chapter one

INTRODUCTION

1.1 The hollow cathode discharge

Since it was first described by *Paschen*[PAS16] in 1916, the fundamental characteristics of the hollow cathode discharge has been studied extensively. Basically, a widely accepted definition of the hollow cathode effect in glow discharges is the increase in the current density, by several orders of magnitude[LIT54] at an almost constant discharge potential, as a result of the cathode geometry. The emission intensity of the coalesced negative glow within the hollow cathode is also greatly enhanced. It is generally believed that these are due to the efficient geometrical confinement of ions, photons and metastable excited atoms in causing secondary electron emission from the cathode and the effective trapping of the pendular electrons in the cavity causing enhanced ionizations[GUN30, LOM39, DRU40, LIT54, BAD58a, HER58, WHI59].

The hollow cathode can take many forms and some of the typical hollow cathode-anode geometries are shown in *Figure 1.1.1*. The outer surface of the hollow cathode is usually insulated so that the negative glow could be confined to within the cathode. However, the disadvantage of the insulation is the introduction of unwanted materials into the discharge which will influence its characteristics, such as the sustaining voltage and the densities of the ions and excited states. The two most common geometries used to investigate properties of the hollow cathode discharge are the parallel plate cathode and the cylindrical hollow cathode. The parallel plate cathode has the adjustability advantage of the potential of each plate and also the plates separation. It is therefore an ideal setup to investigate the transition from a planar to a hollow cathode, to measure the potential distribution, and to investigate the influence of the different mechanisms contributing to the hollow cathode effect.

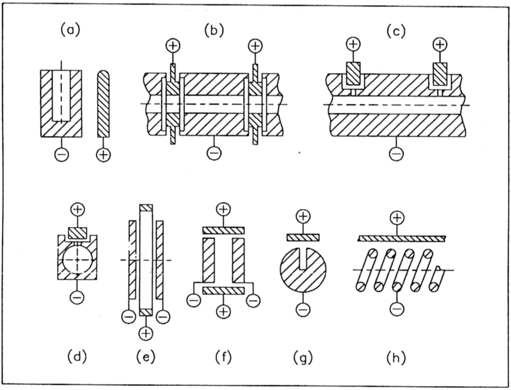

Figure 1.1.1 Some typical hollow cathode geometries: a), b), c) cylindrical; d) spherical; e), f) parallel plates; g) slit; and h) helical.

However, higher plasma densities are achieved with cylindrical hollow cathode. This property combined with the cylindrical geometry makes it an optimum choice for many applications. This hollow cathode configuration is chosen to be investigated in this thesis. Although the most important parameter of cylindrical hollow cathode is its radius r_K, additional geometric parameters which can influence the discharge characteristics include the cathode length l_K, whether both its ends are opened or one end closed, its aperture, the shape and distance of the anode, and the shapes of the insulating walls. A simple cross-sectional visual appearance of the luminous and dark space regions observable in a cylindrical hollow cathode discharge is shown in *Figure 1.1.2*.

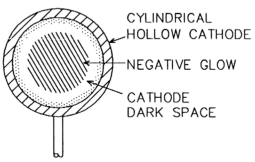

Figure 1.1.2 Cross-section of luminous and dark space regions in a cylindrical hollow cathode.

The hollow cathode discharge to be discussed in this thesis will be operated in the absence of magnetic field. The motion of the charged particles can be significantly altered by magnetic field and subsequently, the region of highest ionization and excitation rates can be shifted leading to shorter cathode dark space and hence, a decrease in the impedance of the hollow cathode discharge[BAD67, TKA72]. The following conditions for a hollow cathode discharge operation are generally applicable:

(i) *1 torr-cm* $< 2pr_K <$ *10 torr-cm* for rare gases, where p is the pressure of the filling gas and r_K is the radius of the hollow cathode cavity (or half the separation of the plane-parallel cathodes) which cannot be less than the cathode dark space width d_K for a particular gas pressure [GEW65]; and

(ii) ratio of the cathode length to the diameter must not exceed approximately 7[WIL74].

