Development of a Vaporizing Liquid Bismuth Anode for Hall Thrusters

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ABSTRACT

Bismuth metal vapor Hall thrusters may have superior performance and economic characteristics when compared to xenon. From increased efficiency to reduced propellant and testing costs, bismuth seems to have a bright future. Of paramount importance when developing a practical bismuth device is the mechanism by which the propellant flow is controlled. This paper reports on an effort to use waste heat from the thruster to control the evaporation of a reservoir of liquid bismuth maintained within the discharge chamber. Research done thus far indicates that mass flow control can be achieved via a segmented anode configuration that serves as a thermostat to control input power into the bismuth reservoir. Thermal modeling has indicated that sufficient thermal gradients can be maintained between anode segments. Laboratory testing on xenon development thrusters validates the scheme to control reservoir temperature through discharge current sharing.

1 Introduction

Bismuth has many attributes that make it well suited for development as a propellant. When compared to more traditional propellants such as xenon, bismuth holds significant advantages. Attractive physical attributes follow from the atomic structure and size of bismuth atoms. Bismuth is significantly more massive then xenon (209 amu vs 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 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 and it need not be a pressure vessel. Table 1 lists additional relevant physical characteristics.

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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

Beyond physical advantages, the economics of using bismuth is also of critical interest. For instance, bismuth retails for about $8/kg as opposed to $7,700/kg for xenon which translates to a huge savings in propellant cost: a negligible $110-per-day to operate a 50-kW Bi thruster compared with $106,000-per-day for an equivalent xenon device (without reclaimation). 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 the cathode mass flow (assuming a xenon cathode)

Although immature as a Hall thruster propellant, the use of bismuth is not without precedent. Soviet work performed in the 1980's and only recently reported in the open literature evaluated bismuth anode-layer thrusters.[1,2] TsNIIMASH researchers reported thrusters with power up to 140 kW and specific impulse as high as 8,000 seconds operating with anode efficiencies exceeding 70%. Papers reporting on this early work give few details on bismuth flow control method or apparatus.

2 DESCRIPTION OF CONCEPT

2.1 Direct Evaporation

While physically superior in the discharge chamber, the obvious engineering challenge associated with bismuth is how to produce and deliver a metered flow of vapor to the thruster in an energy efficient method. A straightforward approach to a Bi mass-flow system might be to heat a reservoir of the metal to high temperatures to induce evaporation and transfer the vapors through heated plumbing to the anode/gas diffuser. This approach was used in early Soviet work.[1,2] Besides the material difficulties associated with high-temperature propellant isolators, valves, and flow control devices, such a system is energetically unfavorable. Any power that is used to drive the evaporation heater and to maintain the temperature of the transfer plumbing is non-propulsive and reduces the overall system efficiency of the thruster.

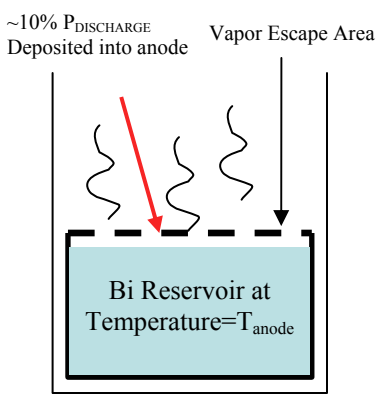

Figure 1 – Diagram of bismuth reservoir. Power is dissipated into the anode face causing bismuth to vaporize which diffuses through the holes in the face.

In the method proposed here, bismuth is supplied to an anode/reservoir within the thruster discharge chamber in solid or liquid form. Naturally occurring thruster waste heat is used to drive direct evaporation from the anode/reservoir into the discharge chamber. The evaporation rate is controlled through the reservoir temperature and the permeated vapor escape area (see Figure 1).

Since it is not feasible to mechanically vary the vapor escape area through the reservoir, the mass flow rate, $\dot{m}$ will be controlled by varying the reservoir temperature within the thruster. The evaporation rate, then, is governed by the equilibrium vapor pressure of the liquid metal and the goal is to maintain the proper reservoir temperature that, when combined with the vapor escape area, yields the correct value of mass flow.

