Performance Characteristics of a LaB$_6$ Bismuth Cathode for use with Hall Thrusters

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Interest in the development of bismuth Hall thrusters has brought about a need to examine cathodes that are capable of running on bismuth at relatively high discharge currents. Recently it has been shown that it is possible for a LaB$_6$ hollow cathode to function using bismuth as a propellant. For this paper, an investigation into the operating characteristics of a bismuth cathode running at constant mass flow was performed. Also reported is a comparison of the cathode using bismuth propellant with both krypton and xenon propellant at the same mass flow and molar flow rates.

Nomenclature

A = cathode orifice area (m^2)
k = Boltzmann constant (m^2·kg/s^2·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 to more conventional propellants such as xenon, bismuth holds significant advantages from both an energetics[1] and cost standpoint. In addition, there are significant ground-test facility cost savings, as 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 effective pumping surface. Additionally, the layer of bismuth that is deposited on the chamber walls will also absorb some of the residual gas. With this in mind, operating a 50-kW bismuth Hall thruster would require only enough pumping speed to keep up with facility outgassing and minor vacuum leaks.

Recently there have been three new programs to develop bismuth Hall thrusters at Busek, Stanford/JPL, and Michigan Tech University. The first successful demonstration of a bismuth thruster in the western hemisphere occurred at Michigan Tech in the spring of 2005.[2] 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. A functioning prototype bismuth cathode was developed in the summer of 2005 and limited operating characteristics were reported.[3] The primary goals of the research stated here 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. Another secondary goal was to evaluate the performance of a bismuth cathode while operating with a bismuth Hall thruster.

II. Description of Apparatus

The cathode described here was designed to operate on bismuth as well as other typical propellants, such as xenon or krypton. A detailed schematic of the hybrid cathode can be seen in Figure 1.

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As shown at the top of Figure 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 also is equipped with a gas inlet line to allow its use on xenon and krypton. Inline with the gas inlet is a propellant line isolator 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. Towards the front of the cathode is a LaB_6 emitter held in place by a tungsten spring as well as a molybdenum pellet holder. The cathode body was fabricated with titanium and has an end orifice of 2.0 mm. 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 8.9cm-diameter, 17.8cm-long cylindrical stainless steel anode (see Figure 2).

All of the testing reported here was performed in the Bismuth Test Facility at Michigan Technological University's Ion Space Propulsion Lab. Research was performed in a 2-meter-diameter by 4-meter-long vacuum chamber. The tank was evacuated using 3 magnetically levitated turbo-molecular pumps capable of pumping at 2000L/s each and backed by a mechanical pump with a pumping capacity of 400ft^3/min. Vacuum pressure of 10^{-6} Torr can be achieved in less than 50 minutes.
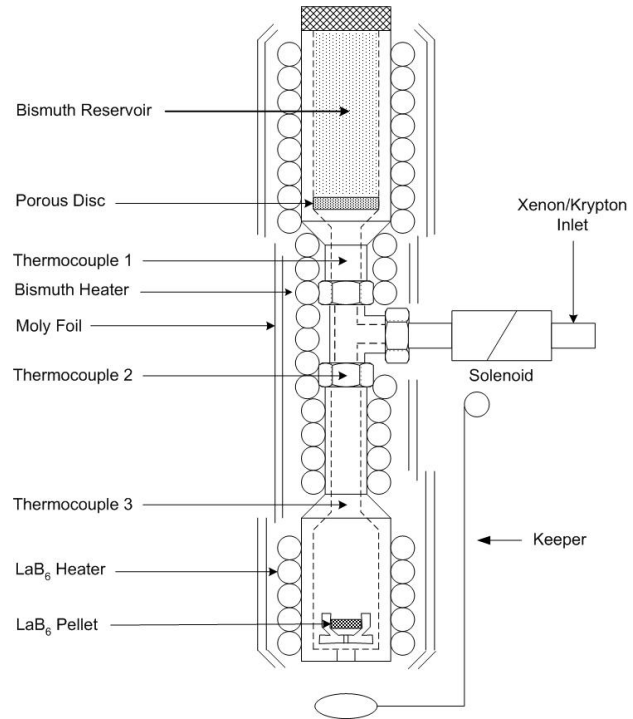

Figure 1. Bismuth cathode schematic.

