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Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Bismuth Hollow Cathode for Hall Thrusters

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Nomenclature

A = cathode orifice area, m^2
k = Boltzmann constant, m$^2 \cdot$ kg/s$^2 \cdot$ K
m = atomic mass, kg
$\dot{m}$ = mass flow rate, kg/s
P_v = vapor pressure, Pa
T = temperature, K

I. Introduction

BISMUTH has several qualities that make it well suited for development as a Hall-thruster propellant. When compared with more conventional propellants such as xenon, bismuth holds significant advantages from both an energetics (lower ionization energy) [1] and cost standpoint. In addition, there are significant ground-test-facility cost savings, because bismuth does not require the use of cryogenic pumps. Unlike traditional propellants, bismuth is solid at room temperature; thus, the exhausted bismuth solidifies on the room-temperature vacuum chamber walls, and consequently the entire vacuum chamber becomes an effective pumping surface. With this in mind, operating a high-power bismuth Hall thruster would require only enough pumping speed to keep up with facility outgassing and minor vacuum leaks. However, there are some difficulties that need to be addressed when using a condensable propellant. Some of the issues include sustaining elevated temperatures for bismuth evaporation, regulating bismuth mass flow, mechanical limitations inherent with using refractory metal components, and bismuth plating of thruster and spacecraft components.

Recently, there have been three new programs to develop bismuth Hall thrusters, with the first successful demonstration occurring in the spring of 2005 [2–4]. In this work, the bismuth thruster was operated using a xenon LaB$_6$ cathode. The encouraging results of the bismuth thruster motivated a study to examine the feasibility of an all-bismuth system using a bismuth cathode. In addition to all of the physical and economical gains, it would be advantageous to incorporate a bismuth cathode to eliminate the need for multiple propellant supplies on an eventual flight unit. In 2005, a functioning prototype bismuth cathode was developed and a limited number of operating characteristics were reported [5]. The primary goals of the present research were to evaluate the operating characteristics of a bismuth LaB$_6$ cathode at different mass flow rates, compare bismuth data with xenon and krypton performance, and to reduce the amount of power required for cathode operation.

II. Description of Apparatus

The cathode described here was designed to operate on bismuth as well as on gaseous propellants such as xenon or krypton. A detailed schematic of the hybrid cathode can be seen in Fig. 1. The overall dimensions of the cathode were 2.5 cm in diameter by 24 cm in length.

As shown at the top of Fig. 1, a bismuth reservoir resides near the back of the cathode and is gravity-fed with hydrostatic pressure to a porous plug that separates the liquefied bismuth from the rest of the cathode. The cathode body is also equipped with a gas inlet line to allow it to operate on xenon or krypton. Inline with the gas inlet is a propellant line isolator (not shown) followed by a solenoid valve. The valve is closed when running on bismuth to prevent any escape of bismuth vapor back through the propellant line. Near the cathode orifice is a LaB$_6$ emitter held in place by a tungsten spring, as well as a molybdenum LaB$_6$ pellet holder. The cathode body was fabricated with titanium and has a 2-mm-diam end orifice. The bismuth and gas inlet were fabricated using 304 stainless steel. As shown in the schematic, there are two separate resistive heaters for the bismuth reservoir and the LaB$_6$ pellet. Three thermocouples were placed along the outside body of the cathode so that the temperature could be monitored and controlled for both the bismuth reservoir and the cathode body. The cathode was operated with both a tungsten keeper and an 8.9-cm-diam, 17.8-cm-long, cylindrical stainless-steel anode (see Fig. 2).

Testing was performed in a 2-m-diam by 4-m-long vacuum chamber. The tank was evacuated using three magnetically levitated turbomolecular pumps capable of pumping at 2000 L/s each and backed by a mechanical pump with a pumping capacity of 400 ft^3/min. An operating pressure of 3×10^{-6} torr was maintained while testing the bismuth cathode. Tank pressure was an order of magnitude greater when testing the xenon and krypton cathode.

