References

[1]Thomas, R. H., and Schetz, J. A., "Distributions Across the Plume of Transverse Liquid and Slurry Jets in Supersonic Airflow," *AIAA Journal*, Vol. 23, No. 12, 1985, pp. 1892–1901.

[2]Inamura, T., Nagai, N., Watanabe, T., and Yatsuyanagi, N., "Disintegration of Liquid and Slurry Jets Traversing Subsonic Airstreams," *Proceedings of the Third World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics*, Elsevier, Amsterdam, 1993, pp. 1522–1529.

[3]Inamura, T., and Nagai, N., "Spray Characteristics of Liquid Jet Traversing Subsonic Airstreams," *Journal of Propulsion and Power*, Vol. 13, No. 2, 1997, pp. 250–256.

[4]Oda, T., Nishida, K., and Hiroyasu, H., "Characterization of Liquid Jet Atomization Across a High-Speed Airstream by Laser-Sheet Tomography," *Proceedings of the 6th International Conference on Liquid Atomization and Spray Systems*, Begell House, New York, 1994, pp. 624–631.

[5]Tsau, F., Elghobashi, S., and Sirignano, W. A., "Prediction of a Liquid Jet in a Gaseous Crossflow," AIAA Paper 90-2067, July 1990.

[6]Wu, P.-K., Kirkendall, K. A., Fuller, R. P., and Nejad, A. S., "Breakup Processes of Liquid Jets in Subsonic Crossflows," *Journal of Propulsion and Power*, Vol. 13, No. 1, 1997, pp. 64–73.

[7]Clark, M. M., "Drop Breakup in a Turbulent Flow—I. Conceptual and Modeling Considerations," *Chemical Engineering Science*, Vol. 43, No. 3, 1988, pp. 671–679.

[8]Ibrahim, E. A., Yang, H. Q., and Przekwas, A. J., "Modeling of Spray Droplets Deformation and Breakup," *Journal of Propulsion and Power*, Vol. 9, No. 4, 1993, pp. 651–654.

Preliminary Mass Spectrometry of a Xenon Hollow Cathode

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Nomenclature

E = kinetic energy
e = elementary unit of charge
I_{ck} = cathode keeper current
I_h = cathode heater current
m = particle mass
n = ion charge number
V_{ck} = cathode keeper voltage, referenced to the grounded cathode

Introduction

XENON hollow cathodes can produce single-point failures in a number of electric thrusters and are an important factor regarding erosion of the screen grid and other components in ion engines. During operation at the high-emission current required for high-power ion propulsion systems, the orifice and any components in the plume erode rapidly.[1] Ions of sufficient energy to cause significant erosion have been observed in plume experiments.[2–4]

Past measurements of the ion kinetic energy distribution in the far field have been performed with a retarding potential analyzer (RPA) or an energy analyzer.[2–4] The results revealed that a very broad energy distribution exists in the high-current regime. The data indicate that ions are abundantly formed with energies as much as several times higher than eV_{ck}. Unfortunately, RPA and energy analyzer devices do not distinguish between xenon ions having different charge states but the same value of E/ne.

The mechanism by which the high-energy ions arise is not established, but two principal hypotheses have been put forward. One theoretical explanation that has been offered invokes the formation of a potential hill a few millimeters downstream from the orifice.[3,5] Although consistent with the data, no clear understanding has emerged of the means by which a hill of sufficient height could be formed. An alternative mechanism has been postulated whereby the current density at the orifice (on the order of 10^4 A cm^{-2}) results in ion acceleration via a magnetohydrodynamic effect.[2] The possible presence of abundant multiply charged ions and their role in producing energetic singly charged species has not been considered in either case.

