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Low-Current, Xenon Orificed Hollow Cathode Performance for In-Space Applications

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An experimental investigation of the operating characteristics of 3.2-mm-diam orificed hollow cathodes was conducted to examine low-current and low flow-rate operation. Cathode power for self-sustaining keeper operation was minimized with an orifice aspect ratio of approximately one or through the use of an enclosed keeper. For spot-mode emission cathode flow-rate requirements were proportional to orifice diameter and the inverse of the orifice length. The minimum power consumption in diode mode was 10 W, and the minimum mass flow rate required for spot-mode emission was approximately 0.08 mg/s. Cathode temperature profiles were obtained using an imaging radiometer, and conduction was found to be the dominant heat-transfer mechanism from the cathode tube. Orifice plate temperatures were found to be weakly dependent upon the flow rate and strongly dependent upon the current.

Nomenclature

AR_x = cathode with an orifice aspect ratio of x
D_o = orifice diameter, m
L_o = orifice length, m
x = orifice aspect ratio

Introduction

ALTHOUGH state-of-the-art electric propulsion systems provide a systems mass advantage compared with chemical thrusters for stationkeeping and primary propulsion applications on satellites with several kilowatts of power generation, a need remains for performance improvements in subkilowatt propulsion systems for small satellites.[1] The performance of sub-500-W ion and Hall thrusters depends heavily upon the power and propellant consumed by the hollow-cathode neutralizer[1]; the cathode in the Hall thruster performs the functions of both main discharge cathode and beam neutralizer. Patterson and Oleson[1] reported that a state-of-the-art neutralizer for a 100-W ion thruster could degrade the efficiency by up to 20% and reduce the specific impulse by as much as 2000 s. Optimization of low-current hollow cathodes is also sought for plasma contactor applications. In general, spacecraft application of hollow-cathode technology demands minimization of power and propellant consumption while maintaining a lifetime of several years demonstrated by state-of-the-art devices used in ion thrusters and for the International Space Station. To develop design tools, an initial experimental investigation was conducted using laboratory model cathodes to determine the similarities and differences of low-power hollow-cathode operation with previous studies.[2–4] This paper reports the results of the experimental investigation of laboratory model 3.2-mm-diam orificed hollow cathodes for low-current applications.

Background

Orificed hollow-cathode technology, used extensively in ion thrusters since the late 1960s, was brought to flight level maturity with xenon propellant as part of the International Space Station program.[5,6] During the hollow-cathode life validation program, assembly and operating procedures were developed, which enabled operation in a dc discharge to 28,000 h.[6] The major operating procedures that led to the extended life of the cathode are a prescribed operating temperature regime and maintenance of electron emission in spot mode. Operation at orifice plate temperatures below 1300°C was chosen as an operational limit for these experiments to be consistent with practices proven to enable lifetimes greater than 10,000 h.[5] The cathode tip temperature has been considered the most representative and readily observable temperature that relates to the insert temperature.[3] If the temperature is too high, the barium in the insert evaporates more quickly than it can be replenished through diffusion, and the discharge becomes unstable; low temperatures are insufficient to drive the diffusion of barium and barium oxide at a rate that sustains the low work function surface of the emitter.[7] Because the lower limit represents a nondestructive condition, the cathodes in this investigation were operated at as low of an orifice plate temperature as stable operation permitted. Only the lifetime of the cathode is addressed in this study, and the lifetime of other components such as the heater and keeper must also be considered in the design of the hollow-cathode system.

Spot and plume modes are the two major electron emission regimes generally considered in orificed hollow-cathode design. Spot-mode emission is characterized by a low coupling voltage to an anode, negligible ac components of the discharge voltage and current, and a bright plasma spot at the cathode orifice plate. Conversely, plume-mode emission is characterized by a somewhat increased coupling voltage to an anode, large ac components of the discharge voltage and current, and a distributed plasma plume downstream of the cathode. The phenomena comprising plume-mode emission lead to increased wear on the cathode orifice plate caused by energetic ion bombardment. The life-limiting nature of plume-mode emission led to the decision to operate the plasma contactor in spot mode, and the success of the 28,000-h hollow-cathode life test validated this design decision; the cathode failure was attributed to depletion of the available barium and barium oxide in the insert, whereas the orifice plate wear was modest.

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Low-current orificed hollow cathodes were developed to flight-ready or near flight-ready status previously.[8–11] In the Ion Auxiliary Propulsion System program 3.2-mm-diam orificed hollow cathodes were operated with mercury propellant at a mass flow of 0.013 mg/s and power ranging from 6 to 7.5 W for the neutralizer keeper.[8,9] More recently, xenon hollow cathodes have been developed for low current applications with flow rates and power consumption ranging from 0.02 to 0.08 mg/s and 8 to 14 W, respectively, for discharges to the keeper only.[10,11] The present investigation sought to examine the relevant geometrical factors in the cathode that would enable improvement of the flow rate and power consumption for space applications.