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

$$\dot{m} = \frac{P_v}{\sqrt{\frac{2\pi kT}{m}}} A \quad (2)$$

Equation 1 gives the vapor pressure, P_v in Pascals for bismuth where T is the temperature in Kelvin[3]. Using equations (1) and (2) it is then possible to calculate the evaporation rate per-vapor-escape-area $\dot{m}$ /A as a function of reservoir temperature.

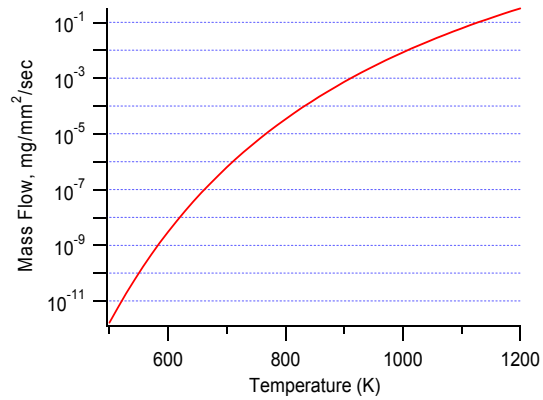

Figure 2 – Bismuth evaporation rate as a function of temperature. It does not take a significant change in temperature to cause a drastic change in mass flow.

Figure 2 illustrates the mass flow rate per-unit-area as a function of reservoir temperature for an evaporative bismuth source. This plot can be used to estimate the required reservoir temperature for a candidate Hall thruster if the anode were used as the reservoir. For instance, a typical 2kW-class hall thruster has about 3,700 mm^2 of exposed anode face and runs on 5.4 mg/sec of propellant. Figuring on a 10% open area on the anode face, a temperature of about 750°C will provide the necessary mass flow rate.

The design goal is then to 1) achieve an anode/reservoir temperature on the order of 750 deg C using only the waste heat from the discharge, and 2) implement some type of temperature control scheme to enable closed-loop control of the evaporation rate through the fixed vapor escape area.

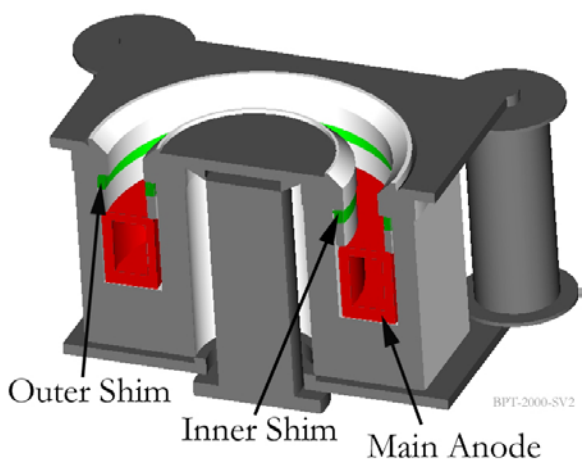

Figure 3 - Cross section of the segmented anode hall thruster showing the three anodes. Discharge power can be shared between any combination of anodes by inducing voltage differences. Thermocouples are located at the tip of each arrow.

2.2 The Segmented Anode Hall Thruster

Obviously, designing a thruster that dissipates exactly the right amount of power into the anode represents an unfeasible open-loop control system. The concept reported here uses a segmented-anode design to achieve closed-loop control of the bismuth reservoir temperature. Our design utilizes three separate anodes: the traditional main anode and two inert "shim" anodes - one inner and one outer –electrically and thermally isolated from the main anode. Figure 3 shows a cross section of the Isp Lab development thruster.

The main anode serves dual use as a propellant diffuser and accelerating electrode very similar to traditional gas fed Hall thrusters. However, in this design the hollow main anode serves as a reservoir of liquid bismuth. Electron current from the discharge plasma heats this anode/reservoir at a rate of approximately 10% of the total thruster power, driving the direct evaporation of propellant into the chamber.

