chapter six

SUMMARY AND CONCLUSIONS

6.1 Summary and conclusions

In the investigation of the breakdown characteristic of the present hollow cathode discharge in helium gas, it is found that it deviates from the Paschen's curve. Though the Paschen minimum always occurs at $(pd)_{MIN}=3cm\text{-}torr$ independent of the cathode configuration, the magnitude of the minimum breakdown voltage $V_{B(MIN)}$ varies with the cathode configuration. $V_{B(MIN)}$ is lowest in the planar cathode arrangement, increasing as the diameter of the hollow cathode is increased but the length kept constant. By mapping the electric field in the space between the electrodes and the most probably trajectories traversed by the electrons, the dependence of the $V_{B(MIN)}$ on the cathode configuration is explained in terms of the Stoletow constant. To the right of the Paschen minimum, the presence of space charges is shown to affect the breakdown voltages V_B.

On the voltage-current(V-i) characteristics of the hollow cathode discharge after breakdown, some "hysterisis loops" are obtained. This is largely attributed to the heating up of the cathode due to inefficient cooling. Various shapes of the V-i curves are categorized; for which the ones whereby V_A rises as i_A increases with its slope getting more gradual at higher i_A, at times manifesting zero or negative slope being likely feature of a fully developed hollow cathode discharge.

The *optimum pressure range* which corresponds to a fully developed hollow cathode discharge is identified from the V-p(i_A fixed) curves. This range generally shifts to higher *ap* (cathode diameter-pressure product) values when a is increased(cathode length l_K fixed) or when the discharge current i_A is increased; but shifts to lower *ap* values when l_K is increased (a fixed). Similar trends are observed for the corresponding sustaining voltage V_A range. Among the various hollow cathode configurations and within the range of discharge current *(0.5-60)mA* studied, the *optimum pressure ranges* have lower limits at *(0.5-5.4)cm-torr* and upper limits at *(3.7-10)cm-torr*. The widths of the *optimum pressure range* W_P (in *torr*) and the corresponding width of the V_A range W_V (in *V*) are shown to vary exponentially with the current density j (in mA/cm^2). Comparing these widths with those obtained by *Kirichenko et al.*[KIR76], it is thus deduced that the *optimum pressure range* depends on the cathode dimensions and material as well.

At constant sustaining voltage V_A, the current density magnification $q=j/j_0$ decreases linearly as the cathode diameter-pressure product *ap* is increased at low *ap* and becomes independent of *ap* at large *ap*. The linear portions is related to a fully developed hollow cathode discharge regime and its slope is estimated at $-(2.64\pm0.06)$. This agrees reasonably to the universal value of -2.5. This linear line shifts to higher *ap* values as V_A is increased though the slope is maintained. The upper limit at which the linear relationship ends increases from *4.5cm-torr* to *6cm-torr* when V_A is increased from *200V* to *300V*.

From the dependence of the dynamic resistance *dV/di* on the cathode configuration and discharge current i_A, it is concluded that the glow discharge gets more resistive as it approaches the planar cathode discharge (when the cathode length to diameter ratio l_K:a is sufficiently small). Negative dV/di observed at high p but low i_A is likely to be due to the transition from a Townsend discharge to the glow discharge regimes; while those observed at low p, $i_A \leq 20mA$ and at mid-pressure range, high i_A are inconclusively linked to the sputtering action.

From the probe diagnostics, the two distinct linear regions observed on the the electron retardation region of the plot of $ln(I_e)$ against V_P is taken as evidence of existence of two groups of electrons with Maxwellian distributions at temperatures T_s (slow electrons) and T_f (fast electrons). T_s and T_f fall within the ranges *(1-3)eV* and *(4-17)eV* respectively. As to their dependences on the discharge current i_A; T_s(axis and side) falls with increasing i_A for most of the pressures p, T_f(axis) increases with i_A up till *20mA* before decreasing (for most p) while T_f(side) increases with i_A. The respective densities n_s and n_f (both at the axis and side) increases almost linearly with i_A but the ratio n_f/n_s(axis and side) decreases with increasing i_A except at *2mbar*(axis). The average electron temperature T_e (axis and side) generally falls with increasing i_A with the exception at *2mbar*(axis) again. The total electron number density n_e(axis and side) increases almost linearly with i_A.

As to the variations of the electron temperatures with the cathode diameter-pressure product ap, T_e decreases with increasing ap exhibiting minimum at approximately *8cm-torr*(axis) and *(4-6)cm-torr*(side) before increasing slightly, T_s(axis) increases with ap showing maximum at *3cm-torr* before decreasing while T_s(side) is similar to the behaviour of T_e(side), T_f(axis) remains constant until approximately *3cm-torr* after which it decreases with increasing ap while T_f(side) increases with ap exhibiting maximum at *6cm-torr* before decreasing. The densities n_e and n_s (both at the axis and side) increase with ap showing maxima at *3cm-torr* before decreasing while n_f(axis and side) decreases with increasing *ap* showing minimum at *6cm-torr*. The variation of the ratio n_f/n_s(axis and side) with *ap* is dictated by the fast electrons. These minima at *6cm-torr* correspond to the upper limit of the *optimum pressure range*.