Experimental Apparatus

Because the lifetime of orificed hollow cathodes is achieved through known operating and design considerations, the present investigation focused on improvements in the power and propellant consumption of low-current devices. The hollow cathodes used in this investigation were designed and fabricated based on existing hollow-cathode and plasma contactor procedures.[12] Becuase the cathodes were laboratory models, a number of the specifications and inspection procedures required for flight hardware were either relaxed or omitted. The authors attempted to follow the flight hardware procedures when it was reasonable to do so in order to facilitate the transition from laboratory models to flight units.

Hollow-Cathode Design

An engineering schematic of the 3.2-mm-diam hollow cathodes is presented in Fig. 1, and the identifying characteristics of the various cathodes tested are listed in Table 1. The orifice diameter for the AR6-A and AR6-B cathodes was chosen based on the Kaufman criterion of 12 A/mm of orifice diameter, and the dimensions reported in this work are normalized to the diameters of AR6-A and AR6-B.[13] The orifice length was chosen by combining machining considerations with numerical results obtained from the model by Mandell and Katz.[14] The resulting orifice had a length-to-diameter L_o/D_o aspect ratio of approximately six, and the two cathodes made with this type of orifice are referred to as AR6-A and AR6-B. Cathodes with orifice aspect ratios of approximately three (AR3-A) and one (AR1) were also constructed. A cathode with an aspect ratio of three (AR3-B) was constructed with an orifice diameter 60% that of the AR6 cathodes and hence lower current-carrying capability. Finally, a third cathode with orifice plate dimensions identical to the AR6 cathodes was constructed for tests in both enclosed (EK6) and open keeper (OK6) configurations; an enclosed keeper consists of a cylindrical tube with an orifice plate that houses the cathode. The cathode tube for EK6/OK6 was approximately 50% longer than the AR6 cathodes. The keeper orifice diameter and gap were held constant in this investigation at normalized values of 17.6 and 7.7 orifice diameters, respectively. The inserts used in this investigation were commercially available low-work function emitters made of porous tungsten impregnated with a 4:1:1 molar ratio of BaO-Al_2O_3-MgO (Ref. 5). The normalized inner diameter and length were 9.4 and 98, respectively.

Table 1 Cathode geometry and configuration (orifice plate dimensions normalized by the AR6 orifice diameter)

Cathode	Normalized orifice diameter	Normalized orifice length	Keeper type	Secondary anode
AR6-A	1.0	5.6	Open	No
AR6-B	1.0	5.6	Open	No
AR3-A	1.0	3.2	Open and mesh	Yes, for plasma; property tests
AR3-B	0.6	1.8	Open	No
AR1	1.0	1.4	Open	No
OK6	1.0	5.6	Open	No
EK6	1.0	5.6	Enclosed	Yes

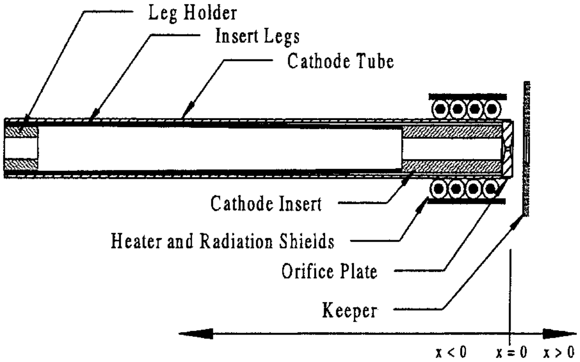


Fig. 1 Schematic of the laboratory model cathodes.

Facilities

All of the facilities used in this investigation were cryopumped with base pressures in the high-10^{-6} Pa range. During cathode operation, the tank pressure in the facilities varied from 3 to 11×10^{-3} Pa, corrected for xenon. In each case high-purity xenon was supplied to the cathode through a flow system accurate to within ± 7-μg/s based upon bubble flow-meter calibrations.

Cathode Performance

When attempting to assess experimentally the effects of varying the orifice geometry on the performance of hollow cathodes, the ideal technique is to change only the orifice plate. This was done by Siegfried,[2] using a slide valve with three orifice geometries. The experiment was conducted on a mercury hollow cathode, and the aspect ratios (L_o/D_o) of the orifices were negligibly small in comparison with those considered in the current investigation. In the present investigation separate assemblies were fabricated and tested so that the cathodes could be easily integrated with thrusters to evaluate system performance. To validate that the observed changes in performance were caused by orifice geometry changes, it was necessary examine the operating variance between cathodes fabricated to identical specifications.