III.   Results

A. Cathode Ignition

The cathode was conditioned by initiating a flow of krypton at 10 SCCM to the cathode and supplying approximately 275 watts of power to the LaB_6 heater. During this time the keeper was biased to 300 volts until discharge occurred. At this point the propellant flow was reduced to 3 SCCM and the keeper was current-limited at 4 amps. At 4 amps the keeper operated at approximately 38 volts. The LaB_6 heater power was then reduced to 90 watts and the bismuth reservoir heater was enabled and raised to a temperature at which the cathode could sustain solely on bismuth. To do this took 160 watts to the bismuth reservoir heater and 30 minutes. The gas flow was then terminated by closing the solenoid valve. The discharge was attached to the cylindrical anode at which point the data were taken. 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 Figure 2.

Previous versions of the bismuth cathode didn't include a gas inlet but numerous failed attempts were made to light the cathode solely using bismuth. It was necessary to use krypton or xenon to "jumpstart" the bismuth cathode. The reason for this is unknown.
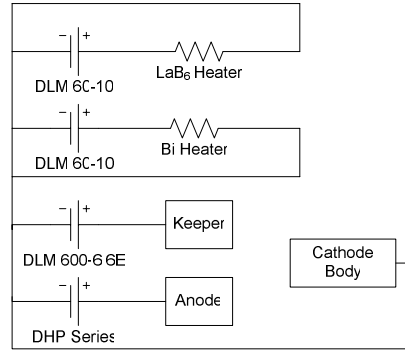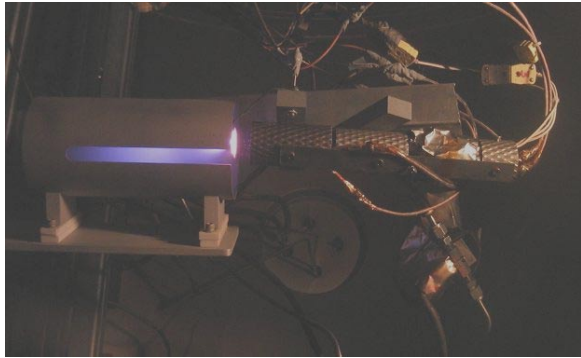
Figure 2. Operating bismuth cathode (left) and electrical schematic (right).

B. Bismuth Operation

The cathode mass was recorded pretest and posttest to determine a time-average rate of propellant mass flow. For this particular experiment the cathode mass flow rate was 0.71 ±0.03 mg/sec of bismuth. Figure 3 shows multiple sets of voltage data taken over 106 minutes while sweeping from 2 to 16 amps in current-limited mode on the cylindrical anode. Temperature data from the three thermocouples can be seen in Figure 4.
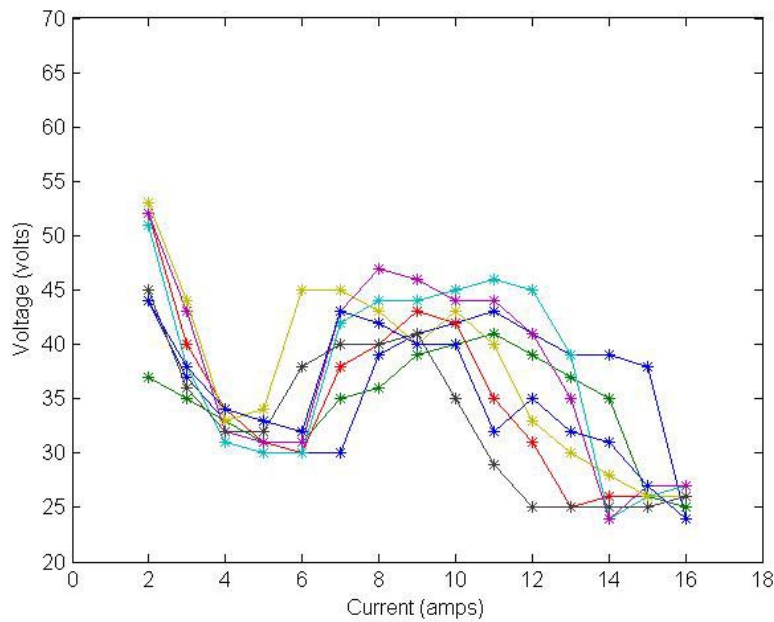