III. Experimental Procedure

A series of tests were done to determine the operating characteristics of a bismuth hollow cathode and to compare them with an identical cathode using gaseous propellant. For the first bismuth cathode experiment, the discharge was started using krypton propellant while steadily increasing the cathode temperature to stimulate sufficient bismuth evaporation so that the krypton flow could be extinguished and the discharge could sustain solely using bismuth. Once this was achieved, discharge I-V sweeps from 2–16 A of discharge current were taken every 5 min over the course of the 106-min experiment. The second experiment involved the same startup procedure stated previously using a gaseous propellant.

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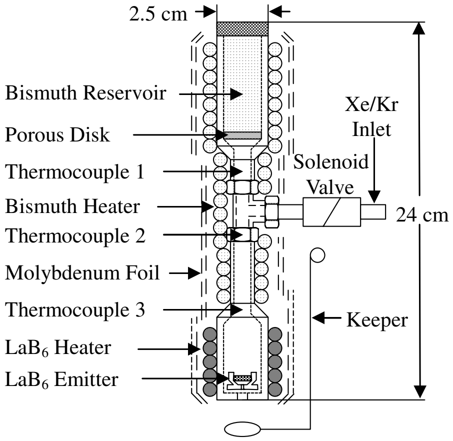

Fig. 1 Bismuth cathode schematic and thermocouple placement.

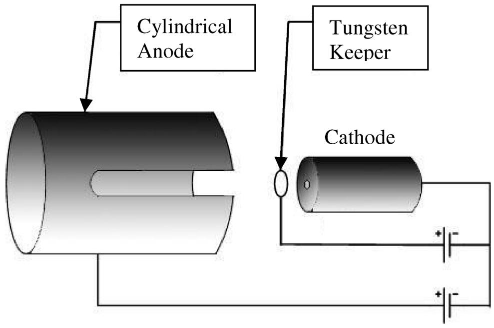

Fig. 2 Electrical schematic of the bismuth cathode.

However, once bismuth discharge was achieved and the cathode reached thermal equilibrium, the discharge current was held constant and the anode voltage was recorded over a 190-min period. The third experiment was performed using an identical cathode operating on krypton and xenon propellant, but with a new LaB_6 emitter. Four data sets were taken in this experiment: two while operating the cathode using xenon at the same mass and molar flow rate as the previous bismuth test and two while operating the cathode at the same mass and molar flow rate using krypton. The fourth, and final, experiment was performed while operating the cathode using xenon propellant and holding the discharge current constant to record changes in anode voltage over a 170-min period.

For the two bismuth experiments, it was thought that the bismuth mass flow would be governed by the temperature of the liquid-bismuth reservoir. The flow rate could be controlled by the evaporation rate of bismuth from the reservoir by controlling the temperature of the porous plug that separates the liquid bismuth from the cathode body. If that were the case, a theoretical prediction of mass flow could be obtained from the plug temperature by relating the bismuth vapor pressure and the reservoir geometry. Equation (1) is a curve-fit for bismuth vapor pressure that, when inserted into Eq. (2), provides a gas kinetic estimate of mass flow per unit area as a function of liquid-bismuth temperature [6]. This estimate, shown in Eq. (3), can be used to approximate the temperature necessary for the cathode to sustain using bismuth propellant. Note that SI units are used in Eqs. (1–3).

$$P_v = \log^{-1}\left[13.317 - \frac{10,114}{T} - 0.86\log T\right] \tag{1}$$

$$\frac{\dot{m}}{A} = \frac{P_v}{\sqrt{2\pi kT/m}} \tag{2}$$

$$\frac{\dot{m}}{A} = \frac{\log^{-1}[13.317 - (10,114/T) - 0.86\log T]}{\sqrt{2\pi kT/m}} \tag{3}$$

The target mass flow rate of each bismuth experiment performed was 0.5 mg/s. Using Eq. (3), the corresponding bismuth reservoir temperature to achieve the target mass flow rate is approximately 650°C. The actual temperature required for the cathode discharge to sustain on bismuth was much higher and will be discussed in greater detail in Sec. V.A.