Spatially resolved experimental measurements of electric potential and the ion velocities near the hollow cathode orifice are needed to fully resolve the mechanistic issue. In the present study, a quadrupole mass spectrometer provided a simple means of monitoring ions according to m/ne and easily resolved the charge states of xenon. Under special circumstances, the same experimental setup was able to detect barium atoms in the plume. The technique is suitable for monitoring cathode effluents during conditioning, startup, and normal operation.

Experimental

The hollow cathode was installed in a 75-cm-diam vacuum chamber, pumped by a 1000 l/s (on nitrogen) turbomolecular pump and a 12,500/4,500/~1,000 l/s (hydrogen/water/xenon) TMP150 cryopump (CVI) mounted on a 10-in. Conflat® flange.[6] The cryopump could be readily isolated from the chamber by an 8-in. electropneumatic gate valve. The base pressure with no xenon flow was 6×10^{-8} torr. Under the fixed xenon flow rate of 0.105 mg/s, the background pressure indicated by an ion gauge positioned far from the cryopump was about 1.5×10^{-5} torr, after applying a standard sensitivity correction for xenon.

The T5 xenon hollow cathode was installed in a fixed orientation, with a quadrupole mass spectrometer (QMS) monitoring the plume centerline through a beam skimmer. The grounded skimmer with 5-mm aperture was mounted 17 cm downstream from the cathode orifice. The entrance of an SRS200 QMS for residual gas analysis was about 22 cm farther downstream, aligned with the hollow cathode orifice and beam skimmer. A simple modification of the QMS electronics allowed operation with the ionizer turned on or off.

The hollow cathode contained an impregnated tungsten dispenser, 1.0-mm i.d. × 2.8-mm o.d. × 11 mm, that acts as a chemical factory to release barium to the surface at an appropriate rate to achieve low work function and long life. The orifice, machined out of solid tantalum, was 0.2 mm in diameter × 1.0 mm long, with a downstream full-angle chamfer of 90 deg. A keeper electrode with 3-mm-diam aperture was positioned just downstream in an enclosed configuration. The hollow cathode had not been operated prior to this study.

Results and Discussion

The mass spectrum of Fig. 1 was obtained with the ionizing filament on. It shows the predominance of xenon as expected, with various trace impurities also present in the background environment. The scan was taken with I_{ck} set at 1.0 A and $I_h = 1.5$ A. Because the QMS ionizes neutrals but its electron energy was set to just 25 eV, ions and neutrals from the cathode and the chamber background both contribute to the spectrum of Fig. 1. Although the scan started at $m/e = 1$, the signal there is dominated, due to finite resolution, by the intrinsic characteristic that all ions are transmitted at $m/e = 0$. A peak corresponding to $m/e = 138$, the most abundant isotope of singly ionized barium, is apparent in Fig. 1. Except at a very high cathode temperature, barium could not be observed. The largest peak was obtained after cathode ignition, before reducing I_h. Ba was also observable under the conditions $V_{ck} = 0$, $I_{ck} = 0$, and $I_h \geq 2.3$ A. BaO was not detected. Barium detection would be enhanced by running the ionizing filament at lower energy than the 25-eV limit of this instrument, with high detector gain.

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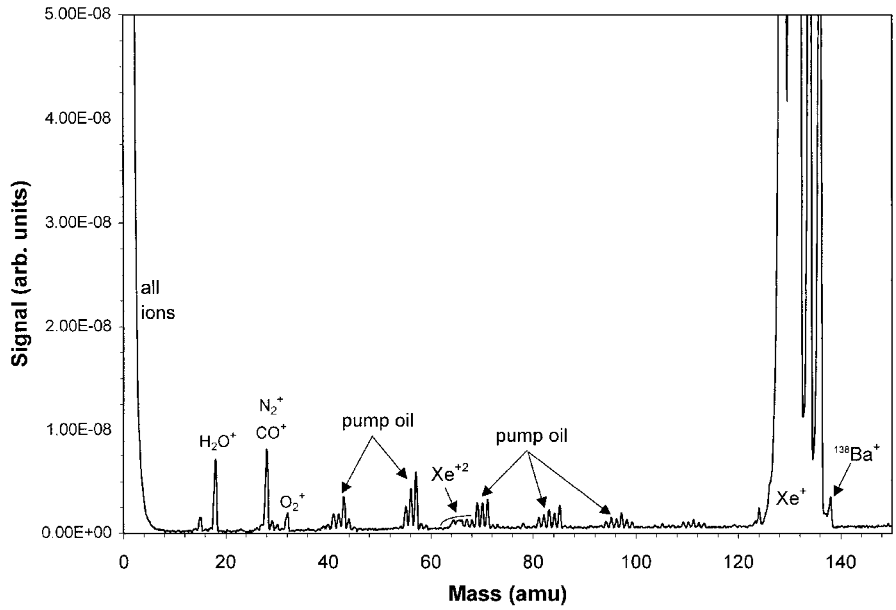