**Figure 3. Anode voltage taken at currents varying from
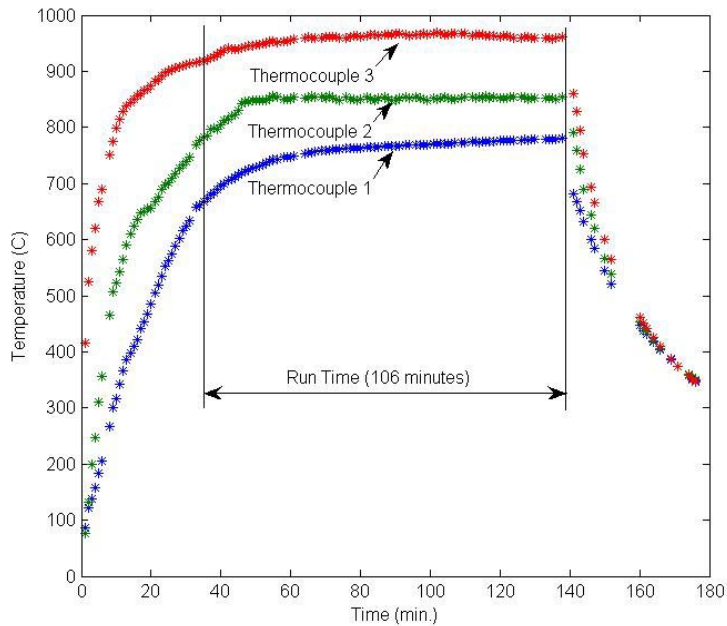2 to 16 amps at a mass flow rate of 0.71mg/sec using bismuth.**

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Figure 4. Cathode temperatures throughout the bismuth cathode test.

C. Comparison with Xenon and Krypton

A cathode of exact geometry was then tested at two different xenon flow rates. The rates were chosen so that the same mass flow was used as in the bismuth case as well as the same molar flow. The equivalent molar flow rate for xenon is 0.45mg/sec. Three sweeps at each flow rate were taken and the results can be seen in Figure 5. The same experiment performed with xenon was then done using krypton. The corresponding molar flow rate in this case is 0.29mg/sec. These results can be found in Figure 5 as well.
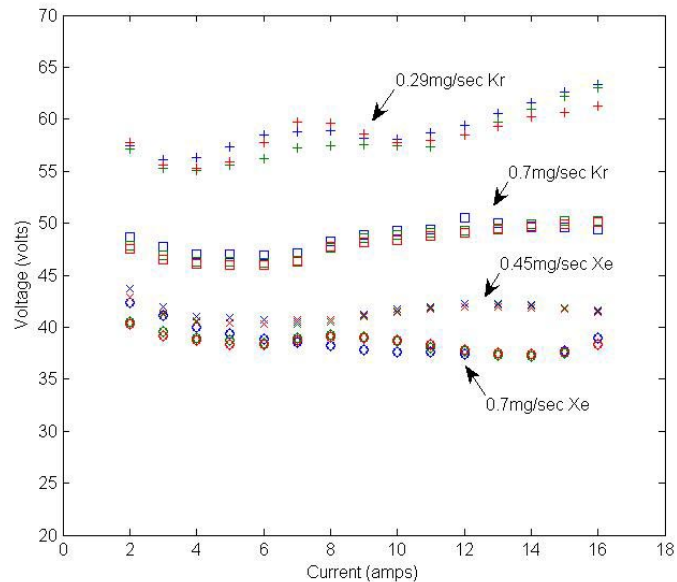

**Figure 5. Anode voltage taken at currents varying from 2 to 16
amps using krypton and xenon propellants.**

IV. Discussion

A. Required Heater Power

The total heater power required for steady-state operation of the bismuth cathode was 250 watts. Approximately 160 watts were necessary for the bismuth reservoir and 90 were input into the LaB$_6$ heater. Further testing with the cathode on a 2-kW bismuth Hall thruster illustrated that the LaB$_6$ heater was unnecessary and that the cathode could operate on only 125 watts input to the bismuth reservoir heater. It should be noted that in each successive bismuth cathode experiment the LaB$_6$ heater power had to be increased to begin a discharge. Over the period of four tests, the necessary power to light the cathode each consecutive time was 220W, 240W, 240W, and 300W 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 that the downstream end of the emitter was lacking emissive material, which made it necessary to increase heater power in further testing.[4] Although impossible to draw any conclusions at this time, the increased degradation of emissive materials may be an artifact of using a metal vapor propellant as opposed to an inert gas.

B. I-V Characteristics

An overall look at the range of anode voltages recorded when using bismuth propellant was found to be between 25 and 50 volts. This is comparable to the voltage range of 35 to 50 volts obtained from xenon and krypton.