IV. Results

A. Bismuth Cathode Ignition

The bismuth cathode was conditioned by initiating a flow of krypton at 0.6 mg/s and supplying approximately 275 W of power to the LaB_6 heater. During this time, the keeper was biased to 300 V until discharge occurred. At this point, the propellant flow was reduced to approximately 0.2 mg/s and the keeper was current-limited at 4 A. The discharge was then attached to the cylindrical anode by increasing the anode voltage to 100 V and slowly decreasing the keeper voltage to zero. While decreasing the keeper voltage, the anode was current-limited at 4 A and the cathode-to-anode voltage was 38 V. The LaB_6 heater power was then reduced to 90 W and the bismuth reservoir heater was enabled and increased to 160 W to stimulate bismuth evaporation. After 30 min, the krypton gas flow was terminated by closing the solenoid valve and the cathode-anode discharge was sustained on bismuth. For each test, the heater power remained constant throughout the duration of data collection so that the cathode could reach an equilibrium temperature. An electrical diagram of the cathode can be seen in Fig. 2.

B. Bismuth Operation

All experiments were performed with the cathode mounted vertically so that the bismuth reservoir was at the top, to keep the bismuth in contact with the porous stainless-steel plug. The entire cathode mass was recorded pretest and posttest to determine a time-average rate of propellant mass flow. For the first experiment, the average mass flow rate was 0.71 ± 0.03 mg/s of bismuth. The temperature data recorded throughout the duration of the test from the three thermocouples shown in Fig. 1 can be seen in Fig. 3. As shown, for the first 30 min, the cathode was operated using krypton. The cathode then operated solely on bismuth for the remainder of the 106-min test.

Equation (3) was plotted in Fig. 4 to show the theoretical mass flow rate per evaporation area at liquid-bismuth temperatures ranging from 700 to 1000°C, to cover the range of cathode temperatures recorded throughout the duration of the experiment.

Figure 5 shows multiple sets of I-V operating points taken over the 106-min bismuth run time. The points were obtained by increasing the discharge current from 2 to 16 A while recording anode voltage over a time span of approximately 1 min. A complete data set between 2 and 16 A was taken approximately every 5 min throughout the 106-min test. It should be noted that taking relatively fast current

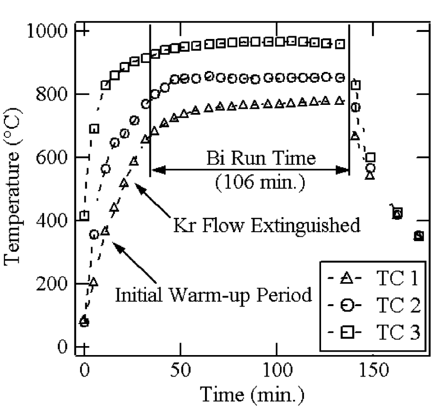

Fig. 3 Temperature data taken near the bismuth reservoir, the cathode center, and the end orifice by thermocouples 1, 2, and 3, respectively, throughout the duration of the bismuth cathode test.

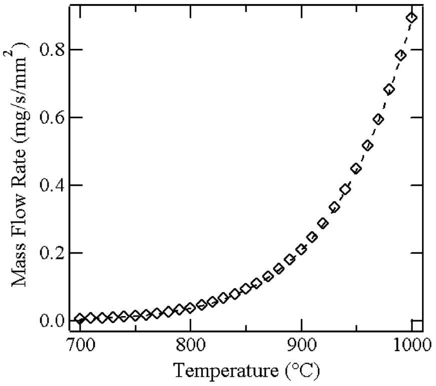

Fig. 4 Bismuth evaporation as a function of bismuth reservoir temperature.

