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Development and Testing of a Prototype Bismuth Cathode for Hall Thrusters

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Using bismuth in place of gases such as xenon for Hall thruster propellant could potentially offer both physical and economical gains. As research continues to develop Hall thrusters that are fueled with bismuth, it will become advantageous to maintain one propellant supply rather than multiple supplies for the anode and cathode. The recent development of a bismuth Hall thruster at Michigan Tech, operated using a xenon LaB_6 cathode, provided a motive to explore the feasibility of developing an entire bismuth system. This paper provides a background on the development and operation of a bismuth vapor LaB_6 cathode. Comparisons of operating parameters are provided for the cathode running on xenon and bismuth propellants along with a description of the mass flow technique used. Complications in determining and controlling the mass flow rate are presented as well.

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 many attributes that make it well suited for development as a Hall thruster propellant. Attractive physical characteristics follow from the atomic properties of bismuth. Bismuth, with an atomic mass of 209 amu, is significantly more massive than the more traditional xenon (131 amu). The large, heavy atoms thus have a lower neutral diffusion velocity and a larger electron-impact cross-section, resulting in a greater probability of ionization and increased propellant utilization. Not only is the ionization probability greater for Bi than Xe, but the energy cost-per-kg of mass flow to create a bismuth plasma is only 37% that of Xe: Bismuth's first ionization level is 7.3 eV, resulting in an ionization cost of 0.035 eV/amu, compared to xenon's

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12.1 eV yielding a cost of 0.092 eV/amu . Density is also an important advantage. Since bismuth is a solid at standard conditions the "propellant tank" can be reduced in volume and it need not be a pressure vessel. Table 1 lists additional relevant physical characteristics.

Beyond physical advantages, the economics of using bismuth is also of critical interest. For instance, bismuth retails for about \$6/kg as opposed to \$1,138/kg for xenon which translates to a huge savings in propellant cost.[2,3] There are significant ground-test facility cost savings as well, as bismuth doesn't require the use of expensive cryogenic pumps. Since bismuth is a solid at room temperature, any exhausted bismuth will hit the tank wall and solidify, turning the entire vacuum chamber into an effective pumping surface. Additionally, the layer of bismuth that is deposited on the chamber walls will also absorb some of the residual gas. With that in mind, operating a 50kW bismuth Hall thruster would require only enough pumping speed to keep up with facility outgassing and minor vacuum leaks.[1]

Table 1 Bi - Bismuth Element 83	
Mass	208.98 amu
Density	9780 kg/m^3
Melting Point	271.3 °C
Boiling Point	1560.0 °C
Thermal Conductivity	8 W/m K
1st Ionization Energy	7.3 eV
2nd Ionization Energy	16.1 eV

In the early 1980's, Soviet work was performed on bismuth anode-layer thrusters.[4,5] There was little stated about the propellant feeding systems or mass flow control methods; however, there was brief mention of a bismuth cathode. During the past two years there have been three new programs to develop bismuth Hall thrusters at Busek, Stanford/JPL, and Michigan Tech University/Aerophyiscs/Aerojet. The first successful demonstration of a bismuth thruster in the Western hemisphere occurred at Michigan Tech in the spring of 2005.[6] 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. Aside from all of the physical and economical reasons listed, it would be advantageous to incorporate a bismuth cathode to eliminate the need for multiple propellant supplies on an eventual flight unit.

The main goal of the research reported here was to design a prototype cathode that could operate using bismuth as its sole source of propellant, evaluate the operating characteristics of the cathode, and identify key issues for further development.

II. Description of Apparatus

The cathode reported here was designed to operate on both bismuth and xenon. A schematic of the bismuth cathode is shown in Figure 1. A LaB$_6$ emitter is held in place behind 4.25-mm-diameter orifice. Xenon is fed to the cathode through a propellant line that is located at the outer wall of the cathode. Behind the LaB$_6$ pellet is a tungsten filament heater that is insulated using a ceramic tube as well as multiple layers of molybdenum foil. The bismuth reservoir is located near the back of the cathode and has a separate tungsten heater so that its temperature can be controlled independently of the LaB$_6$. A thermocouple was placed behind the bismuth reservoir so that the temperature of the bismuth could be closely monitored to determine bismuth