For reference, the work on the Space Station Plasma Contactor (SSPC) has demonstrated variances of ± 0.5-V above 0.7 mg/s of Xe, increasing to approximately ± 1.0-V around 0.5 mg/s (Ref. 12). The flow rate where the spot-to-plume mode transition occurred appeared to be invariant.[12] Sarver-Verhey[6] demonstrated that over the life of a 6.4-mm-diam cathode the operating voltage for a given flow rate and current varies by approximately ± 1.0 V. The fluctuations referred to here occur over many tens of thousands of hours.

The voltage flow-rate characteristics of two mechanically identical cathodes, AR6-A and AR6-B, at 1.25 A are presented in Fig. 2. The spot-mode voltages were within 1.5 V from unit to unit, and the transition flow rate varied by as much as 40 μg/s. These variances were typical of those observed throughout the range of operating

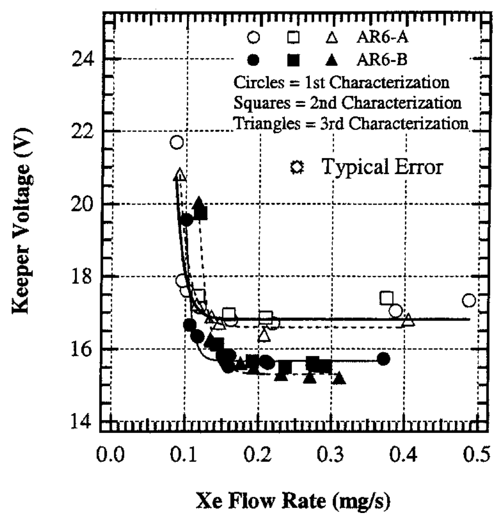


Fig. 2 Performance variance at 1.25 A for two mechanically identical hollow cathodes.

conditions evaluated. The keeper voltage fluctuations for individual cathodes were examined over the course of tens of hours and were found to be on the order of 0.2 V when operated at constant current and flow rate. Inspection of Fig. 2 shows that the variance between subsequent characterizations was on the order of 0.2 V. The transition flow rate generally increased with time. This effect was attributed to an increase in the orifice diameter, and comparison of microscopic images of the orifice supported this conclusion. Given that similar fabrication and operating procedures were employed with both the 3.2-mm-diam hollow cathodes and the SSPCs, the variance exhibited in Fig. 2 was taken to be a reasonable representation of the performance variance expected with these cathodes. Consequently, the unit-to-unit voltage and transition flow-rate variances were taken to be ± 1.4 V and ± 25 μg/s.

Minimizing Power in a Diode Discharge

Most of the experiments reported in this paper involved diode discharges between a hollow cathode and a keeper, and cathode power was defined as the product of the cathode-to-keeper voltage and current. By focusing on a diode discharge, comparison between the performance of the hollow cathodes was straightforward. This approach assumes that the total emission current, the sum of the keeper and secondary anode emission currents, dominates the conditions at the cathode, regardless of the distribution of the current to the anodes. The tests were conducted by varying the flow rate at constant current.

Figure 3 illustrates a typical performance characterization. The performance characterizations were conducted at intervals of several tens of hours of operation to obtain a more representative assessment of the cathode operating regimes than from a single characterization. Detailed information on the cathode performance appears in Domonkos et al.[15,16] The portion of the curves where the voltage is only weakly dependent upon the flow rate is considered spot mode. The power spectra of the spot and plume mode voltage for AR3-A appear in Fig. 4. The magnitude of the voltage oscillations appeared to be limited only by the output capability of the power supply. Analysis of the power spectra of the data in Fig. 4 revealed the absence of any dominant frequencies in the spot mode data, whereas the plume mode data exhibited prominent frequencies at several megahertz. The frequencies observed in plume mode were of the same order as the ion plasma frequency in the cathode-to-keeper gap.[17]

As Fig. 3 shows, for a given current a certain minimum flow rate is required to maintain spot-mode emission. Cathode power consumption at the minimum flow-rate condition for spot-mode emission is plotted as a function of the discharge current in Fig. 5. When comparing AR1, AR3-A, and AR6-B, the smallest aspect-ratio cathode consumed the least amount of power at a given current. Although this result was expected because power scales with orifice length according to Ohms law, AR3-A and AR6-B operated at roughly

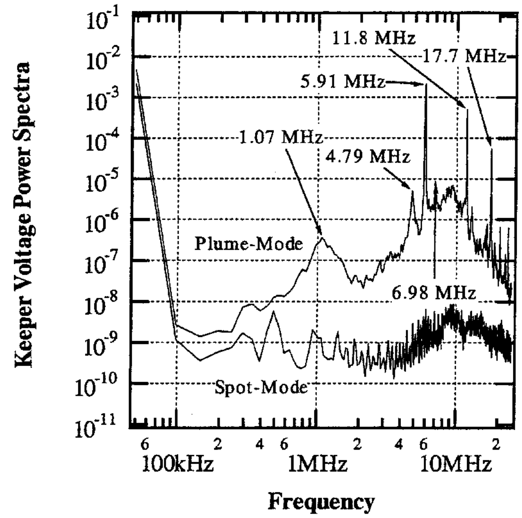


Fig. 4 Comparison of high-frequency oscillations characteristic of spot and plume modes.