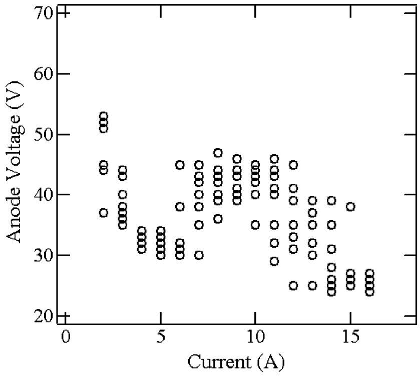

Fig. 5 Anode voltage taken at currents varying from 2 to 16 A at a mass flow rate of 0.71 mg/s using bismuth.

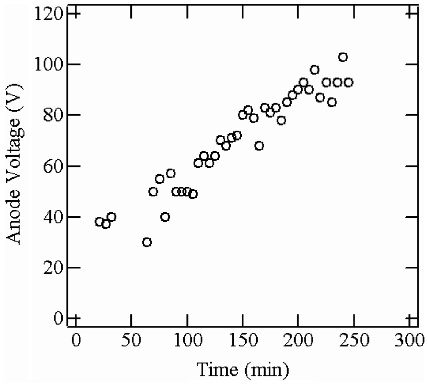

Fig. 7 Anode voltage recorded while current-limiting the cylindrical anode discharge at 4 A and operating using bismuth propellant.

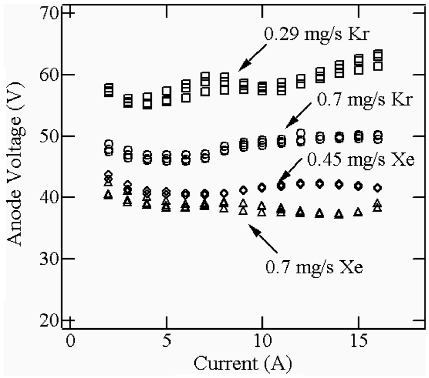

Fig. 8 Anode voltage taken at currents varying from 2 to 16 A using krypton and xenon propellants.

sweeps from 2 to 16 A may not allow for the cathode to reach temporal equilibrium at each discharge current. The data were taken quickly so that the overall cathode temperature would remain constant; the large variability in the I-V characteristic will be discussed later.

The second experiment was performed using the same cathode as in the first experiment. The cathode was initially heated using the LaB_6 heater at 200 W for approximately 20 min until discharge was achieved using xenon. At this point, the LaB_6 heater was reduced to 90 W and the bismuth reservoir heater was enabled and increased to 140 W to stimulate bismuth evaporation. After 40 min, the xenon flow was extinguished by closing the solenoid valve and the cathode discharge sustained for a 190-min period of time solely on bismuth, as shown in Fig. 6.

For the duration of the 190-min bismuth cathode operation, the discharge current was held constant at 4 A and the anode voltage was recorded. This was done to determine if a large variation in anode voltage existed as time elapsed. Data are shown in Fig. 7. This experiment had a time-average mass flow rate of 0.51 ± 0.02 mg/s of bismuth.

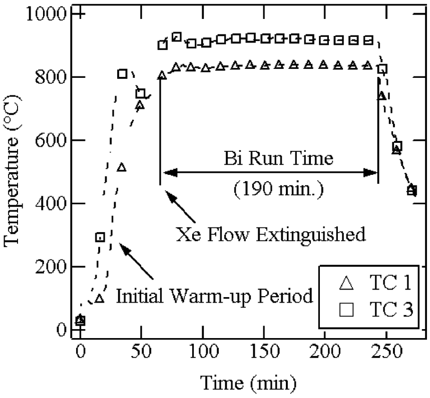

Fig. 6 Temperature data taken near the bismuth reservoir and the end orifice by thermocouples 1 and 3 throughout the duration of the constant discharge current experiment.

