Phenomenological Model Describing Orificed, Hollow Cathode Operation

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Abstract

ORIFICED, hollow cathodes serve as sources of electrons in a number of plasma producing devices. In ion thrusters they are used as a source of electrons for both the main discharge region and the neutralizer. Recent experiments[1,2] have provided such important physical data regarding hollow cathode operation as plasma properties within the cathode, insert temperature profiles, internal cathode pressure, and emission current density profiles over a wide range of cathode operating conditions. The physical understanding gained through these experiments has led to the development of a simple phenomenological model describing physical processes which take place inside the hollow cathode.

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The experimental studies[1,2] noted above showed that, for a cathode operating on mercury vapor at discharge currents of a few amperes, typical plasma conditions found in the vicinity of the orifice plate were a plasma density of a few times 10^{14} cm^{-3}, a plasma potential of ~ 8 V, and an electron temperature of ~ 0.8 eV. The experiments also showed that $\sim 85\%$ of the total electron discharge current came from the last few millimeters at the downstream end of the insert where typical emission temperatures of $\sim 1000°C$ were measured for discharge currents of a few amperes. The simultaneous measurement of emission current and emission surface temperature in these studies provided sufficient information to allow calculation of the emissive surface work function. That the calculated value of this work function was reasonable for the materials being used supported the underlying assumption on which the calculations were based; namely, that the surface emission mechanism for the cathode is that of field-enhanced, thermionic emission.

The following physical description of orificed, hollow cathode operation is based on the results of these studies. The cathode orifice maintains a high neutral density inside the cathode by restricting the propellant flow and provides a current path to the downstream discharge. The electrons that exit through the cathode orifice are produced within the cathode both by surface emission and by volume ionization. As indicated in the schematic of Fig. 1, the surface electron emission comes uniformly from a narrow band ($\ell \approx 2$ mm) on the insert downstream end. The electrons are produced at the insert surface by field-enhanced, thermionic emission (the very strong electric field is a consequence of the very dense plasma which produces a very thin plasma sheath across which the plasma potential drop occurs). The electrons produced at the insert surface are accelerated across the plasma sheath by a potential of 8-10 V, thereby gaining sufficient energy to produce ion/electron pairs in the bulk plasma. A dense internal plasma is established by this ionization. Because of the low electron energies the ionization process is predominantly a multistep process. Since the mean free path for inelastic collisions of the electrons accelerated by the sheath is on the order of the internal cathode diameter, this "ion production" region can be idealized as the volume circumscribed by the insert emission region. This is indicated schematically by the dotted area in Fig. 1. Ions produced in this volume diffuse out of it at the Bohm velocity and strike the insert surface with sufficient energy to heat it to the emission temperature. These ions are neutralized at the insert surface and thus complete the current path between the cathode surface and electrons produced in the ion production region.

The plasma properties in the ion production region are coupled into the problem by the energy balance at the insert surface in the following manner. The plasma properties determine the ion flux and, therefore, the energy input to the emission surface. For a given emission current, the surface temperature is determined by the energy balance which requires that the thermal losses from the surface due to electron production, radiation, and conduction are balanced by the energy input from the ion flux. The plasma properties also affect the required emission temperature because they determine the magnitude of the electric field at the emission surface and, thereby, the degree of field enhancement in the emission process. Therefore, for a given emission current the surface temperature and plasma properties must be consistent to the extent that they satisfy the energy balance at the surface.

All cathode surfaces that contact the plasma receive ion currents proportional to the Bohm velocity and the plasma density adjacent to the surface. Electron emission, on the other hand, can be assumed to come predominantly from the 2-mm band on the downstream end of the insert. The total electron current (I_T) from the cathode is equal to the sum of the ion currents to the various cathode surfaces and the current of the emitted electrons.

Certain aspects of this phenomenological model can be expressed analytically in a simple form which allows comparison with experimental results and which should be useful for design purposes. The plasma density (n_j) adjacent to a particular surface (j) can be calculated based on the Bohm condition using

$$n_j = \frac{j_j(i)}{ev_{\text{Bohm}}} = \frac{I_j(i)}{A_j e[kT_e/m_i]^{1/2}} \tag{1}$$

where $I_j(i)$ is the ion current to the surface, A_j the surface area, T_e the Maxwellian electron temperature (K), m_i the ion mass, e the electronic charge, and k Boltzmann's constant. For an electron emitting surface, the measured current to the surface is determined by both collected ions and emitted electrons, so that the total current to emitting surface (j) is

$$I_j = I_j(i) + I_j(e) \tag{2}$$

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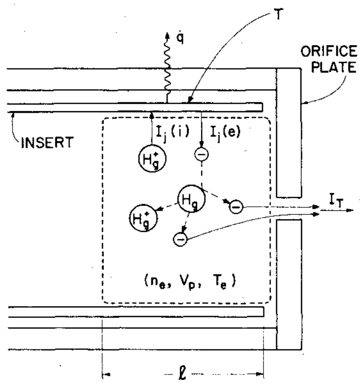

