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NOVEMBER 1971 AIAA JOURNAL VOL. 9, NO. 11

A Study of Hollow Cathode Discharge Characteristics

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The operation and performance of small-orifice hollow cathodes for use in electron bombardment ion thrusters is described. Using mercury propellant, vaporized either in a small boiler or by a heated porous plug, cathodes have been operated in both a simple test facility and in an ion thruster. Voltage-current characteristics were obtained by a novel rapid-scan technique, and the dependence of these on parameters such as vapor flow rate and temperature has been studied. An examination of such characteristics has enabled a qualitative theory of the cathode discharge to be proposed, which is consistent with the observed behavior. Cathodes have been operated for periods exceeding 1000 hr without any apparent deterioration of performance.

Introduction

THE majority of electron bombardment ion thrusters using mercury propellant employ hollow cathodes[1] for both the main discharge and neutralizer.[2] In order to make the most efficient use of such cathodes in these applications, it is necessary to obtain extensive information concerning the dependence of their characteristics on parameters such as vapor flow rate, temperature, and constructional dimensions. It was the aim of the work described here to develop a suitable cathode, to obtain this information both in a simple test facility and in an operating thruster, and to optimize the design to achieve high efficiency and long operational life.

At the present time, a successful cathode design has been evolved, and preliminary life tests have shown that orifice erosion can probably be overcome. Using mercury vapor from either a small boiler or a porous plug vaporizer, cathodes have been operated under widely varying conditions in both a laboratory vacuum chamber and in an ion thruster test facility.

Voltage-current characteristics have been obtained using a new technique and indicate that suitable operating points exist for both main discharge and neutralizer applications. In addition, it was possible, using the information gained, to propose a discharge mechanism, including appropriate electron emission processes, which was qualitatively consistent with experiment.

Presented as Paper 70-1087 at the AIAA 8th Electric Propulsion Conference, Stanford, Calif., August 31–September 2, 1970; submitted October 21, 1970; revision received May 7, 1971. The author wishes to thank D. G. Fearn for helpful advice throughout the course of this work. Thanks are also due to A. A. Wells of Culham Laboratory and G. L. Davis and M. G. Charlton of Mullard Ltd. for many fruitful discussions.

Index category: Electric and Advanced Space Propulsion.

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Cathode Construction

The types of hollow cathode used were similar in configuration to the neutralizer cathode described by Rawlin and Pawlik,[2] the basic design features being illustrated in Fig. 1. The cathode tip was a tungsten disk (1 mm thick and 3.5 mm diam) electron-beam welded into a tantalum tube. It was provided with a central orifice of between 100 and 350 μm diam formed by either spark erosion or diamond drilling. A stainless-steel flange at the upstream end of the cathode was provided for mating with other components.

Cathode Heater

Two methods were used for encapsulating the cathode heater, which was made from 15 turns of 200-μm-diam tungsten-3% rhenium wire, electro-polished before winding. One method employed alumina particles flame-sprayed onto the cathode body. In this case, a thin intermediate layer of molybdenum was applied to the tantalum tube to provide a bond for the alumina and to prevent an alumina-tantalum reaction at elevated temperatures. In the second method, a zirconia-based ceramic adhesive was applied in paste form and was subsequently hardened and cured.

Emitting Surface

To produce an electron-emitting coating, a layer of triple carbonate mixture was applied to the internal surface of the tantalum tube. The carbonates were reduced on raising the temperature to about 1200°K in vacuo, and a low work function surface of chiefly barium oxide was formed.

Apparatus

Most of the experiments were performed in a glass chamber evacuated by a mercury diffusion pump. The pressure was monitored by means of Pirani and ionization gages. The hollow cathodes were bolted, either directly or via an inter-

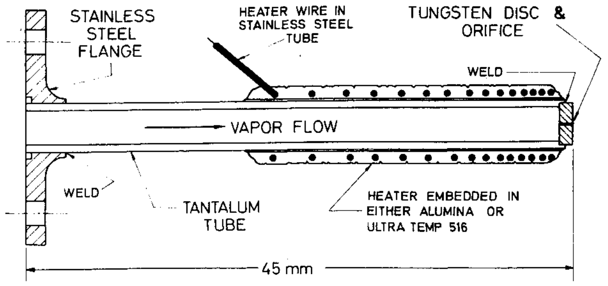


Fig. 1 Hollow cathode.

mediate auxiliary heater, to the vapor feed system, and sealed by gold O-rings or commercial gasket material. To initiate the discharge, a keeper was used. This consisted of a thin molybdenum disk with a 2-mm central hole, and it was spaced about 1 mm from the cathode tip. The anode, or beam simulator electrode, was normally a disk of stainless steel whose distance from the cathode could be varied.