C. Comparison with Xenon and Krypton

The third experiment was performed using a cathode identical to the device used for bismuth characterization. It was tested at two different xenon flow rates and two different krypton flow rates using a new LaB_6 emitter. The rates were chosen so that the same mass flow was used as in the bismuth case, as well as the same molar flow rate. The equivalent molar flow rate for xenon is 0.45 mg/s. Three anode I-V data sets were taken by increasing the discharge current from 2–16 A at each flow rate and recording the anode voltage. These results can be seen in Fig. 8. Each data set was taken at a facility background pressure near 2×10^{-5} torr. The same experiment performed with xenon was then done using krypton. The identical cathode was used for krypton experimentation, including the LaB_6 emitter. The corresponding molar flow rate for krypton is 0.29 mg/s. These results can be found in Fig. 8 as well.

The fourth, and final, experiment was done using the same cathode as in the third experiment. For this test, the cathode was operated at 0.45 mg/s using xenon propellant and a tungsten keeper. The cathode was run for 170 min to record keeper voltage while current-limiting the discharge at 4 A, as shown in Fig. 9.

V. Discussion

A. Mass Flow Analysis

After operating the cathode numerous times using bismuth propellant, it seems that the most critical flow-limiting region is at the end orifice of the cathode, rather than at the bismuth reservoir. It is possible that the rate of evaporation from the porous disk is greater than that of the end orifice and that bismuth is condensing and

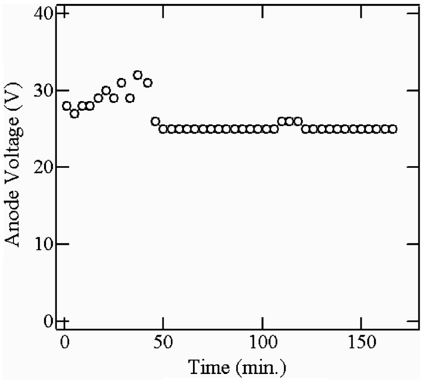

Fig. 9 Keeper voltage recorded while current-limiting the tungsten keeper discharge at 4 A and operating using xenon propellant.

accumulating within the cathode. The accumulated bismuth could then account for transient periods of increased mass flow when the orifice region experienced localized heating at high discharge current.

In the first bismuth experiment, the temperature that was recorded from the thermocouple nearest the LaB_6, thermocouple 3 in Fig. 1 was $960 \pm 10°C$ throughout the test. At this temperature, the corresponding cathode mass flow rate is 1.7 mg/s, based on the end orifice area. Thermocouple 1, nearest to the bismuth reservoir, yielded a temperature of $760 \pm 15°C$, which would correspond to a mass flow rate of about 6.8 mg/s, based on the porous vapor-escape area. Because there is a larger mass flow rate of bismuth at the reservoir than at the end orifice, based on temperature and vapor-escape area, it is possible that bismuth is condensing and building up within the cathode.

B. Required Heater Power

The total heater power required for steady-state operation of the bismuth cathode was 250 W: approximately 160 W were necessary for the bismuth reservoir and 90 were input to the LaB_6 heater. Additional heat was input to the LaB_6 through the discharge and ranged from 40 W when the discharge current was at 2 A up to 540 W when the discharge current was increased to 16 A. It should be noted that in successive bismuth cathode experiments, the LaB_6 heater power had to be increased to begin a discharge. Over a testing period of two weeks, the necessary LaB_6 heater power to initially light the cathode using gaseous propellant each consecutive time was 220, 240, 240, and 300 W for the final test. It is interesting that a similar phenomenon was observed with a mercury hollow cathode using a 2% thoriated tungsten emitter. It was determined by Rawlin [7] that the downstream end of the emitter was lacking emissive material, which made it necessary to increase heater power in further testing. The increased degradation of emissive materials may be an artifact of using a metal vapor propellant as opposed to an inert gas.

C. I-V Characteristics

When using bismuth propellant, the range of anode voltages recorded was found to be between approximately 25 and 50 V over the discharge current range of 2–16 A. This is comparable with the voltage range of 35 to 50 V obtained from the varied mass flow data from the xenon and krypton experiments, with the exception of the lowest flow rate (0.29 mg/s) of krypton. At this particular flow rate, the anode voltage was higher and ranged between 55 and 65 V over the discharge current range of 2–16 A.