These conditions do not apply to the external-type hollow cathode structure whereby the negative glow is not confined to within the hollow cathode cavity. Neither are they applicable to the slotted- or segmented-type[KIR95] whereby the cathode is designed such that one hollow cathode structure is embedded within another.

1.2 Applications of the hollow cathode discharge

The interest invested in the study of the hollow cathode discharge carried out throughout the decades seems to be influenced by its application. Its various discharge properties are suitably employed for different purposes. Its first use is based on its greatly enhanced intensity of the emission lines from the glow in the hollow cathode cavity as well as the copious spectral lines of the cathode material resulting from considerable sputtering of cathode metal atoms within it. This led to it being an excellent source for absorption and emission spectroscopic studies[RAM68, CAR85]; and many hollow cathode lamps are commercially available today. Its radiation stability and its versatility in exciting the analytical sample further renders it a suitable source of excitation in analytical measurements and a review on its analytical applications is given by *Mavrodineanu*[MAV84], where he has also cited hundreds of references related to the low pressure hollow cathode discharge over six decades. For this application, the hollow cathode discharge is usually operated continuously with current typically below *1A*. Current up to *kA* has also been obtained[KIE71] when it is operated in the pulsed mode.

As high excitation rates, high current densities with low cathode fall, and high energy electrons are needed to initiate a lasing process, the hollow cathode discharge is a suitable excitation source for the laser discharge. It was first used as a laser discharge by *Smith*[SMI64] to obtain oscillation in a *He-Ne* mixture on *Ne 2s–2p* transitions in the near-infrared. Since then, various types of hollow cathode discharge structures used in population inversion or oscillation have been reported by many workers. For example, in *Ne*-other gas mixture by *Chebotayev*[CHE65a], *Afanas'eva et al.*[AFA67]; in CO_2 and *He* by *Willet and Janney*[WIL70]; in ionized Ar^+ by *Huchital and Rigden*[HUC67]; and in metal-vapour ion lasers as reviewed by *Gerstenberger*[GER80]. These are typically operated with continuous discharges and currents increasing into the *100A* regime. The use of hollow cathode discharge in laser discharge is still actively investigated at present as evident by the numerous works reported[CHA94, MIZ94, MIZ95, SZA95, PRA95].

More recently, interest in the transient hollow cathode discharge has increased significantly. Owing to its capability in achieving high current density in a short time, the pulsed hollow cathode discharge is suited for application as a high-power switch. Used as a high current closing switch[KOL71], high current density with unheated cathode was attainable without the usual erosion associated with an arc, and, therefore, can have greater lifetime than spark gap under similar conditions. Even more recently, the development of the pseudospark switch[CHR79] has enhanced interest in the hollow cathode effect which is utilized at least during the discharge initiation period and this switch operates at the left branch of the Paschen curve. The role of the hollow cathode on the breakdown mechanism as well as the electron beam formation in the initial stage of the pseudospark has been much studied[GUN90, IEE95]. Hollow cathodes are also considered as electrodes for atmospheric pressure diffuse discharge devices such as TEA lasers and diffuse discharge switches[SCH84]. It is assumed that the onset of discharge instabilities is shifted towards higher current densities. However, for these applications, the scaling of hollow cathode operation to high pressures has to be investigated first. For atmospheric pressure the holes should have diameters of the order of a few *microns* depending on the filling gas.

Other applications of the hollow cathode discharge include film deposition by means of hollow cathode arc evaporation device[STE95], dc hollow cathode sputtering[MOR95], plasma jet system[BAR95] and also as ion sources[BEL94, MIL94, VIS94].