Mercury Boiler

Hollow cathodes were first operated using mercury vapor from a small stainless-steel boiler. The reservoir, surrounded by a cylindrical heater jacket into which it could slide, was easily removable for replenishing or weighing. A thermocouple measured the temperature of the boiler, and enabled the vapor pressure of the mercury to be deduced.

Unfortunately, it was not possible to deduce the mass flow rate when using the boiler, since it was not clear which regime of flow existed in the cathode orifice. Considerations of the orifice dimensions and pressure suggest that the flow was in the transition region, a similar deduction being made by Csiky.[3] However, the calculated flow rate and that measured directly (by weighing the reservoir before and after heating the boiler for a fixed time interval) often differed by more than an order of magnitude. In addition, it was probable that the flow was significantly dependent on discharge conditions.

Vaporizer

A direct measurement of the mass flow rate was possible using a mercury vaporizer, and such a device was employed

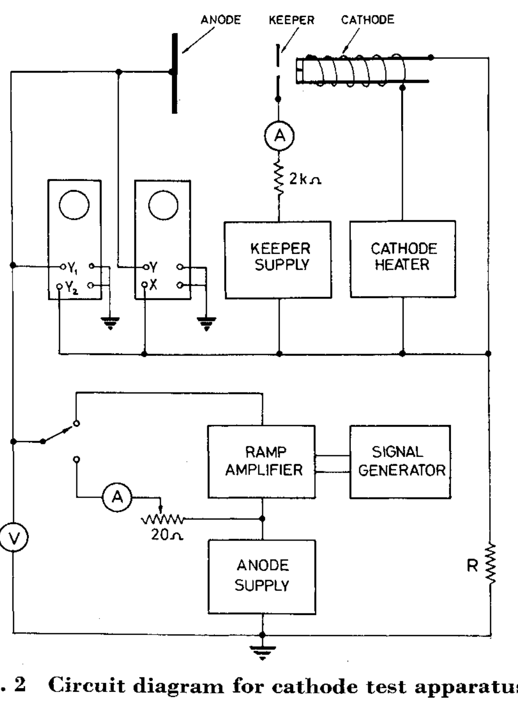


Fig. 2 Circuit diagram for cathode test apparatus.

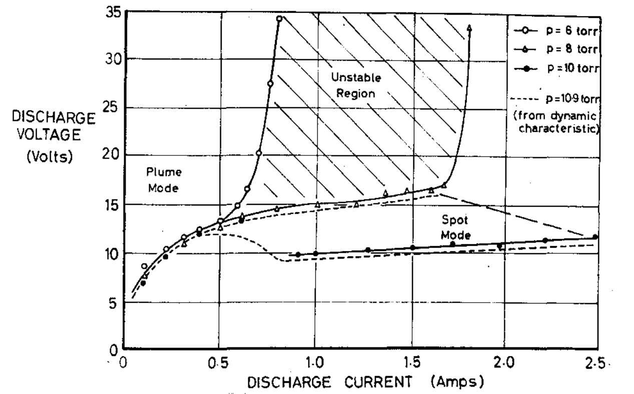


Fig. 3 Hollow cathode characteristic using the static method.

in the more recent experiments. Liquid mercury was vaporized at the surface of a porous tungsten plug phase separator, whose temperature could be varied by means of an external heater. The flow rate was measured by the fall of mercury in a capillary tube, and in this way a temperature-mass flow rate calibration was obtained. The output of a thermocouple attached close to the plug was fed into a control circuit which maintained the vaporizer at a constant temperature, with a deviation of less than $\pm 1°C$. By placing other thermocouples on the downstream side of the vaporizer, it was possible to insure that there was no condensation of mercury within the vapor feed assembly.