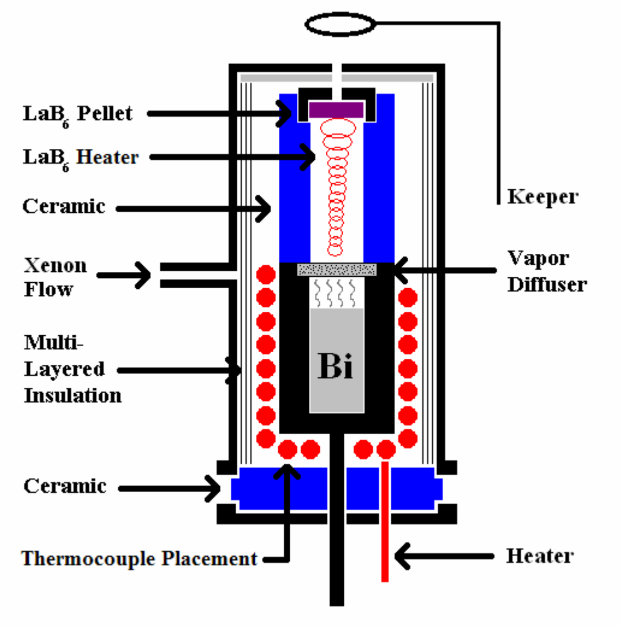

Fig. 1 Bismuth cathode assembly schematic.

evaporation. As seen in Figure 1, the cathode contains a closed reservoir that is preloaded with a fixed supply of bismuth.

All of the testing that was done on this cathode was performed in the Ion Space Propulsion Lab's Bismuth Test Facility at Michigan Technological University.[1] The centerpiece of this facility is a 2-meter-diameter by 4-meter-long vacuum chamber. Rough vacuum is achieved using a mechanical pump with blower that has a pumping capacity of 400 ft^3/min. High vacuum is reached using 3 magnetically levitated turbo-molecular pumps capable of pumping at 2000 L/s each.

III. Results

The cathode was conditioned by initiating a xenon flow of 10 SCCM and heating the LaB_6 pellet with 300 W for 15 minutes. At this point, a tungsten keeper was biased to 250 volts until discharge occurred. The keeper then began to operate at 29 volts at a current limit of 2 amps. After allowing the cathode to run for five minutes, the discharge current was shifted from the keeper to a cylindrical anode, as can be seen in Figure 2. The keeper was then left to float, and the anode ran steadily at 2 amps and 30 volts. The LaB_6 heater was reduced to approximately 150 watts and the bismuth reservoir temperature reached equilibrium at roughly 750°C with no power into the bismuth reservoir heater. At this point anode operational characteristics were taken at three different xenon mass flow rates as shown in Figure 3. An electrical diagram of the cathode can be seen in Figure 2.

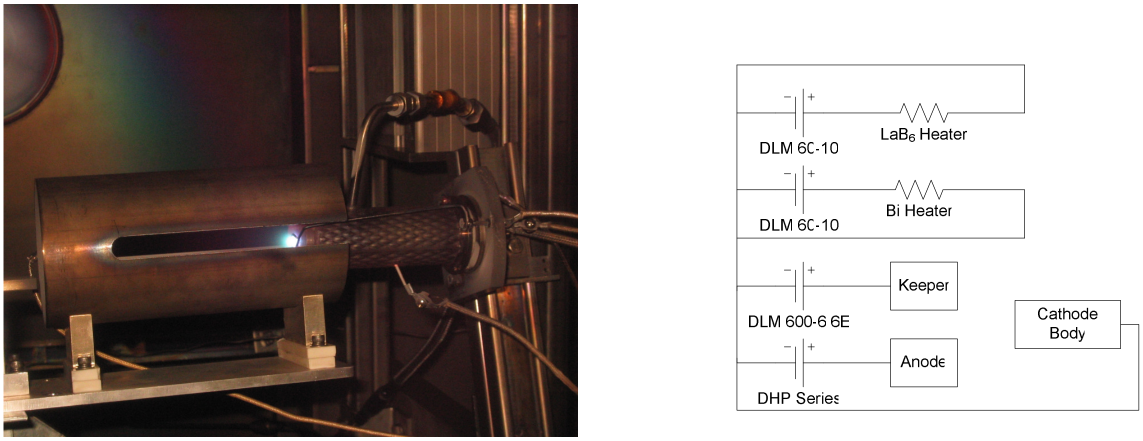

Fig. 2 Bismuth cathode running (left) and the electrical set-up (right).

