An Investigation of Physical Processes in a Hollow Cathode Discharge

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Theme

TO make the most efficient use of hollow cathodes for both neutralizer and main discharge applications in a mercury electron bombardment thruster, knowledge of the processes occurring is desirable. An attempt to obtain this information has been made by identifying those parameters important in cathode emission and by devising experiments to investigate them independently.

Content

The cathodes studied were similar to those used in the SERT II program and in the initial phase of the present work,[1] except that bifilar heaters were employed. Triple carbonate was usually applied to the internal surfaces, although for long periods of operation, various barium dispensers were used. Experiments were conducted in a diode discharge system[1] and mercury vapor was supplied from a conventional vaporizer.[2]

There is considerable evidence[1] to suggest that electron emission occurs internally at constant current density J; about 2 to 5×10^5 amp/m^2. Although these values of J probably cannot be explained by simple thermionic emission despite the use of barium, considerable field-enhancement may occur in the presence of the dense internal plasma.[1] This extends over an "active zone" having a length determined by the current drawn. Electric fields E in the plasma sheath of about 10^8 v/m are necessary to account for observed data solely on the basis of this process. Another mechanism capable of giving the required current density and also relying on the presence of an internal plasma covering an active zone is the release of electrons by the impact of metastable atoms. High yields are expected when the excitation energy is close to the work function of the surface, as is the case for mercury impacting on tantalum, and the mechanism does not depend on the presence of an alkali metal.

A small cylindrical Langmuir probe near the keeper orifice was used to measure electron temperature T_e, electron number density n_e and plasma potential V_p in the external plasma. It was also often convenient to use the keeper itself[3] to obtain T_e and V_p. T_e was in the range 1 to 2.5×10^4K and increased with decrease of flow rate $\dot{m}$ and increase in I. The former dependence was ascribed to the fall of pressure with $\dot{m}$, which resulted in the electrons gaining more energy between collisions. T_e was independent of tip temperature T within the range 1000–1400°C. V_p was usually 14–19 v, decreasing as T was raised, and n_e was about 10^{18} m^{-3}.

To investigate the internal plasma a cylindrical Langmuir probe was inserted into a cathode. T_e, derived from semi-logarithmic plots, again decreased with increasing $\dot{m}$ (Fig. 1). The electron saturation current was used to estimate n_e, which rapidly decreased with increasing $\dot{m}$ (Fig. 1). The low values, which did not exceed 5×10^{17} m^{-3}, were attributed to considerable perturbation of the plasma by the probe and to its positioning in the diffusion edge of the plasma. The latter was also consistent with the decrease of n_e with increase of $\dot{m}$ and with the proposed constant J emission mechanism. Since the ambipolar diffusion coefficient is inversely proportional to the neutral density, the boundary of the plasma became steeper with increasing $\dot{m}$, and the probe sampled a region of progressively falling degree of ionization.

Using the internal probe, $V_p \sim 4.5$ to 7.5 v at low $\dot{m}$. These values were typically 12 v below the external ones, for $I = 1.5$ amp and $T = 1250$°C. There was, consequently, an axial electric field of about 12 kv/m in the orifice tending to extract electrons. The effective electrical conductivity was about 4×10^3 mho/m, some 4 orders of magnitude greater than a value derived theoretically.

Although partially explainable by ion currents, pressure gradients and emission within the orifice, this discrepancy confirmed that n_e must have considerably exceeded the values in Fig. 1.

Assuming that the internal plasma sheath was of the order of a Debye length thick and taking $T_e = 4$ to 6×10^3K, $n_e = 10^{19}$ m^{-3} and $V_p = 4.5$–7.5 v, $E - 3$ to 5×10^6 v/m, which is less than the required 10^8 v/m. While n_e may be considerably underestimated here, a further process[4] may be responsible for increasing E. This involves the adsorption onto metal surfaces of alkali metal atoms from a seeded plasma. Under certain conditions, the ion density in the sheath can be several orders of magnitude greater than in the bulk of the plasma, causing a very large enhancement of E and thus of J.

According to the emission theory,[1] the presence of barium is not an absolutely essential requirement. Consequently, a cathode was constructed containing no triple carbonate, but a cylindrical tantalum insert[5] (Fig. 2). It was possible to initiate the discharge

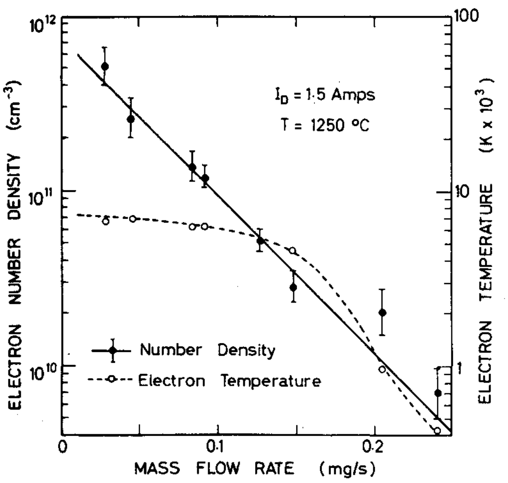

Fig. 1 Hollow cathode internal electron number density and temperature as functions of flow rate.