Throughout the eight decades of the applications of the hollow cathode discharge mentioned above, various aspects of its properties have been studied. A critical review of spectral and related physical properties of the hollow cathode discharge is given by *Pillow*[PIL81], citing works over a period of fifty years. More recently, *Schaefer and Schoenbach*[SCH90] presented a review of the basic mechanisms contributing to the hollow cathode effect (which will be discussed in a later section). Both agree that a systematic study and complete understanding of the hollow cathode discharge does not exist presently although a very large number of papers has appeared in the open literature. One reason is that most experimental investigations have been carried out over a narrow range of operating parameters; or there exists a very large gap among the published works on the effect of cathode parameters upon discharge behaviour. This makes it difficult to make comparison between results obtained from different workers.

1.3 The hollow cathode effect

Several mechanisms have been suggested to contribute to the hollow cathode effect phenomenon. They are as follows:

(i) Electrons emitted from the cathode surface inside the hollow cathode structure which are accelerated in the cathode fall mainly contribute to ionization in the weak field region of the negative glow. Those that survive collisions will penetrate into the opposite cathode dark space, and suffer a reversal of direction, re-entering the glow at approximately their previous speed. These pendular electrons can therefore make multiple passages within the cavity, enhancing the ionization rate in the negative glow[GUN23, HEL72]. In fact, *Helm*[HEL72] provided the experimental verification of this pendular electron effect. This effect significantly influences the electron energy distribution function in the hollow cathode plasma as evident by the presence of a peak at the high energy end close to the cathode fall potential[BOR66, GIL77] which will be further discussed in *Section 2.3*.

(ii) The cathode dark space in the hollow cathode under high current density conditions can be significantly thinner than in a planar cathode, reducing the probability for charge transfer collisions. Therefore, the average ion velocity at the cathode surface is increased, causing an increased secondary electron emission rate[BAD60a]. The evidence of high energy ions will be shown and discussed in *Section 2.4.*

(iii) A more efficient geometric confinement of the energetic neutral particles(such as photons and metastables) as well as the positive ions in causing secondary emission of electrons from the surface of the cathode[DRU40, LIT54, BAD58a, CIO58]. Thus a hollow cathode with larger ratio of the length or depth to its diameter or aperture would be able to trap these particles more efficiently, increasing the probability of hitting the surface of the cathode. However, too large a ratio would introduce significant axial and radial inhomogeneities to some of the characteristics within the hollow cathode cavity which will be discussed in *Chapter 2*.

(iv) The higher plasma density inside the hollow cathode makes multi-step processes more likely[STU67, WIT71]. This includes the cumulative ionization processes discussed by *Sturges & Oskam*[STU67], whose rate is strongly dependent on the electron and excited states densities of the negative glow.

(v) The confined geometry of the hollow cathode leads to a higher density of sputtered atoms from the cathode material with lower ionization potential which influence the secondary processes at the cathode and in the volume of the discharge[WHI59;MUS62a]. Penning ionization can also occur in rare gas hollow cathode discharge.

All these mechanisms depend on a number of parameters such as the operating conditions (characterized by the pressure p, current i and voltage V), the hollow cathode geometry (characterized by its shape and the ratio of its length to its diameter $l_K:a$) and material and the filling gas. It is an open question as to which of these mechanisms is the dominant process, if indeed there is a dominant one. Different authors have favoured different processes depending on their application and operation of the hollow cathode discharge as well as the configuration of the hollow cathode; and this makes it difficult to make reasonable comparison among them.

The hollow cathode effect has also been defined in a number of ways according to its phenomenological properties. *Little & von Engel*[LIT54] and *Badareu & Popescu*[BAD58a] have presented the effect based on a visual inspection of a coalesced negative glow when two parallel cathode plates are brought sufficiently close together, resulting in enhanced intensity of the emission as well as the current. This led to a linear relationship between the current amplification and the product of the hollow cathode diameter with the pressure *ap* as described by *Ciobataru*[CIO64]. *Borodin & Kagan*[BOR66] described an optimum mode of the hollow cathode effect on the basis of the fraction of fast electrons in the glow being at maximum. However, *Kirichenko et al.*[KIR76] preferred to define an *optimum pressure range* for a fully developed hollow cathode discharge in which the cathode fall potential increases with the pressure at fixed current. Again these investigations have been carried out under different hollow cathode configurations and operating conditions lending difficulty in making any correlation among them.