Fig. 1 Mass spectrum obtained on the axis of hollow cathode plume, I_{ck} = 1.0 A, I_h = 1.5 A.

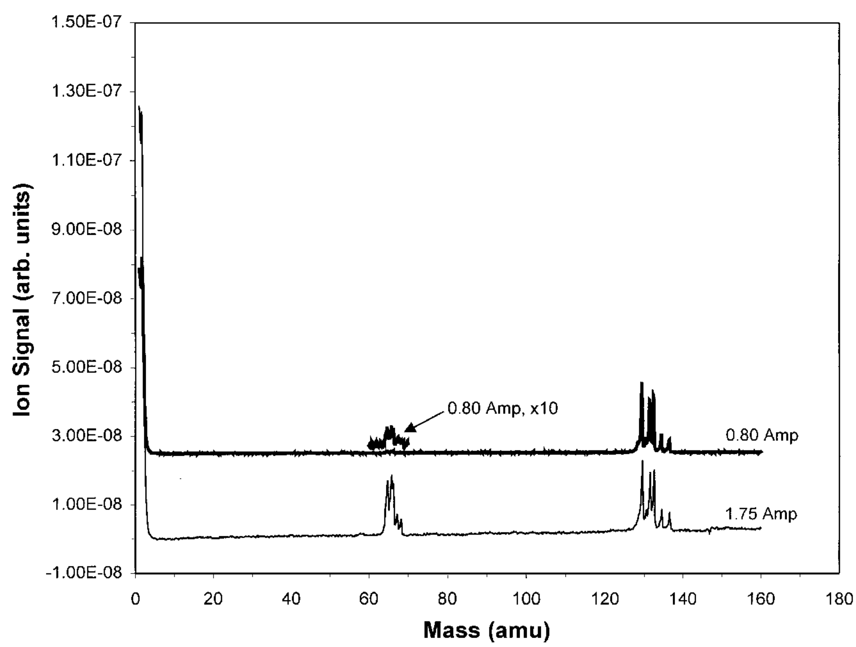

Fig. 2 Mass spectrum at two levels of cathode keeper current, sampling along hollow cathode axis, with baseline raised by 2.5×10^{-8} for the low-current setting.

To investigate the possible role of Xe^{+2} in raising the energy of plume Xe^+ via momentum transfer, both ion species were monitored at constant flow rate as a function of I_{ck}, with the filament off. Figure 2 indicates the uncorrected mass scans obtained at $I_{ck} = 0.80$ and 1.75 A, $V_{ck} = 24$ and 20 V, respectively. The only significant ions observed are Xe^+ and Xe^{+2}, in multiplets that reflect xenon isotopic abundance. The uncorrected Xe^{+2}/Xe^+ ratio determined by integration over all isotopic peaks for each ion was 0.80 at the higher I_{ck} setting and 0.03 at the lower. Even accounting for the slightly higher quadrupole throughput and detection efficiency of the electron multiplier for the doubly charged ion[7] (each correction is roughly $\sqrt{2}$ for a combined $\times 2$ estimated reduction in the ratio), Xe^{+2} is about 40% of the Xe^+ flux level at $I_{ck} = 1.75$ A and accounts for nearly 30% of the total far-field ion flux, on the centerline. The ratio may have been reduced during the plume expansion, given the influence of charge exchange at the high ion and neutral densities near the orifice and the presence of 1.5×10^{-5} torr background xenon over the flight distance to the detector. Previous investigators assumed that the Xe^{+2}/Xe^+ ratio was small.