Looking closer at the bismuth data in Figure 3, the data doesn't follow the increasing voltage trends of krypton and xenon. In fact, it does the opposite. Anode voltage decreases as though mass flow is increasing. This happens until the anode current reaches about 6 amps. At this point the anode voltage increases by about 15 volts. The reason for the voltage increase is not known at this point in time but it is possible that the cathode switched into a new operating mode. After the 15 volt increase, the anode voltage continues to decrease again. One hypothesis for this is that the addition of heat due to discharge current into the cathode causes the vapor pressure inside the cathode body to be increased which then increases the mass flow rate. It has been shown by Goebel that increases in flow rate cause a decrease in anode voltage.[5] Since the mass flow of bismuth is entirely temperature dependant it would make sense that by inputting more power to the cathode the flow rate would increase. Mass flow is discussed more in-depth below.

C. Mass flow analysis

Attempting to control the mass flow rate of bismuth was done by controlling the temperature of the reservoir. 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.[6] S.I. units are used in both Equations 1 and 2.

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

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

Figure 6 is a visual representation of the mass flow rate per evaporation area at internal temperatures ranging from 700 to 900°C. Assuming that the crucial temperature for bismuth flow is that of the cathode orifice, than it would have to maintain a temperature between 850 and 855°C to yield a flow rate of 0.71mg/sec through the 2.0mm diameter orifice. However, taking sweeps of discharge current from 2 to 16 amps would cause large instantaneous changes in the temperature at the cathode end orifice. The increase in temperature would cause an increase in mass flow, which is what appears to be happening when the anode is given greater than 8 amps of discharge current.
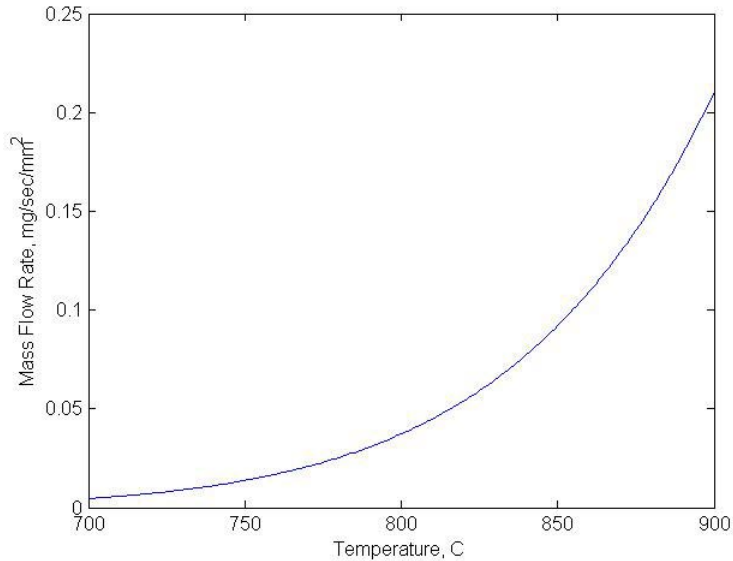
The thermocouple nearest the LaB$_6$, thermocouple 3 in Figure 1,

Figure 6: Bismuth evaporation rate per evaporation area as a function of temperature.

read 960±10°C throughout the test. At this temperature the cathode would have a mass flow rate of 1.7mg/sec based on the end orifice area. Thermocouple 1 read 760 ±15°C which would have a mass flow rate of about 6.8mg/sec based on the porous vapor escape area. Initially it was thought that the governing temperature would be at the porous disc. After operating the cathode numerous times using bismuth propellant it seems more likely that the most critical flow-limiting region is at the end orifice of the cathode. The fact that the theoretical rate was only about twice that of the observed rate at the end orifice also adds confidence to this case.

D. Conclusions

In these experiments it has been shown that obtaining constant mass flow data with this cathode design while sweeping anode currents may be difficult. The increase in discharge power may have an effect on the amount of bismuth being evaporated from the end orifice. It appears that the most influential temperature for mass flow is at the end orifice rather than the porous stainless disc. However, the porous disc temperature is also important since it must be hot enough to allow for sufficient bismuth evaporation to the orifice region.

Also mentioned was the fact that the cathode had to be "jumpstarted" with krypton. For these particular experiments, it was necessary to use an inert gas to get the cathode to sustain on a bismuth discharge.

Acknowledgments

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