Electrical Circuit

Figure 2 shows the circuit used for measuring current-voltage (I-V) characteristics by both a point-by-point (static) method and an automatic swept-voltage (dynamic) technique. All heaters were supplied by d.c., and up to 750 v from a stabilized supply was available to initiate a discharge to the keeper electrode. The anode-stabilized power supply, used when recording static characteristics, could deliver up to 10 amp at 50 v.

The swept voltage technique was developed to enable I-V characteristics to be displayed instantaneously on an oscilloscope and to provide a photographic record of the trace. There was considerable difficulty in maintaining certain parameters, such as cathode tip temperature, constant for the time required to obtain a characteristic by the static method; the dynamic technique eliminated this disadvantage. A triangular waveform from a signal generator was current amplified, and the output was applied to the anode and to the Y-plates of an oscilloscope. The discharge current was measured by applying to the X-plates the small voltage developed across a standard resistance R, which was usually 0.1 or 1.0 Ω. In this manner a continuous I-V characteristic was displayed on the oscilloscope screen by using a sufficiently rapid voltage rise time (about 10 msec). For reference purposes, the current and voltage were sometimes displayed as functions of time on a second oscilloscope. The circuit also incorporated a switch so that the manually operated d.c. supply could be substituted for the automatic system when required.

With voltage sweep periods of the order of 10 msec, it is clear that the boiler or vaporizer temperatures remained constant during the time needed to record a characteristic. Because of the large amount of energy delivered to the cathode through ion bombardment, it is not quite so obvious that the tip temperature remained essentially constant during this time. However, knowing the thermal mass of the cathode, and assuming the worst possible case in which all the discharge power was dissipated in the cathode, it can easily be shown that the tip temperature variation was about 1°C. This is negligible at the usual operating temperature of about 1000°C.

It can also be shown that the application of a rapid voltage sweep did not alter the form of the ion and electron velocity distributions. For meaningful characteristics to be recorded, the sweep time must be considerably greater than a representative relaxation time in the plasma. This allows each point on a swept characteristic to be realistically identified with a corresponding point on a characteristic obtained with the static method. Considering electrons and ions separately, Spitzer[4] derived the following expression for the self collision time t_c for momentum transfer in a plasma dominated by Coulomb collisions:

$$t_c = \frac{m^{1/2}(3kT)^{3/2}}{8 \times 0.714\pi n e^4 \ln\Lambda} \quad \text{sec}$$

where $\Lambda = 1.24 \times 10^4 T^{3/2}/n^{1/2}$, and the ions are assumed singly ionized. A similar expression was derived for the electron-ion collision time t_{ei} for the usual case of $T_e \geqslant T_i$. Here m, T, and n are the mass (g), temperature (°K), and number density (cm^{-3}) of the species considered, and e and k are the electronic charge (4.8×10^{-10} esu) and Boltzmann's constant (erg °K^{-1}). For mercury ions and electrons respectively, t_c reduces to

$$t_{ci} = 161.2 T_i^{3/2}/n_i \ln\Lambda_i \quad \text{(ions)}$$

$$t_{ce} = 0.266 T_e^{3/2}/n_e \ln\Lambda_e \quad \text{(electrons)}$$

$$t_{ei} = 0.714 t_{ce}$$

Subscripts e and i refer to electrons and ions, respectively. In the absence of probe data for the present experiments, values of n and T measured in an almost identical hollow cathode discharge were used.[5] Putting $n_i = n_e = 2 \times 10^{11}$ cm^{-3} and $T_e = \frac{1}{2}$ ev (4×10^3 °K) into the preceding equations yields an upper value for t_c, i.e., $t_{ce} = 4 \times 10^{-8}$ sec for electrons and, assuming $T_i \simeq 10^3$ °K, $t_{ci} = 3.7 \times 10^{-6}$ sec for ions. It is therefore clear that the sweep time was much greater than these collision times, and the use of the dynamic method for recording characteristics was justified.

Results

Activation and Starting

The procedure followed for activating the cathode and starting the discharge was almost identical to that described by Rawlin and Pawlik[2] and Csiky,[3] and need not be elaborated here.

Static Experimental Technique

This method of obtaining characteristics was mainly restricted to the earlier experiments in which a boiler was used. After the introduction of the dynamic technique, the static method was used chiefly to confirm the results of the former, and for life-testing cathodes at a fixed value of discharge current. The difficulty of maintaining temperatures constant has already been mentioned; another major difficulty was the presence of high-frequency oscillations in some discharge regimes, which precluded accurate measurements of the current and voltage with the meters available.