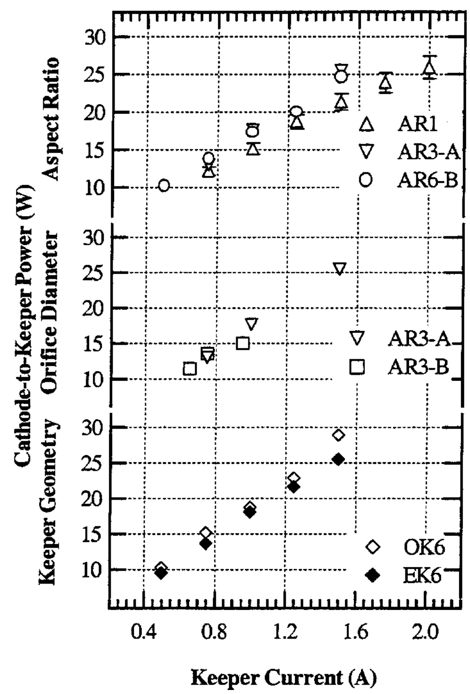


Fig. 5 Power consumption at the spot-mode minimum flow rate.

equal power levels throughout the range of currents. This result suggests that the change in power consumption with orifice length occurs more rapidly at small aspect ratios. The power consumption for AR1 was the lowest of all of the cathodes tested. Changing the orifice diameter resulted in a negligible change in the power consumption, as evidenced by Fig. 5. The use of an enclosed keeper reduced the power requirement on the order of 5–10% over the open-keeper configuration. Because the enclosed keeper provides a superior radiation environment, the small improvement in power consumption by using the enclosed keeper suggests that conduction was the dominant heat-transfer mechanism for the cathode tube; if the cathode were radiating strongly, the enclosed keeper would improve the performance more significantly than observed. The results of the thermographic investigations substantiate this finding and are presented later.

The flow rate required for spot-mode emission, plotted in Fig. 6, also strongly influences efficiency in low-power thrusters. The model by Mandell and Katz[14] predicts that ion production within the orifice, and consequently ion flux out of the orifice, increases with

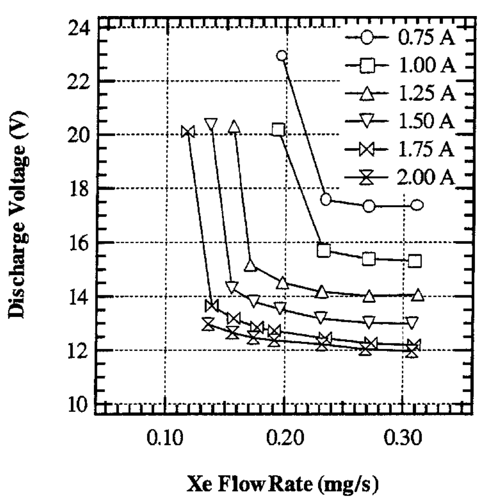


Fig. 3 Performance characteristics of AR1 after 60 hours of operation.

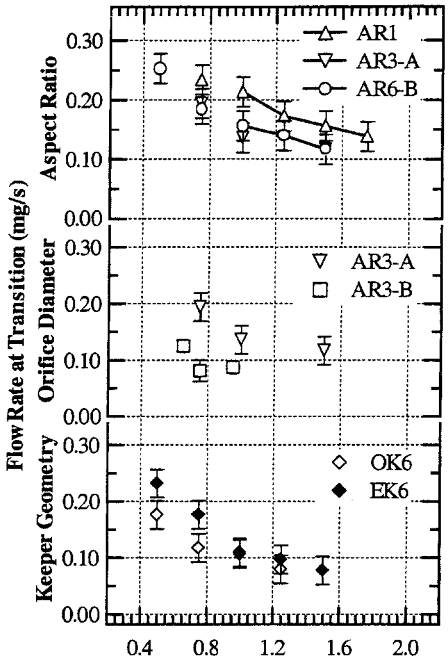


Fig. 6 Spot-to-plume mode transition flow rates.