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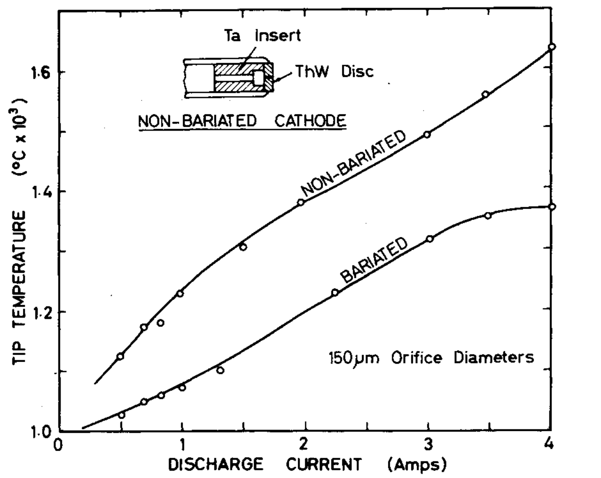

Fig. 2 Tip temperature as a function of discharge current for non-bariated and conventional hollow cathodes.

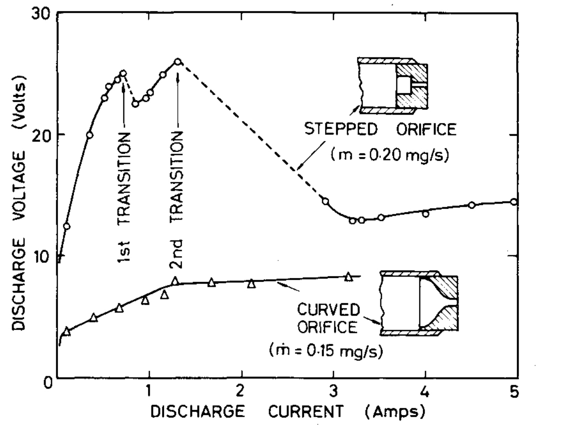

Fig. 3 Voltage-current characteristics for stepped and curved orifice cathodes.

in the usual way, provided that T was sufficiently great, but very much higher values of T were recorded during operation than with a conventional cathode (Fig. 2). Although the discharge voltage V was higher than normal, the form of V–I characteristics closely resembled those obtained previously.[1] The function of the tantalum insert[5] is not fully understood, and it is doubtful if it was necessary. Its only role was probably to increase the temperature of the internal surfaces by acting as a thermal impedance. However, the small increase calculated was totally inadequate to explain the emission by the field-enhanced thermionic mechanism. It was therefore concluded that the impact of metastable atoms is probably the dominant mechanism in a cathode containing no barium. With barium, both mechanisms probably occur simultaneously, causing T and V to be reduced.

In order to test the constant J model, two molybdenum cathodes were constructed with special orifice shapes. The first had a stepped orifice (Fig. 3) and, according to the model, two transitions were expected. These were in fact observed (Fig. 3) and yielded values of J between 2.3 and 3.4×10^5 amp/m^2.

The second special orifice had a curved profile (Fig. 3), with the aim of allowing the plasma to expand gradually into the cathode. This prediction that the plume mode would be absent at much lower flow rates than hitherto was verified (Fig. 3), although for $\dot{m} < 0.05$ mg/sec it reappeared, possibly due to slight irregularities in the orifice profile.

Of considerable interest was the rather rapid deterioration with time of this and conventional cathodes having triple carbonate mix on their internal walls. This was attributed to barium depletion and an increasing reliance on emission by metastable impact, and emphasized that very little is known about the optimum methods of barium dispensation, or of the factors contributing to its rate of depletion. Similar conclusions have resulted from investigations at much higher currents and flows than reported here.[6]

Starting characteristics of various cathodes were investigated using the normal technique of applying a high voltage to the keeper. Under fixed conditions the breakdown voltage V_b fell unpredictably within a range determined by $\dot{m}$ and T.[3] At low temperatures and flows V_b varied widely, but the range diminished as T and $\dot{m}$ were increased. V_b then became almost reproducible and very low values, down to 15 v, were consistently recorded.

Results were strongly dependent on the type of barium dispenser, the tantalum foil variety allowing starting with T as low as 650°C. With $\dot{m} = 0.1$ mg/sec and $T = 1150$°C, V_b was 20–500 v with a tubular insert having an external barium coating, but only 20–50 v with the spiral dispenser. The curved orifice cathode was the easiest to start; even with $\dot{m}$ as low as 0.05 mg/sec, V_b was consistently as low as 20 v at 1100°C and, at 0.17 mg/sec and 800°C, the range of V_b was only 10 v whereas a comparable range was not achieved with the tubular insert until 1350°C. This was attributed to the ease with which barium could migrate into the orifice. The starting characteristics of the nonbariated cathode confirmed that barium is essential for easy discharge initiation, since T had to be about 350°C above normal. The results thus indicated that barium plays a dominant role in discharge initiation, suggesting that thermionic emission is an important mechanism.

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