In general, it was found that two distinct discharge modes were present, often separated by an oscillatory transition regime. One, characterized by low currents and high voltages, is referred to as the plume mode,[3] and the other, which occurred at high currents and lower voltages, is known as the spot mode. The dominant factor, which determined whether either or both modes were present, appeared to be the boiler pressure p or flow rate $\dot{m}$; other parameters, such as cathode tip temperature, seemed to have a secondary effect on the recorded characteristics.

Typical characteristics, obtained by the static method, are shown in Fig. 3 for a number of different values of p. The orifice diameter was 360 μm, the anode-cathode spacing was 1.8 cm, and the anode was 6.3 cm diam. At the lowest boiler pressures, only the plume mode could be obtained, the current limiting, usually with violent oscillations, at a value dependent on p. On increasing p above about 9 t, a rapid rise in current and drop in voltage were observed, and the oscillations vanished. The discharge also changed visibly from the bright purple-blue plume mode, filling the chamber, to the spot mode, which was almost nonluminous except for an intense blue-white spot at the cathode orifice. In order to obtain the spot mode at intermediate pressures, it was necessary to increase the applied voltage to a high value, typically 35 v and dependent on anode-cathode spacing, to initiate the mechanism responsible for the high emission currents in this mode. Once this had been established, apparently while the cathode was operating in the unstable oscillatory regime, the current increased dramatically, and external limitation was necessary until the applied voltage could be reduced. This behavior, which was more clearly demonstrated by the dynamic technique, has also been mentioned by other investigators.[1,3]

It should be mentioned that, because of ion bombardment, the tip temperature increased considerably when a discharge was running, and the energy supplied was usually sufficient to enable the cathode to be operated with no external heater power, even with discharge currents as low as 0.1 amp.

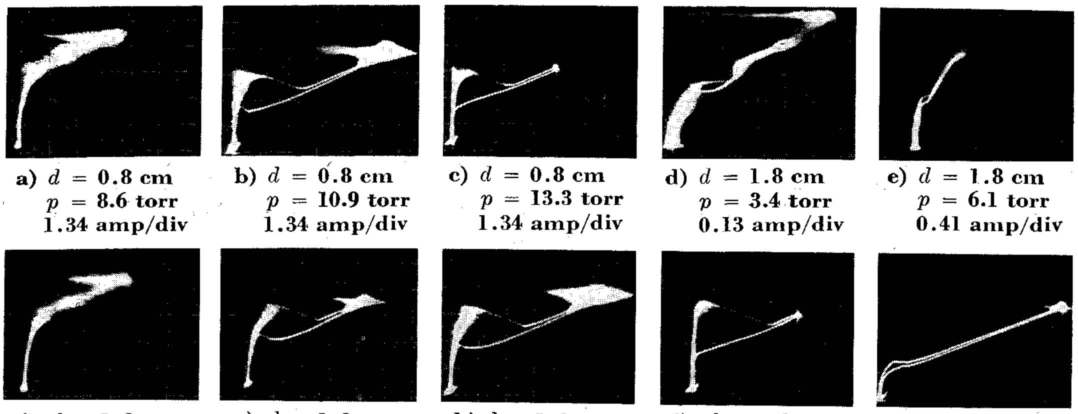
Dynamic Experimental Technique

A large number of characteristics was obtained using this method, and Figs. 4 and 5 show a representative selection of oscillograms for cathodes of $\simeq$360 μm diam orifice. In Fig. 4, the change in characteristic shape with boiler pressure is illustrated for two different anode-cathode separations, whereas Fig. 5 shows a series of characteristics at different flow rates for an anode-cathode distance of about 2 cm. Both rising and falling voltages are represented on each oscillogram; in nearly all cases, the upper trace corresponds to the upward sweep of the voltage waveform.

Considering Fig. 4 and the lower boiler pressures first, it can be seen that an initial increase in voltage produced very little change in current until a point was reached at which current oscillations and noise started to develop. Thence the mean current increased with voltage to a value where the oscillation amplitude became extremely large. Still further increase in applied voltage up to its peak value of 30 to 35 v resulted only in a greater oscillation amplitude without any observed change in the mean current value. At this point, the discharge current had become limited or "saturated." The return characteristics, i.e., the variation of current with decreasing voltage, were not very different from the forward characteristics at these low pressures, and the curves were noisy everywhere except at the smallest currents. The plume mode dominated in such cases.