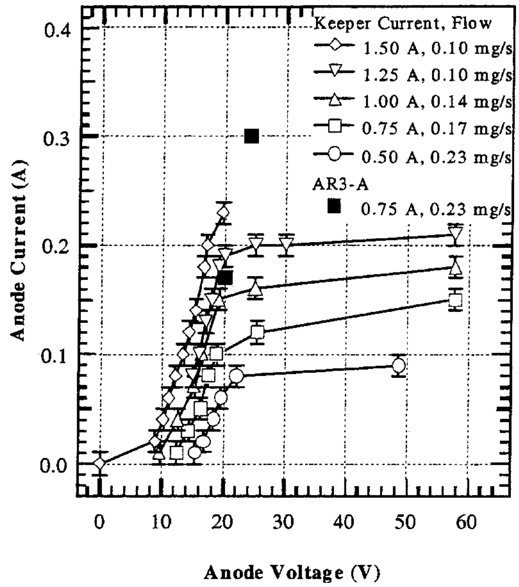


Fig. 7 Electron emission current for EK6 at several operating points exhibiting saturation at approximately 20 V.

orifice length for a given diameter and flow rate. As the orifice length is increased, the electron temperature in the orifice also increases as a result of ohmic heating.[14] The elevated electron temperature and increased channel length facilitate ionization. The transition to plume mode operation occurs when the ion production in and near the orifice is insufficient to maintain charge neutrality in the cathode-keepergap. Figure 6 shows that the model predictions were consistent with the trends observed for aspect ratios between 1 and 6. The AR6-B and AR3-A cathodes appeared to transition at approximately the same flow rates, suggesting diminishing returns in optimizing the transition flow rate by increasing the orifice length. Indeed, one must also consider the ion losses as the orifice aspect ratio is increased. The results in Fig. 6 demonstrated the expected trend that as orifice diameter decreases the flow rate required for spot-mode operation also decreases. The increased current density within the orifice facilitates ion production and emission, maintaining the discharge. The transition flow rate was less for the open-keeper configuration than for the enclosed keeper. This result suggests that the increased neutral density in the cathode-to-keepergap of the enclosed-keeper configuration leads to increased electron-neutral and ion-neutral collisions and impeded ion transport.

Electron Emission Characteristics

A secondary, planar anode 48 mm in diameter was placed 60 mm downstream of EK6 to assess the electron emission capability of the 3.2-mm-diam hollow cathodes. The flow was set to the minimum for spot-mode operation in a diode discharge, and the secondary anode was biased with respect to the cathode. The resulting characteristics are shown in Fig. 7. Despite decreasing flow rates, the emission current scaled with the keeper current. Additionally, current saturation appeared to set in at a bias of approximately 20 V. This result implies that the current conduction is predominantly a function of electron number density. Because the mesh keeper and orifice geometry were expected to contribute weakly to the change in emission current, the effect of increasing the flow at 0.75 A to the keeper was established; an increase of 35% flow-rate increase led to a 100% increase in the emission current.

Cathode Temperature Distribution

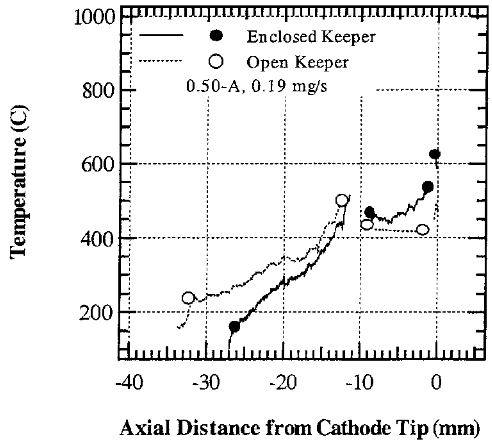
By understanding the dominant heat-transfer mechanisms, improvement of the cathode thermal isolation, and thereby power consumption, is facilitated. A model developed by Salhi[3] considered cathode operation in the limit of high power density where electron cooling was the only significant cooling mechanism. Because the focus of the present investigation was cathode operation in the limit of low-power density, additional cooling mechanisms were evaluated to determine their importance to the energy balance. A thermographic investigation was conducted to provide experimental data describing the significant heat-transfer mechanisms at low current.

Themographic Diagnostic Description

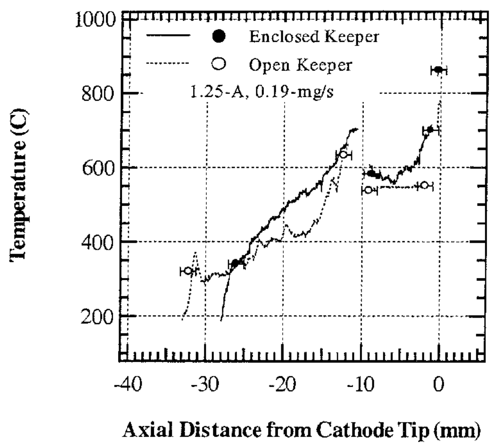
The experimental procedures are summarized here, and a detailed description of the thermography diagnostic appears in Domonkos et al.[18] An imaging radiometer with 8-bit range scanned the infrared emissions from 8–12 μm. A close-up lens was used to enhance the resolution capabilities. Type-R thermocouples were used to calibrate the radiometer output. Type-R thermocouples consist of platinum and platinum 90%/rhodium 10% wires welded to each other at the ends. The ANSI tolerances for type-R thermocouples are $\pm 1.4^\circ$C from 0 to 538°C and ± 0.25% from 538 to 1482°C (Ref. 19). Systematic errors in the thermocouple measurements were most likely to occur as a result of poor thermal contact with the cathode material. To minimize the error caused by contact thermal resistance, the thermocouples were spot welded to the cathode surfaces. In the worst case for the thermocouple attached to the orifice plate, the power conducted away from the site was on the order of 1000 times smaller than the discharge power and comparable to the radiative component in the absence of the thermocouple.[20] Consequently the thermocouple data had an estimated uncertainty of less than 1%. The temperature distributions reported here are for a line parallel to the cathode axis. A slit was cut in the enclosed keeper so that the cathode surface temperature could be monitored. The slit width was approximately 10% of the keeper diameter to permit the cathode surface to be viewed while minimizing the perturbation to the thermal environment.