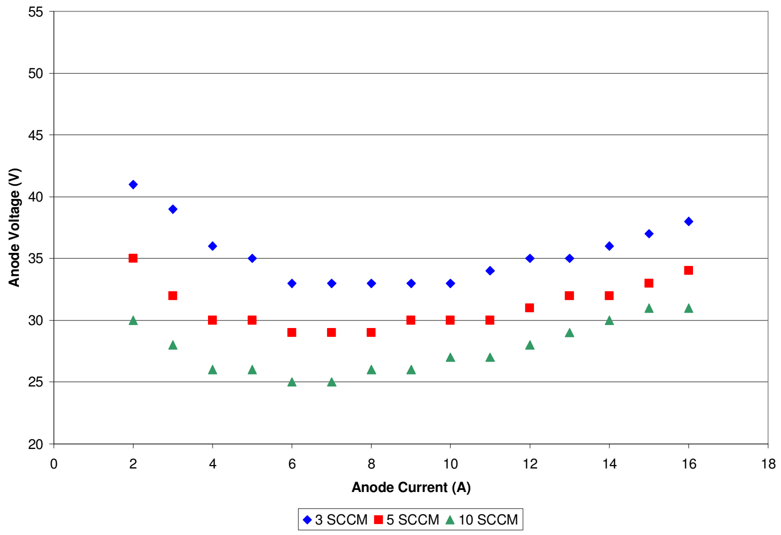

Fig. 3 Operating characteristics of the cathode using xenon propellant.

After recording data with xenon at three mass flow rates for about 15 minutes, the temperature of the bismuth reservoir had increased to 784°C. At this point, the xenon flow was reduced to 1 SCCM and approximately 150 watts were sent through the bismuth reservoir heater to increase the temperature of the bismuth to achieve a sufficient vaporization rate for cathode operation. Indication of bismuth flow was seen as a steady drop in the voltage required to maintain operation at 5 amps as illustrated in Figure 4. When the voltage dropped to 34 volts, the xenon mass flow was set to zero and the cathode discharge was sustained solely on bismuth vapors. Discharge characteristics were then recorded using bismuth propellant while keeping the temperature of the bismuth reservoir at 960°C ± 5 in an attempt to maintain a constant mass flow rate. This data can be seen in Figure 5.

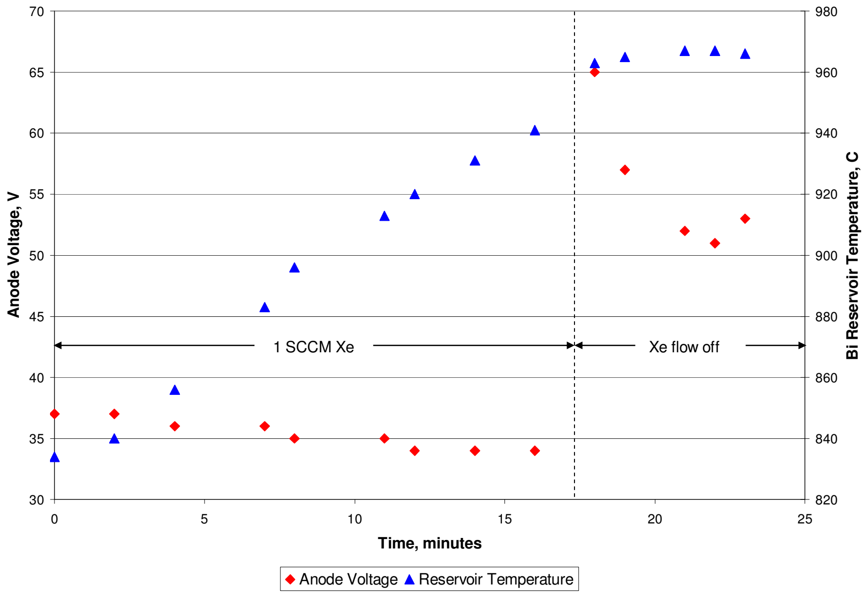

Fig. 4 Effect on the anode during xenon to bismuth propellant transition. The cathode was operated in current-limited mode at 5 A.

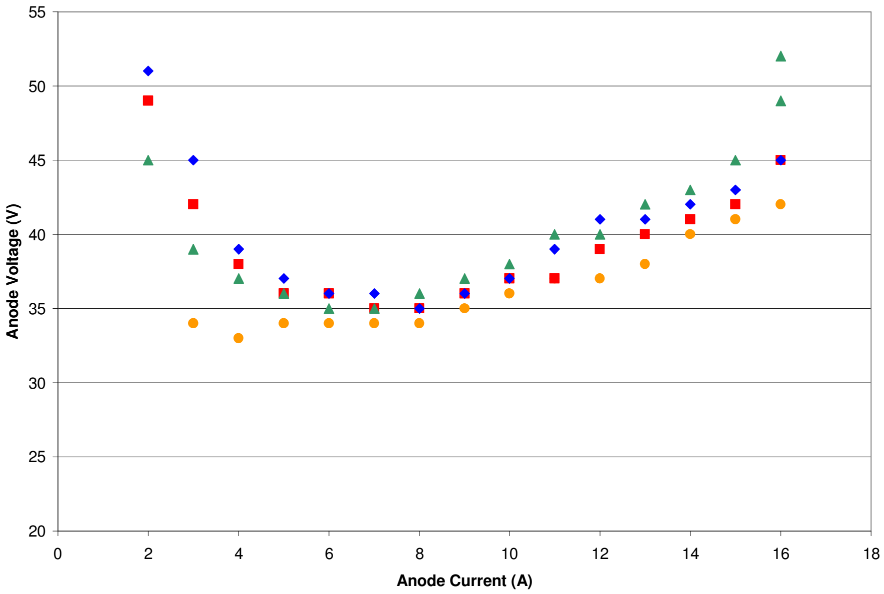

Fig. 5 Operating characteristics of a cathode using bismuth propellant.