At boiler pressures above about 9 t, the characteristic shape began to change markedly. Once the voltage had reached a certain value in its upward sweep, the current, instead of remaining oscillatory and saturating, increased rapidly and was usually accompanied by a drop in discharge voltage. Beyond this point, a practically noise-free trace was obtained as the current continued to increase with voltage, eventually reaching a limit where oscillations and apparent saturation were again observed. In the reverse characteristic, the nonoscillatory trace continued down to very small currents, often passing through a slight voltage minimum.

Finally, it was found that, at high pressures, the characteristic very rapidly changed to the form illustrated by Fig. 4j, in which it was no longer necessary to pass through the high-voltage noisy regime to obtain the nonoscillatory high-current mode of operation.



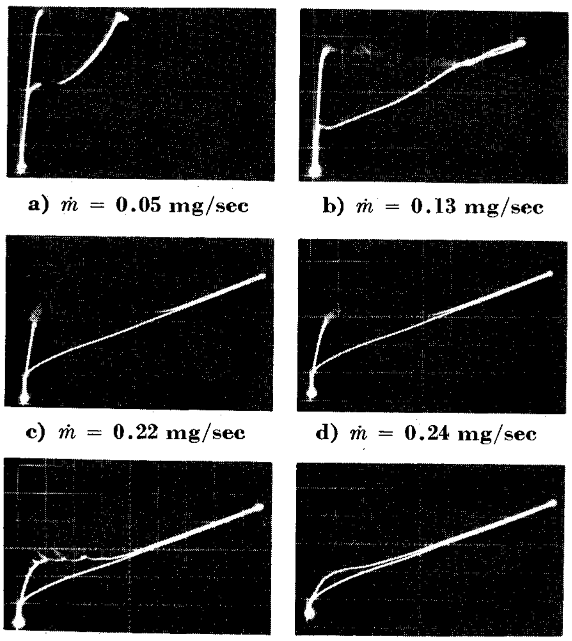
a) d = 0.8 cm, p = 8.6 torr, 1.34 amp/div
b) d = 0.8 cm, p = 10.9 torr, 1.34 amp/div
c) d = 0.8 cm, p = 13.3 torr, 1.34 amp/div
d) d = 1.8 cm, p = 3.4 torr, 0.13 amp/div
e) d = 1.8 cm, p = 6.1 torr, 0.41 amp/div
f) d = 1.8 cm, p = 8.6 torr, 1.34 amp/div
g) d = 1.8 cm, p = 9.8 torr, 1.34 amp/div
h) d = 1.8 cm, p = 10.9 torr, 1.34 amp/div
i) d = 1.8 cm, p = 13.3 torr, 1.34 amp/div
j) d = 1.8 cm, p = 14.2 torr, 1.34 amp/div

Voltage sensitivity: 4.2 v/div ↑ Current sensitivity as marked →

Fig. 4 Voltage-current characteristics for hollow cathode.

It seems reasonable to assume that the noise-free parts of the characteristics represented the spot mode of the discharge, whereas the rather oscillatory low-current regions were typical of the plume mode. If this is the case, then these results agree well with the limited information obtained using the static method.

The characteristics shown in Fig. 5, in which a vaporizer was used to provide the flow, correspond closely with those obtained using a boiler. These are probably of more value in determining optimum operating points, since it is not easy to correlate pressure accurately with flow rate. Below flow rates of 0.05 mg/sec, it was not found possible to obtain a spot mode discharge, the current always saturating first. However, for flow rates exceeding about 0.1 mg/sec, spot mode discharges were obtainable, the voltage required to reach a suitable operating point becoming progressively lower as the flow rate was increased. For flow rates greater than about 0.3 mg/sec, both forward and reverse characteristics were practically identical, and the plume mode was completely absent.



a) $\dot{m}$ = 0.05 mg/sec
b) $\dot{m}$ = 0.13 mg/sec
c) $\dot{m}$ = 0.22 mg/sec
d) $\dot{m}$ = 0.24 mg/sec
e) $\dot{m}$ = 0.28 mg/sec
f) $\dot{m}$ = 0.33 mg/sec

5 v/cm ↑ 1 amp/cm →

Fig. 5 Voltage-current characteristics for hollow cathode.