Plots of Xe^{+2} and Xe^+ signal levels as a function of I_{ck}, determined from the height of the tallest peak in each multiplet and uncorrected for QMS detection efficiency, are presented in Fig. 3. The trends could be approximated by $y = a_1 I^3$ and $a_2 I^4$ phenomenological functions for the single and double charge cases, respectively, except that the Xe^+ cubic relation completely failed for I_{ck} above about 1.3 A, with detected Xe^+ flux substantially lower (and the Xe^{+2} quartic relation similarly failed at $I_{ck} \geq 2.0$ A). The detailed explanation for this behavior is unclear, but it may be associated with the existence of nearly 100% ionization of the available xenon atoms at the higher current settings. Past studies have indicated that

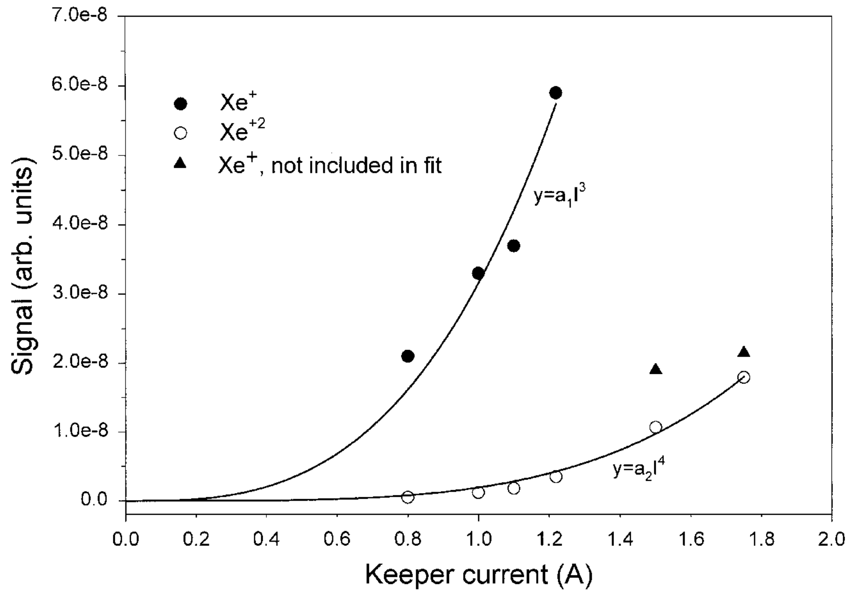

Fig. 3 Dependence of Xe^+ and Xe^{+2} flux levels on cathode keeper current.

hollow cathodes utilizing an alkali metal to lower work function could achieve full ionization.[8]

Multiply charged ions formed just downstream from the hollow-cathode orifice, near the keeper electrode, may acquire energies in the weak field between keeper and far-field ground potential, of approximately neV_{ck}. They may acquire a higher energy due to the influence of a positive potential hill[5] or magnetohydrodynamic effect[2] near the orifice. A doubly charged ion would have $\sqrt{2}$ higher velocity than Xe^+, neglecting collisional effects. Collisions between these species can result in momentum transfer, with Xe^+ being the partner that gains energy. Charge exchange will interchange the energy distribution of the collision partners, to a good approximation. The conversion of multiply charged ions to Xe^+ in the plume through charge exchange with neutrals and other ions, therefore, produces high-energy Xe^+ species. If multiply charged species are formed efficiently in the hollow cathode, as Figs. 2 and 3 suggest they are, the momentum transfer and charge exchange that take place in the expanding plume will have a significant influence on the measured ion energy distributions. A recent study of SPT-100 far-field ions suggests that significant momentum transfer can take place from Xe^{+2} to Xe^+ at the modest density levels and Xe^{+2}:Xe^+ ratio (~12%) of that thruster,[9,10] providing additional supporting evidence.