IV. Discussion

The most challenging aspect of a bismuth vaporization system is measurement and control of the vapor flow rate. A rudimentary calculation of flow rate was done by recording the mass of the cathode pre- and post-test which resulted in a flow rate of approximately 3 mg/sec ± 3, which was much higher than expected. Much of the large uncertainty arose due to leakage of liquid bismuth from the cathode interior.

Since it is not feasible to mechanically vary the vapor escape area through the reservoir, the mass flow rate can be thermally controlled. This can be done by varying the reservoir temperature within the cathode, which regulates the internal equilibrium vapor pressure. The goal is to maintain the proper reservoir temperature such that, when combined with the vapor pressure and escape area, the desired value of mass flow can be obtained.[1]

Equation 1 is a curve-fit for bismuth vapor pressure that when inserted into Equation 2, provides a gas kinetic estimate of mass flow per unit orifice area as a function of bismuth liquid temperature.[7] The target flow rate for this research was 0.5 mg/sec which, as can be seen in Figure 6, corresponds to a temperature of approximately 750°C. However, the cathode would not run independently of a xenon flow of 1 SCCM until the temperature of the back of the reservoir reached 960°C, which theoretically would give a flow rate of over 8 mg/sec. Post test inspection showed a considerable amount of liquid-bismuth leakage from the internal

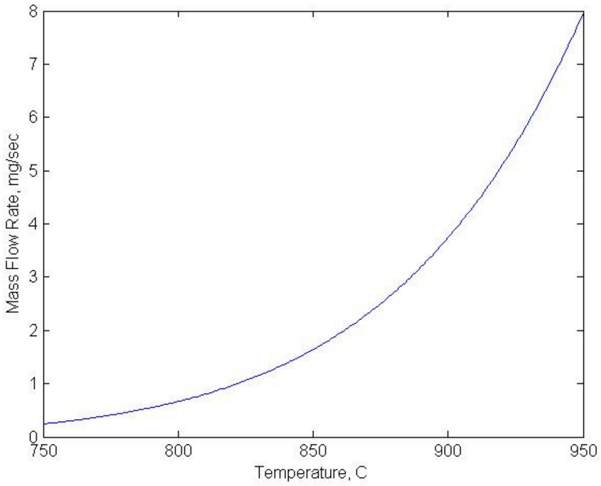

Fig. 6 Bismuth evaporation rate through cathode orifice as a function of temperature.

volume of the cathode onto the vacuum chamber floor. It is likely that bismuth vapors were escaping through numerous non-vacuum-tight passages from the cathode internal volume possibly accounting for the need to induce a very high flow rate to permit enough vapor to exit via the cathode orifice. Although post-test material characterization of the LaB_6 emitter was not performed, it is noted that multiple tests with bismuth vapors have been completed over a number of weeks with no need to replace the LaB_6 pellet in each test.

$$P_v = \log^{-1}\left[13.317 - \frac{10114}{T} - 0.86\log T\right] \tag{1}$$

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

V. Conclusions

Through these experiments it was shown that bismuth can be utilized as a propellant for LaB_6 cathode construction. By using two separate heating mechanisms for the LaB_6 and the bismuth reservoir it was possible to sustain a discharge until the finite amount of bismuth was vaporized. Although the cathode ran at higher discharge voltages than when using xenon, similar trends were present when observing the data taken between 2 and 16 amps.

It is clear that a more accurate way of controlling the mass flow rate of bismuth into the cathode must be designed. The simple means that were used in this experiment had a large error percentage. Accountability for much of this error could be due to the vapor leakage through the back of the cathode on the ceramic-to-metal interface. Had all of the vapors traveled to the discharge orifice it is likely that the cathode could have operated at the desired temperature of 750°C using only the LaB_6 heater rather than requiring a greater than expected temperature and mass flow rate. With further investigation, this issue can be resolved, and the cathode may have the ability to run using a single heater at the same operating characteristics as a LaB_6 xenon cathode since the bismuth reservoir reached 784°C under xenon conditions.

VI. Acknowledgements

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