Infrared Imagery Derived Results

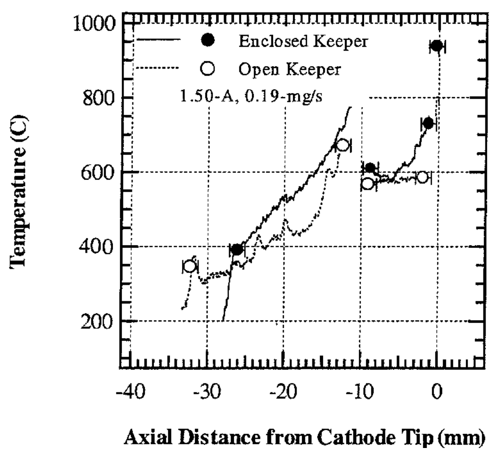
The degree to which the temperature profile deviates from linearity indicates the relative importance of radiation heat transfer with respect to conduction. Several of the temperature profiles acquired in this investigation are plotted in Fig. 8, based on the coordinates illustrated in Fig. 1. The data markers represent the calibration locations for the thermocouples. All of these data were taken in a diode discharge with the keeper. At 0.50 A the shape of the profiles appeared similar upstream of the heater radiation shields. The



a) 0.50 A to keeper

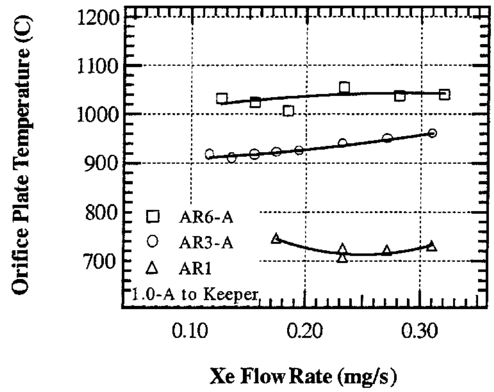


b) 1.25 A to keeper

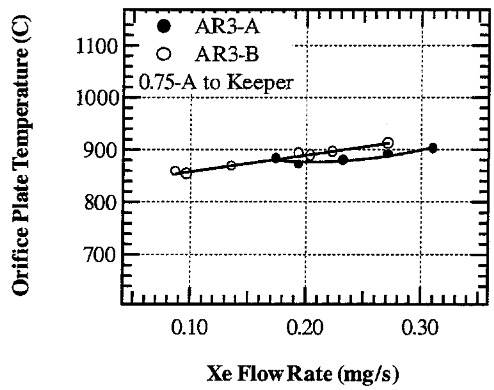


c) 1.50 A to keeper

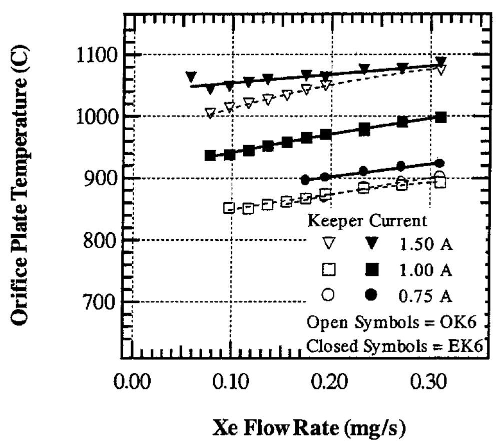
Fig. 8 Axial temperature profiles for the open- and enclosed-keeper configurations.



a) Aspect-ratio dependency



b) Orifice-diameter dependency



c) Keeper-geometry dependency

Fig. 9 Pyrometer-observed orifice plate temperatures for several geometries.