Conclusions

The hollow cathode is a principal component of electric thrusters and other devices. Its physics and chemistry are interesting and technologically important.

The high level of observed plume Xe^{+2} suggests that the fractional ionization of xenon may approach unity when xenon hollow cathodes are operated with an orifice current density $\geq 5 \times 10^3$ A/cm^2 at the flow rate of about 0.3 g/cm^2 s. This corresponds to an approximate electron efflux to atomic particle efflux ratio of $\geq$20. At twice the kinetic energy Xe^{+2} is a much more effective erosive agent than Xe^+. It is further implied that existing models used to explain observed ion energy distributions in the plume may be inadequate. If full ionization is indeed readily approached, and if a sizable ion current flows through the keeper aperture, the xenon hollow cathode might present a means to construct a simple and efficient, low-thrust propulsion device.

The ability to directly monitor barium permits the use of parametric studies to examine the influential factors in its production and presents a new way to study cathode degradation and aging. Direct monitoring of the flux levels of singly and multiply charged ions is a useful aid for study of the device physics and its erosive effects in the surrounding environment. Further experimental and theoretical investigation is required to achieve an adequate understanding of the plasma potential distribution and plasma dynamics near the orifice.

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References

[1] Kameyama, I., and Wilbur, P. J., "Zenith-Angle Distributions of Erosion Rates Near High-Current Hollow Cathodes," AIAA Paper 96-3208, July 1996.

[2] Latham, P. M., Pearce, A. J., and Bond, R. A., "Erosion Processes in the UK-25 Ion Thruster," *Proceedings of the 22nd International Electric Propulsion*, Electric Rocket Propulsion Society, Paper 91-096, Oct. 1991.

[3] Friedly, V. J., and Wilbur, P. J., "High Current Hollow Cathode Phenomena," *Journal of Propulsion and Power*, Vol. 8, No. 3, 1992, pp. 635–643.

[4] Kameyama, I., and Wilbur, P. J., "Characteristics of Ions Emitted from High-Current Hollow Cathodes," *Proceedings of the 23rd International Electric Propulsion*, Electric Rocket Propulsion Society, Paper 93-023, Sept. 1993.

[5] Kameyama, I., and Wilbur, P., "Potential-Hill Model of High-Energy Ion Production Near High-Current Hollow Cathodes," *Proceedings of the 21st International Symposium on Space Technology and Science*, Japan Society for Aeronautical and Space Sciences, Paper 98-a-2-17, May 1998.

[6] Crofton, M. W., "A Small Diagnostics Facility for Electric Propulsion Issues: Initial Hollow Cathode Results," AIAA Paper 99-0454, Jan. 1999.

[7] Kurz, E. A., "Channel Electron Multiplier," *American Laboratory*, Vol. 8, No. 110, 1979, pp. 67–82.

[8] Baksht, F. G., and Rybakov, A. B., "Fully Ionized Dense Plasma in a Hollow-Cathode Arc," *Soviet Physics—Technical Physics*, Vol. 23, No. 2, 1978, pp. 141–146.

[9] King, L. B., and Gallimore, A. D., "Propellant Ionization and Mass Spectral Measurements in the Plume of an SPT-100," AIAA Paper 98-3657, July 1998.

[10] King, L. B., and Gallimore, A. D., "Ion Energy Diagnostics in the Plume of an SPT-100 from Thrust Axis to Backflow Region," AIAA Paper 98-3641, July 1998.