Using photographic data such as those presented in Figs. 4 and 5, some rather approximate graphical relationships were derived as shown in Figs. 6 and 7. In Fig. 6, the value of current at which saturation finally occurred, I_{lim}, is plotted as a function of boiler pressure. It can be seen that this limiting current remained of the order of 1 amp at the lower pressures but rose quite rapidly as the pressure was increased above 6 t, reaching about 9 amp at 14 t. When a minimum occurred in the reverse characteristic, the value of voltage at this point was plotted as a function of pressure for various anode-cathode separations, as shown in Fig. 7. The minima were essentially the smallest current and voltage obtainable in the spot mode before the discharge made the transition back to the plume mode, and represent the point at which a spot mode discharge can be operated with least power. Of particular interest is the fact that, as the pressure increased, the minimum voltage tended toward the rather low value of about 7 v.

Cathode Life-Testing

Hollow cathodes with various orifice diameters between 100 and 350 μm have been operated successfully at a discharge current of 3 amp for periods up to 1300 hr. Quite rapid erosion of the smaller-diameter orifices occurred, but erosion of the larger diameters was less serious and would probably be acceptable for typical ion thruster mission durations. No deterioration in performance was evident during life-testing, and the operating and starting characteristics showed little change.

Ion Engine Tests

A number of hollow cathodes have been tested in an operating ion thruster[6] for over 500 hr, and Fig. 8 shows a series of static characteristics at various total flow rates. The vapor flow rate through the cathode was $\simeq$0.07 mg/sec. Although the absolute values of voltage are much higher than those obtained in the laboratory test facility, presumably because of the very different geometry and the presence of a magnetic field and baffle assembly, the results confirm that the operating voltage decreases considerably as the flow rate is increased. A limiting current, typically 0.7–1.0 amp, was found below which the discharge was extinguished. This corresponded to the transition back to the plume mode. It was possible, under some conditions, to reduce this minimum slightly by increasing the cathode flow rate.

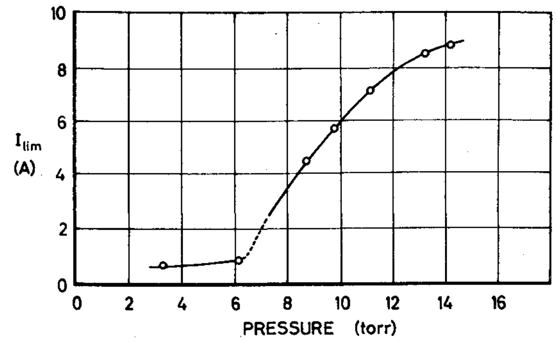


Fig. 6 Limiting current as a function of pressure.

Very little cathode erosion was observed during these experiments, despite occasional operation at 5 amp discharge current. On some occasions, when only a small quantity of carbonate mixture had been introduced into the cathode, it was found that the cathode heater power had to be increased to augment that supplied by ion bombardment, probably because of barium starvation.

Discussion

It is not possible at the present time to put forward a comprehensive explanation of the phenomena encountered during the operation of hollow cathodes, since information is still lacking as to many of the processes likely to be occurring. However, the results obtained suggest certain emission mechanisms that may account for the observed behavior.

It seems certain that thermionic emission is necessary to initiate the discharge from the present form of hollow cathode, but the site of this emission has not been established. However, modification to include an internal auxillary electrode has shown that starting by field emission is quite feasible, even in the absence of electron-emitting coatings. Thus, thermionic emission is not a fundamental requirement.

Once breakdown has occurred and a current is drawn to the anode, thermionic emission cannot possibly account for the high current densities obtained. Wells and Harrison,[5] in similar experiments, have evidence to suggest that the discharge current may be emitted from the cathode surface at constant current density. They propose that the plume mode starts with emission from the downstream end of the orifice, and, as the current increases, the emitting area increases as the plasma moves into the orifice. The plume/spot mode transition takes place when the plasma reaches the upstream end of the orifice, and emission is then required from the internal walls of the cathode. Preliminary data obtained in the course of the present work, using an internal probe, have indicated the presence of the necessary plasma within the cathode.