Radial homogeneity of the hollow cathode discharge in terms of the ratio of T_e and n_e measured at the axis to those at the side(*2mm* and *4mm* off-axes in the HC6512 and HC1612 respectively) is reasonably achieved only in larger discharge currents and higher pressures.

The electron energy distribution obtained from the second derivative of the probe characteristics varies with the discharge current i_A and pressure p. Increasing i_A at fixed p results in a growth in the height of the peak of the distribution function. It is similar when p is increased (i_A fixed) up to *12mbar*(HC6512), after which the peak of the distribution function decreases in height. This peak shifts to occur at lower electron energy upon increasing p up to *12mbar*(HC6512) before shifting to higher energies. The point of change at *12mbar*(HC6512) is equivalent to *ap=5.85cm-torr* which is the upper limit of the *optimum pressure range*.

In comparing the shape of the electron energy distribution functions obtained at the axis to that at the side, both of them are comparable in height and shape within the *optimum pressure range* though the distribution function at the side displays slightly narrower peak To the right of the *optimum pressure range*, they are comparable in height and shape again but the one at the axis displays slightly narrow peak instead. On the other hand, the two distribution functions differ a lot in height and shape to the left of the same range.

When compared to the normalized Maxwellian and Druyvesteynian distribution funtions, only the discharge at *2mbar*(axis) in the HC6512 has a measured electron energy distribution function which fits better to a Maxwellian. The electron energy distribution functions(axis and side) within the optimum pressure range fit quite well to a Druyvesteynian. Those in the HC1612 do not fit the Maxwellian nor the Druyvesteynian types.

On the emission line studies, the radial profile of the glow intensity in the hollow cathode discharge shows a maximum at the axis, at times with two lower maxima to the left- and right- of the glow edges for low p. The maxima at the glow edges grow radially outwards as p is increased. At sufficiently large p, only the maxima at the edges are present. In plotting the ratio of the maximum intensity at the axis to that at the glow edge $I_{MAX\text{-}AXIS}$:$I_{MAX\text{-}EDGE}$ with respect to p, the point at which the ratio dips below unity occurs at higher p for larger i_A. This trend is consistent with those of the upper limit of the *optimum pressure range*.

The discharge conditions under which the *HeII 468.57nm* emission line from the singly ionized state is detected corresponds to the fully developed hollow cathode discharge regime. With reference to the excitation function of this emission line, it is indirectly indicated that a fully developed hollow cathode discharge can sustain electrons of energy as high as the cathode fall potential. The emission profile of this ionic *HeII* line gives a true picture of the density distribution of these high energy exciting electrons. By comparing the radial profiles of *HeI 501.57nm*, *HeI 587.56nm* and H_α *656.28nm* emission lines and their respective excitation functions, it is deduced that the radial distribution of the electrons at energies a little more than *12eV* changes little with p while relatively more and more electrons at energies around $23eV$ and $100eV$ move radially outwards as p increases under a fully developed hollow cathode discharge conditon.

The total intensities of the *HeI* emission lines vary proportional to $i_A^{(0.8-1.2)}$ in the HC6512 and $i_A^{(0.6-1.2)}$ in the HC1612 while that of the *HeII* emission lines is $\propto$ $i_A^{3.3}$. From the variation of the slope of the logarithmic plot of the total intensity against i_A with p, it is deduced that the fully developed hollow cathode discharge encourages the total intensity to increase the fastest with i_A.

The electron temperature deduced from the intensity ratio method contradicts those obtained via the probe. This implies the inapplicability of this method for the type of plasma in the present hollow cathode discharge.

The width of the cathode dark space d_K estimated from the radial intensity profiles of the emission lines are shown to decrease with increasing p except in the optimum pressure range where it remains almost constant. The reduced electric field E/p is then deduced with the assumption that the electric field is maximum at the cathode surface falling to zero at the boundary between the glow and the cathode dark space and the plasma potential being equal to the cathode fall potential. Relatively larger reduced field E/p occurs at low p but high i_A and this results in the increase in the sputtering rate as evident from the relatively heavier coating on the glass window. From a qualitative analysis, it is deduced that the coating is due to sputtering of the cathode material.

From the above summary, it is concluded that the fully developed hollow cathode discharge operates within the applicability conditions given in *Section 1.1.* Though it deviates from the Paschen's relation, the breakdown voltage V_B is still a function of the electrodes separation-pressure product pd. From the study of the dependences of various parameters on the cathode diameter-pressure product ap in relation to defining a fully developed hollow cathode discharge, reasonable consistency can be said to have been achieved. These parameters include the *optimum pressure range* from the V-p(i fixed) curves, current density magnification $q=j/j_0>1$, constant cathode dark space width d_K as well as the radial profile of the intensity of the emission lines which shows a bright central column.

6.2 Suggestions for further work

The following are suggested as further work in relation to the present investigation:

(a) Similar investigation can be carried out but using different filling gas (or gas mixtures) so as to study the contribution of different excitation processes to the hollow cathode discharge.

(b) Hollow cathodes of different materials in rare gases of higher Z values such as Ar could be used so as to study the sputtering action in the hollow cathode discharge.

(c) A numerical simulation of the hollow cathode discharge could be carried out so as to support or confirm the various contributing factors to the mechanisms involved in the discharge.