enclosed-keeper cathode operated approximately 100°C warmer at the tip. The slopes and slope changes in the profiles for both the open and enclosed configurations are approximately equal beyond −12 mm upstream. Estimates limited the radiative transfer to a peak value of 0.4 W/cm of axial length at −12 mm, and the temperature drop along the length of the cathode limited the total radiative power to a few tenths of a watt, typically. Calculations showed that the conductive heat loss was several watts. Consequently, thermal conduction was found to be the dominant heat-transfer mechanism in the upstream section of the tube at low current. The resolution of the camera was insufficient to determine accurately the profile at the cathode tip. At 1.25 and 1.50 A the enclosed-keeper upstream profiles were noticeably more linear than the open-keeper distributions. By limiting the radiative transfer, the use of an enclosed keeper simplifies the problem of cathode optimization; minimizing the heat losses is accomplished by limiting thermal conduction. The profiles on the heater shield and the cathode tip temperatures followed the same trends as the upstream cathode tube temperature distribution throughout the range of currents tested. As is shown in the next section, the temperatures were weakly dependent upon on the flow rate, and the data presented in Fig. 8 were representative of the distributions at all of the flow rates tested.

Tip Temperature Variations with Cathode Geometry

A disappearing filament optical pyrometer with emissivity correction was used to determine the orifice plate temperatures. The variation of the orifice plate temperatures with geometry, current, and flow rate is presented in Fig. 9. The temperature was observed to scale in proportion with the aspect ratio. As the aspect ratio increases, the power loss in conducting current through the orifice also increases, leading to the observed temperature differences. A reduction in the orifice diameter led to a curtailed operating regime. The AR3-B cathode was limited to approximately $\frac{2}{3}$ of the maximum current of AR3-A. Figure 9c shows the orifice plate temperatures for EK6 and OK6 as a function of flow rate for three currents. In all cases the enclosed keeper operated at higher temperatures than the open keeper. Most of the data in Fig. 9 showed a slight increase in temperature at the onset of plume mode, the lowest flow rate for each curve. The contributing factors are the bombardment of the orifice plate by ions created in the cathode-keeper gap and increased power deposition to the anode, thereby altering the thermal radiation environment.

Discussion of Low-Current Hollow-Cathode Applications

Given the preceding presentation of the state of hollow-cathode development, it is useful to consider the ways in which these cathodes fulfill the requirements of low-power electric propulsion systems. Ion thrusters in the 100–300 W range consume approximately 0.15–0.29 mg/s of xenon in the discharge chamber, whereas comparable Hall thrusters require 0.49–1.46 mg/s. (Ref. 21). In each case the neutralizer flows of 0.08–0.25 mg/s in this study substantially reduce the specific impulse and efficiency, and the keeper discharge power consumes a more significant fraction of the total when compared to kW-class thrusters. Patterson and Oleson[1] have shown that a neutralizer cathode operating at and above 0.05 mg/s will reduce the efficiency of a 100-W ion thruster by up to 30%. Additionally, the power consumed between the cathode and keeper is on the order of 10% of the thruster power for the cathodes tested in this investigation. Hall thrusters can be operated without a keeper, mitigating the power loss in this discharge. When the emission current of the cathode is expected to be less than 1 A, such as the neutralizer for a low-power ion engine or the cathode for a sub-200-W Hall thruster, operation with a keeper electrode might be necessary to sustain the discharge. The performance of the hollow cathodes tested in this investigation indicates the need for cathodes optimized for the low-power role. The findings of this investigation revealed that cathode optimization is approached through the design of the orifice, keeper, and cathode tube, and further improvements for space applications are left to future work.

Conclusions

This paper described an extensive experimental investigation targeting the operational and mechanical drivers that determine the effectiveness of hollow cathodes for low-power electric propulsion. Five separate 3.2-mm-diam orificed hollow cathodes were designed and tested in a number of different configurations. After establishing the performance variance between mechanically identical cathodes, power and expellant consumption were evaluated for several different orifice and keeper geometries. Power consumption increased with orifice length, while the minimum flow rate decreased. Both of these findings were predicted by the model described in Ref. 14. The use of an enclosed keeper reduced the power consumption; however, the minimum flow rate was observed to increase.

The behavior of the cathode external temperatures was also studied to determine the important heat-transfer modes. Conduction dominated the heat transfer from the emission zone. The condition was more pronounced when an enclosed keeper was used. This conclusion means that cathode performance at low power can be readily improved by choosing materials with a low thermal conductivity for cathode construction.

The performance of the cathodes used in this study was comparable to other 3.2-mm-diam cathodes reported in the literature.[11] Nevertheless, further optimization is likely necessary to enable sub-500-W ion and Hall thrusters to yield benefits for small satellites similar to those realized in larger craft. The cathode orifice, tube, and keeper design all contribute strongly to the performance of the cathode, and further optimization of the 3.2-mm hollow cathodes is left to future work.

References

[1]Patterson, M. J., and Oleson, S. R., "Low-Power Ion Propulsion for Small Spacecraft," AIAA Paper 97-3060, July 1997.

