

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

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

a) The persistence time increases with the arc current.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

where

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

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

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

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

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

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

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

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

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

The quantity within the bra~~k~~cket will be a constant for all the spectral lines and we get

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

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

Table 8.18

Arc electrode	Wavelength Å	$\frac{d}{di}\left(\frac{I_{ul}}{I_0}\right)_{exp}$	f_{lu}	$\frac{\frac{d}{di}\left(\frac{I_{ul}}{I_0}\right)_{\lambda_1}}{\frac{d}{di}\left(\frac{I_{ul}}{I_0}\right)_{\lambda_2}}$	$\frac{(f_{lu}\lambda_{ul})_{\lambda_1}}{(f_{lu}\lambda_{ul})_{\lambda_2}}$
Silver	5645.5	0.4903	0.5771	0.91	0.99
Silver	5209.1	0.5398	0.6102		
Cupper	5218.2	0.7422	0.4593	0.93	0.97
Cupper	5153.2	0.7941	0.4771		
Iron	5364.4	2.041	0.2536	2:0:82	1:92:6
Iron	5014.9	0.8342	0.0835	:1	:1
	4383.5	1.0187	0.1620		

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

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

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

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

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

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

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

Theoretical consideration

The heat flow processes in the positive column of a low pressure mercury arc has been considered in a detailed mathematical analysis by Ghosal, Nandi and Sen (1979). Considering the one dimensional case and assuming that the charged particles are undergoing ambipolar diffusion in the Z direction the steady state perturbed distribution function f_{e1} may be given by the relation

$$v_z \frac{\partial f_{eo}(z, v_x, v_y, v_z)}{\partial z} + \frac{eE_z}{m_e} \frac{\partial f_{eo}}{\partial z} = -\nu_{me} f_{e1}$$

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

$$f_{eo}(z\, v_x\, v_y\, v_z) = \phi(z) \left(\frac{m_e}{2\pi k T_e}\right)^{3/2} e^{-\frac{m_e v^2}{2kT_e}}.$$

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

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

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

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

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

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

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

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

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

where it has been shown that

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

$$\overset{0}{Q}_D = 5\pi \frac{\mu_i}{\mu_e} \frac{K^2}{e^2} \frac{\sigma_0}{\Lambda} T_e^{\,2}$$

$$\overset{0}{Q}_n = 2\pi \frac{K_n}{\Lambda} \left(T_{n0} - T_{n\omega} \right)$$

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

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

The experimental procedure has been described in the paper by Ghosal, Nandi and Sen (1979). The experimental values of σ_0 and Λ for three arc currents are σ_0 = 6.26 mhos/cm for 2.3 amp. arc current, σ_0 = 18.05 mhos/cm for 3.1 amp. and σ_0 = 26.55 mhos/cm for 4.0 amp and Λ = 0.8800, 1.0561 and 1.0676, for the three discharge currents. From these data and actual measurement of temperature at the axis and at the wall of the discharge tube the following table has been prepared Table (8.19).

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

It has further been shown that

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

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

Table 8.19

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

CONCLUSION

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

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

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

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

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

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

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

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

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

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

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SUMMARY AND CONCLUSION

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

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

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

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

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

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

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

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

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

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

E. Hall Effect in an Arc plasma.

The Hall voltage in a mercury arc plasma carrying a current of 3 amps., with a background air pressure of 0.2 torr has been measured for a range of magnetic field varying from 64 gauss to 526 gauss. Taking into consideration the variation of arc current and radial electron density in a transverse magnetic field as deduced by Sen and Das et al from the theoretical formulation of Beckman, the expression for Hall voltage in an arc plasma has been deduced. The value of electron density and drift velocity have thus been calculated which are in agreement with literature values.

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

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