The experimental data of Wells and Harrison indicate a constant current density of $\sim$50 amp/cm^2. In the present experiments, where the plume/spot mode transition current was about 0.7 amp and the orifice area was 1.2×10^{-2} cm^2, the current density was also of this order. Furthermore, experiments carried out using cathodes with different orifice diameters, in the range 100–300 μm, showed that the transition current increased with increasing orifice diameter, and that, within experimental error, the current density was constant. It must be pointed out, however, that this model does not predict the variation in spot/plume mode transition as the flow rate or pressure is changed. In particular, it is difficult to see how it can account for the absence of the plume mode (Fig. 5f) at high flow rates and pressures and for the observed dependence of the transition on external pressure as well as internal pressure. Moreover, the actual emission mechanism remains to be identified.

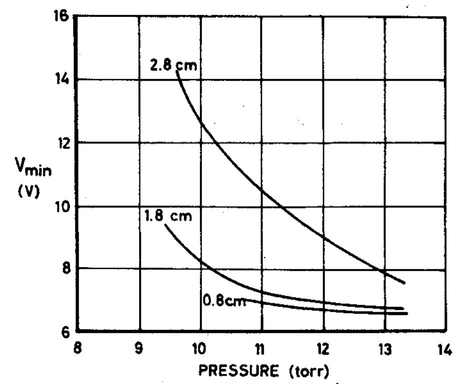


Fig. 7 Variation of minimum discharge voltage with pressure for several anode-cathode separations.

The emission mechanism must therefore account for current densities of about 50 amp/cm^2 if the preceding model is appropriate or much larger values if the emission takes place from a smaller area, as would be the case if cathode spots were involved. However, the photographic study of the orifice by Rawlin and Kerslake[1] indicated that cathode spots were probably not involved. One possibility is field-enhanced emission (Schottky effect) caused by sufficiently high electric fields across the space charge sheath separating the walls of the cathode from an internal plasma. Using the Richardson-Dushman equation, the following expression can be derived easily to relate the current densities with and without an electric field (J and J_0) with the potential gradient (G) and the absolute temperature of the wall (T):

$$\ln(J/J_0) = e^{3/2}G^{1/2}/kT$$

Assuming that the maximum value of J_0 is of the order of 1 amp/cm^2,[7] a potential gradient of about 10^5 v/cm is necessary for $J \simeq 50$ amp/cm^2. Such fields may be established in the presence of suitable plasmas. The conditions within the hollow cathode are unknown, but it is possible that T_e will be close to the value measured outside (4×10^3 °K) and that n_e will be much higher owing to the larger pressure and the presence of barium. Taking $n_e \simeq 10^{13}$ cm^{-3} and assuming that the sheath is of the order of a Debye length (λ_D) thick, where

$$\lambda_D = (kT_e/4\pi n_e e^2)^{1/2} \quad \text{cm}$$

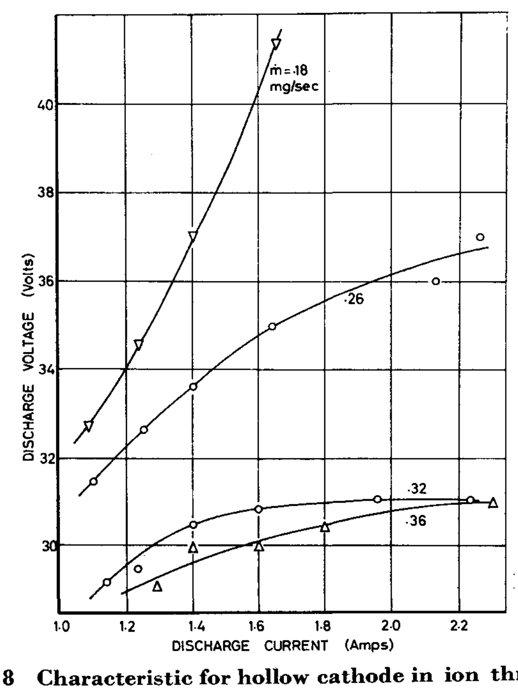


Fig. 8 Characteristic for hollow cathode in ion thruster.

then $\lambda_D \simeq 10^{-4}$ cm and $G \simeq 4 \times 10^4$ v/cm for a plasma potential of 5 v. Although this is barely sufficient, unless n_e or the plasma potential is larger, Sajben[8] has shown that, in plasmas seeded with alkali metals, greatly enhanced electric fields may occur. This results from a large increase in the ion density in the sheath at the negative electrode, probably to values several orders of magnitude greater than the prevailing ion density in the plasma. In a mercury plasma seeded with barium ions, large Schottky effects would therefore be expected.