Fig. 1 Cross section of cylindrical, orificed, hollow cathode.

where $I_j(e)$ is the electron emission current. The ratio of ion to electron currents can be estimated from an energy balance on the emitting surface. In such a balance the ion heating power is equated to power conducted and radiated from the surface plus the power required to boil off electrons. The equation[3] describing this is

$$I_j(e)\bar{\phi}_e + \dot{q} = I_j(i)\,(V_c + V_i - \phi_s) \tag{3}$$

where $\bar{\phi}_e$ is the effective work function of the surface, $\dot{q}$ the thermal power transferred away from the surface, V_c the plasma sheath potential drop, V_i the ionization potential, and ϕ_s the surface work function (a material property). Equations (2) and (3) can be combined to give the electron emission current from the surface,

$$I_j(e) = [\,(I_j - a\dot{q})\,/\,(1 + a\bar{\phi}_e)\,] \tag{4}$$

where

$$a \equiv (V_c + V_i - \phi_s)^{-1}$$

Ions leave the ion production region at the Bohm velocity; then, if it is assumed that the plasma properties are uniform throughout this region, the total electron current through the cathode orifice is given by

$$I_T = I_j(e) + I_j(i)\,[\,(A_j + 2A_c)\,/\,A_j\,] \tag{5}$$

where A_c is the cross-sectional area of the end boundary of the ion production region and the subscript j refers to the insert emission surface. Emission from the insert surface is assumed to be given by the Schottky equation[3] for field-enhanced, thermionic emission

$$I_j(e) = A_j A_0 T^2 \exp\left[-\frac{e\bar{\phi}_e}{kT}\right] \tag{6}$$

where $A_0 = 120$ A/cm^2 K^2 and the other parameters are as previously defined. The average effective work function $\bar{\phi}_e$ is given by

$$\bar{\phi}_e = \phi_s - \left[\frac{e|E|}{4\pi\epsilon_0}\right] \tag{7}$$

where ϵ_0 is the permittivity of free space and E, the electric field adjacent to the surface, can be estimated using

$$E = \frac{-\mathrm{d}V}{\mathrm{d}x} = \frac{-4}{3}\,\frac{V_c}{\lambda_D} = \frac{-4V_c}{3}\left[\frac{ne^2}{\epsilon_0 k T_e}\right]^{1/2} \tag{8}$$

Here the factor of 4/3 comes from Child's law considerations[3] and the sheath thickness is estimated as one Debye length (λ_D).

This model is useful for two reasons. First, the physical understanding of the electron production processes in the cathode should be useful when considering design changes of existing cathodes or in developing improved cathode designs. Second, the model can be used to make a rough estimate of the insert operating temperature. In order to use the model to calculate an insert emission temperature, it is necessary to know or to assume values for the electron temperature T_e, the plasma potential V_c, the emitting length of the insert ℓ, and the thermal loss from the insert $\dot{q}$. It is suggested that the following values will give reasonable results for cathodes a few millimeters in diameter operating on mercury vapor at a few amperes current under normal flow conditions: $T_e = 0.8$ eV, $V_c = 8$ V, and $\ell = 2$ mm. These values were found experimentally to hold over a wide range of operating conditions. Furthermore, the analysis is rather insensitive to the values of these parameters, particularly electron temperature and plasma potential, over their normal range of variation. (A more recent study presents a method for estimating the emission length based on the energy exchange mean free path.[4]) The thermal loss from the insert $\dot{q}$ is a function of the emission surface temperature and must be estimated by considering the radiation and conduction heat transfer for the particular insert/cathode configuration. If the surface work function ϕ_s and the parameters discussed above are specified, then Eqs. (1-8) are sufficient to estimate the emission surface temperature T for a desired current I_T.

It should be pointed out that the model deals with only one aspect of hollow cathode operation; that is the emission process and the accounting of charge carriers in the internal discharge. The model as it stands does not contain sufficient detail to make a priori predictions of plasma properties or their spatial variation and, therefore, cannot explain or predict the location at which the emission will take place or the overall operating characteristics of the cathode such as discharge voltage or discharge mode. A complete model capable of providing these details would require a description of the plasma processes not only within the cathode but also within the orifice region and the keeper/anode region downstream of the cathode. However, the model does provide an experimentally verified description of the electron production processes taking place inside the cathode and can be used to provide an estimate of the insert temperature which is a critical parameter in determining both the cathode lifetime and performance.

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