1.4 Objectives and layout of thesis

From the above discussion, it can be realised that the properties of the hollow cathode discharge or the hollow cathode effect depends on a number of parameters which can be grouped into the hollow cathode geometry and the discharge operation conditions. It has further been brought to the attention that though many investigations on the hollow cathode discharge have been carried out, the parameters used and the properties studied are too varied, making comparison or correlation among them very difficult. It is indeed inherent of gas discharges to have any of its chosen property to depend on a number of others. It is therefore necessary to seek for some simplification by grouping some of these parameters together as in the similarity laws[FRA56]. One of the formulation of the Townsend similarity law is: "In geometrically similar electrode systems, the potential difference V required to maintain a given discharge current i is the same, if the product of the gas pressure p and any given dimension is the same." This leads to the derivation of various invariant groups of parameters, one of which is given as $V=f(px, j/p^2)$, where j is the current density and x represents any linear dimension of the discharge tube. Another one relates the breakdown potential V_B to the product of the pressure p and electrode separation d such that $V_B=f(pd)$. Although *Allis*[ALL57], *White*[WHI59] and *Musha*[MUS62] have reported that the similarity relation do not hold good in the hollow cathode discharge, pd_K (where d_K is the cathode dark space width) is still a fundamental parameter of the discharge[LIT54]. However, it is more appropriate to use ap (where a is the diameter of the hollow cathode or the double cathode separation) in the hollow cathode discharge; and reasonable compliance to the Townsend similarity law can still be achieved if the Faraday dark space width is not included in a and the combined width of the negative glows is smallest relative to the two cathode dark space widths.

This thesis aims to correlate and compare some of the suggested mechanisms contributing to the hollow cathode effect in relation to a varied range of operating parameters of the hollow cathode discharge and geometry of the hollow cathode. These shall be done with reference to various documented works as well as to the experimental investigation of the hollow cathode discharge carried out in the present work. The parameters used for the operation of the present hollow cathode discharge setup will cover the range of validity conditions mentioned earlier and beyond. As discussed in *Section 1.3*, various ways have been used to define a fully developed hollow cathode discharge in terms of different optimum range of parameters. Thus, the present work shall also aim to link these optimum range of parameters and possibly unify the various definitions.

With respect to the objectives given above, a review of the properties and the basic mechanisms in the hollow cathode discharge shall be given in *Chapter two*, among which agreements and contradictions as to the important mechanisms shall also be discussed. Also included are the various hollow cathode discharge modelling performed with reference to some of its properties.

Chapter three will outline the experimental setup together with the relevant background theory. The diagnostic techniques employed and the considerations of the limits of their applicability are also discussed.

The experimental results relating to the electrical properties which include the breakdown characteristics of the hollow cathode discharge and its voltage-current (*V-i*) curves are presented in *Chapter four*. From these results, the current magnification and the dynamic resistance in the hollow cathode discharge are determined. The *optimum pressure range* as defined by *Kirchenko et al.*[KIR76] is also estimated and discussed.

Chapter five presents the plasma parameters deduced from the Langmuir probe characteristics and the spatial distribution of the light emission from the discharge within the hollow cathode. The sputtering action in the present hollow cathode discharge shall be discussed with respect to the coating found on the glass window at one end of the hollow cathode. The correlation of the various spectral and physical properties of the hollow cathode discharge resulting in a fully developed hollow cathode discharge will also be discussed.

A summary and the conclusion drawn on the present investigation of the hollow cathode discharge are given in *Chapter six*. Also included are some suggestions for further work.