[2]Siegfried, D. E., "A Phenomenological Model for Orificed Hollow Cathodes," Ph.D. Dissertation, Dept. of Mechanical Engineering, Colorado State Univ., Fort Collins, CO, 1983.

[3]Salhi, A., "Theoretical and Experimental Studies of Orificed, Hollow Cathode Operation," Ph.D. Dissertation, Dept. of Aeronautical and Astronautical Engineering, Ohio State Univ., Columbus, OH, 1993.

[4]Rawlin, V. K., and Pawlik, E. V., "A Mercury Plasma-Bridge Neutralizer," *Journal of Spacecraft and Rockets*, Vol. 5, No. 7, 1968, pp. 814–820.

[5]Sarver-Verhey, T. R., "Extended Test of a Xenon Hollow Cathode for a Space Plasma Contactor," NASA CR 195402, Nov. 1994.

[6]Sarver-Verhey, T. R., "28,000 Hour Xenon Hollow Cathode Life Test Results," *International Electric Propulsion Conference*, edited by R. M. Myers, Electric Rocket Propulsion Society, Vol. 2, Santa Fe, NM, Paper 97-168 Aug. 1997, pp. 1030–1037.

[7]Suitch, P. R., "Thermochemical Reactions in Tungsten-Matrix Dispenser Cathodes Impregnated with Various Barium-Calcium-Aluminates," Ph.D. Dissertation, Georgia Inst. of Technology, Atlanta, GA, 1987.

[8]Williamson, W. S., Dulgeroff, C. R., and Williams, R. L., "8-cm Engineering Model Thruster Technology: A Review of Recent Developments," AIAA Paper 79-2103, Oct.–Nov. 1979.

[9]Dulgeroff, C. R., Beattie, J. R., Poeschel, R. L., and Hyman, J., "IAPS (8-cm) Ion Thruster Cyclic Endurance Test," *International Electric Propulsion Conference*, Paper 84-37, May 1984.

[10]"Space Flight Hollow Cathode," Electric Propulsion Lab., Inc., brochure, Monument, CO, 2002.

[11]Hruby, V., Monheiser, J., Pote, B., Freeman, C., and Connolly, W., "Low Power, Hall Thruster Propulsion System," *International Electric Propulsion Conference*, Electric Rocket Propulsion Society, Santa Fe, NM, Paper 99-092, Oct. 1999.

[12]Patterson, M. J., Verhey, T. R., Soulas, G., and Zakany, J., "Space Station Cathode Design, Performance, and Operating Specifications," *International Electric Propulsion Conference*, edited by R. M. Myers, Electric Rocket Propulsion Society, Vol. 2, Santa Fe, NM, Paper 97-170, Aug. 1997, pp. 1038–1045.

[13]Kaufman, H. R., "Technology of Electron-Bombardment Ion Thrusters," *Advances in Electronics and Electron Physics*, Vol. 36, 1974, pp. 265–373.

[14]Mandell, M. J., and Katz, I., "Theory of Hollow Cathode Operation in Spot and Plume Modes," AIAA Paper 94-3134, June 1994.

[15]Domonkos, M. T., Gallimore, A. D., and Patterson, M. J., "An Evaluation of Hollow Cathode Scaling to Very Low-Power and Flow Rate," International Electric Propulsion Conference, edited by R. M. Myers, Electric Rocket Propulsion Society, Vol. 2, Santa Fe, NM, Paper 97-189, Aug. 1997, pp. 1160–1166.

[16]Domonkos, M. T., Gallimore, A. D., and Patterson, M. J., "Parametric Investigation of Orifice Aspect-Ratio Effects on Low-Current Hollow Cathode Power Consumption," AIAA Paper 98-3345, July 1998.

[17]Domonkos, M. T., "Operation of Low-Current Orificed Hollow Cathodes," Ph.D. Dissertation, Dept. of Aerospace Engineering, Univ. of Michigan, Ann Arbor, MI, Oct. 1999.

[18]Domonkos, M. T., Gallimore, A. D., and Patterson, M. J., "Thermographic Investigation of 3.2-mm-Diameter Orificed Hollow Cathodes," AIAA Paper 98-3793, July 1998.

[19]McGee, T. D., *Principles and Methods of Temperature Measurement*, Wiley, New York, 1988.

[20]Yaws, S. L., *Handbook of Thermal Conductivity, Volume 4: Inorganic Compounds and Elements*, Gulf Publishing Co., Houston, TX, 1997.

[21]Patterson, M. J., Grisnik, S. P., and Soulas, G. C., "Scaling of Ion Thrusters to Low-power," *International Electric Propulsion Conference*, edited by R. M. Myers, Electric Rocket Propulsion Society, Vol. 1, Santa Fe, NM, Paper 97-098, Aug. 1997, pp. 609–616.