As for the bismuth data in Fig. 5, there was a large amount of scatter in the anode voltage as the discharge current was increased, which may have been due in part to the relatively fast current sweeps that were done. Increasing the discharge current more slowly to allow for the cathode to reach equilibrium conditions at each discharge current could have reduced some of the scatter; however, the cathode temperature would have increased with discharge power, which would have then increased mass flow. In general, anode voltage from the bismuth cathode varied as much as 57% while increasing the discharge current from 2 to 16 A, which was significantly larger than the Xe and Kr data. As the anode current is swept from 2 to 16 A while operating using bismuth, the anode voltage has an overall decrease. Typically, in gaseous cathodes, anode voltage decreases are associated with mass flow increases [8,9]. However, thermal data were taken throughout the duration of the experiments to ensure that the cathode was at thermal equilibrium. Because the temperature of the liquid bismuth determines the evaporation rate, the cathode mass flow rate should have remained constant for this experiment, and some factor other than temperature variation must be responsible for the change in discharge voltage over time. One hypothesis for the apparent increase in mass flow is that increased cathode current while sweeping from 2–16 A of discharge current causes localized heating near the orifice, which would not have been picked up by the thermocouples, due to their relatively distant placement from the orifice. This localized increase in power density would then increase the bismuth mass flow rate, because the evaporative mass flow of bismuth is entirely temperature-dependent. However, the only way an increase in mass flow could be possible is if there were a sufficient supply of bismuth to be locally heated near the end orifice. Posttest inspection of the inside of the cathode allows for this possibility, because bismuth condensation is visible within the cathode.

The next experiment was done to examine what type of relationship exists between the cathode-anode voltage over time, while holding the cathode at thermal equilibrium. The data in Fig. 7 were taken while current-limiting the discharge at 4 A. It is interesting to see that the bismuth cathode discharge voltage increased from about 30 to 100 V over a 190-min period of time. This is characteristic of a decrease in mass flow rate; however, posttest inspection of the reservoir showed a sufficient quantity of bismuth remaining, and so there must be some other factor influencing the discharge power.

The xenon data of Fig. 8 display a variation in anode voltage of only 8% at 0.45 mg/s and 12% at 0.7 mg/s, and the current was adjusted from 2 to 16 A. When operating using krypton propellant, the variation in anode voltage was 9% at 0.7 mg/s and 13% at 0.29 mg/s. Figure 9 shows the discharge voltage of the cathode while operating at a current-limited discharge of 4 A using xenon propellant and a tungsten keeper. It is shown that after some initial transients during the first 25 min of operation, the discharge voltage variation damps to a consistent voltage of about 24 V. This trend contradicts what was found when operating the bismuth cathode at a constant discharge current over a long period of time, but the reason is unknown to the investigators at this time.

VI. Conclusions

A versatile LaB_6 cathode assembly was tested using bismuth, xenon, and krypton as propellant. For bismuth operation, it was necessary to start the discharge on krypton and then switch to bismuth. It was demonstrated that 250 W of total heater power was sufficient for the bismuth cathode to sustain a stable discharge. Anode voltages were then recorded while sweeping the discharge current from 2 to 16 A at a bismuth mass flow rate of 0.71 mg/s. The anode voltage varied between 23 and 54 V.

For comparison, data were then taken using an identical cathode with a new LaB_6 emitter and gaseous species. Experiments were done with this cathode operating using both krypton and xenon propellants. Discharge current was swept between 2 and 16 A and the anode voltages were recorded. The anode voltage for krypton and xenon ranged from 35 to 61 V.

To account for the difference between the bismuth, xenon, and krypton trends, it was determined that an increase in discharge power may have an effect on the amount of bismuth being evaporated from the end orifice. We were unable to determine a single critical-temperature monitoring point in the cathode that correlated with the evaporation of bismuth. It appeared that localized heating near the orifice region elevated the evaporation rate during high-current operation. This was indicated by a decrease in cathode-anode voltage as the current was increased.

Acknowledgments

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