Another emission mechanism that could be very effective in the hollow cathode is the release of electrons by the impact of excited atoms. High yields are to be expected when the excitation energies are not much greater than the work function of the emitting surface. For mercury metastables impacting on tantalum, Gurevich and Yavorski[9] calculated that between 0.55 and 0.75 electrons would be released per excited atom.

This theory was originally proposed by von Engel and Robson[10] to explain the high current densities obtained by emission from cathode spots. In the present case, it is not necessary to postulate the existence of true cathode spots, as mercury vapor is supplied from an external source. Excited mercury atoms can be formed by a number of processes in the discharge, such as collisional excitation or charge transfer, provided that the electron-neutral and ion-neutral mean free paths are less than a typical orifice dimension. By considering the emission and absorption of resonance radiation, von Engel and Robson showed that it is probable that all of the atoms back-scattered toward the cathode by collisions with ions reach a small area of the cathode surface in excited states and thus cause electron emission. The orifice erosion observed in the present work confirmed that a considerable ion flux reached the cathode tip, indicating that significant back-scattering of atoms occurred.

The flux of atoms that release electrons from the cathode must be sufficient to produce a current density of the order of 50 amp/cm^2 if the previously mentioned model is applicable. If the effect of back-scattering by ions is not included, this flux is given by $S = \frac{1}{4} N\bar{c}$, where $N = p/kT_g$, $\bar{c} = (8kT_g/\pi m)^{1/2}$, and T_g is the gas temperature. Typical values of p and T_g are 10 t and 1200°K, giving a flux of 7.2×10^{20} atoms-cm^{-2}-sec^{-1}. Using the previously mentioned yield of electrons per excited atom impact and assuming that each atom is a metastable, the emission current is between 4.0×10^{20} and 5.4×10^{20} electrons-cm^{-2}-sec^{-1}, or 66–90 amp/cm^2. These values would be much greater if the back-scattering effect were included.

This emission mechanism, therefore, is capable of providing the required current density, and further evidence for its existence is privided by the ability of stable spot mode discharges to operate at potentials considerably lower than the ionization potential of mercury. From Fig. 7, it can be seen that the minimum discharge voltage approached a value close to 6 v as the pressure was increased. This corresponds to the maximum of the cross section for excitation of mercury atoms to the 4.9 ev metastable level, and these are very effective at producing emission.

It will be noted that the preceding mechanism is not in any way dependent on the presence of an alkali metal within the cathode, and it should therefore operate successfully in the absence of the triple carbonate coating. It was, in fact, found that a discharge could be run without this coating, but the voltage required was considerably higher than normal. This suggested that a mechanism requiring the coating normally operated in conjunction with that dependent on metastable atoms, and it is possible that the theory formulated by Sajben[8] is appropriate to the former.

The hollow cathode mechanism is undoubtedly more complex than the preceding treatment would suggest. Although it seems likely that, in some cases, either or both of the emission processes discussed are dominant, others may be necessary to explain all of the data satisfactorily. It is clear that further experimental work is required before detailed calculations can be performed to test the validity of the foregoing arguments.

Conclusions

Small orifice hollow cathodes have been reliably operated with mercury vapor flows for periods of over 1300 hr. A novel rapid scan technique has enabled large numbers of current-voltage discharge characteristics to be obtained, and analysis of these results has revealed much interesting information. The two discharge regimes (plume and spot modes) are normally suitable for neutralizer and main thruster operation, respectively, and significant oscillatory components can easily be avoided. The existence of one or both of these discharge modes is strongly dependent on the mercury vapor pressure within the hollow cathode or the flow rate through the orifice.

Based on the information available, two possible emission mechanisms, which could each provide the required high current density, are discussed. These are Schottky effect field emission and the release of electrons by impact of mercury metastable atoms, both of which are consistent with the observed behavior.

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