Main anode temperature is controlled by sharing the plasma discharge current with a set of electrically isolated shim anodes on the inner and outer wall. The shim anodes are inert (stainless or molybdenum) and are not bismuth vapor sources. By varying the shim voltage with respect to the main anode, the plasma current and, hence, heating can be shared between the shims and main, thus controlling the main anode temperature and the evaporation rate. The mass flow rate is then bounded above by the equilibrium main-

anode temperature that obtains when 100% of the discharge current is attached to the main, and bounded below by the temperature achieved when 100% of the current is attached to the shims.

Thermal modeling was conducted to evaluate the temperature range and, hence mass-flow range, that can be expected within the proposed device. Figure 4 is a composite image of two different test cases analyzed for the thruster used in subsequent laboratory testing. In the top case, all of the discharge current was placed into the main anode which, for the 2-kW device considered here, was estimated to produce a 10%, or 200 W, heat input. In the bottom case, all of the power was placed into the inner shim anode. As can be seen, temperature changes on the main anode varied by approximately 50°C. Because of the steep slope of the bismuth vapor pressure curve, a ΔT of 50°C would enable nearly an order of magnitude throttleability in mass flow.

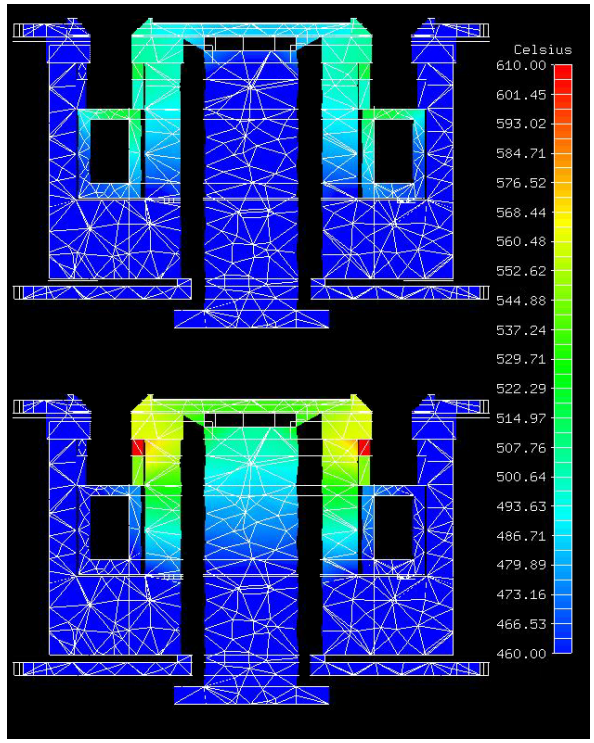

Figure 4 - Thermal simulations of two different modes of operation. In the top, 100% of the power is being deposited into the main anode. In the bottom, 100% of the power is deposited into the inner shim anode.

3 STATUS OF DEVELOPMENT

3.1 Experimental Set-up

The goal of research reported here was to experimentally verify the ability to control main anode temperature by sharing the discharge current with shim electrodes. Towards this effort, a proof-of-concept development thruster was fabricated with segmented electrodes and tested in the MTU Isp Lab. The thruster was not operated on bismuth. Instead, the validation tests used xenon for propellant and relied on laboratory mass-flow controllers to uncouple the thruster thermal response from the propellant supply rate.

Figure 5 - Picture of the thruster ready to test. Due to the extra wiring required by the anodes and thermocouples, thrust measurements were not taken.

The thruster used was a modified Aerojet BPT-2000 Hall thruster. While the overall geometry and magnetic circuitry of the BPT-2000 was preserved, the interior electrode structure was modified to accommodate the three-electrode configuration pictured in Figure 3. Each of the three electrodes was wired independently to allow for independent control of voltage and current. In order collect thermal data, thermocouples were placed at seven different locations on the thruster – back of the main anode, outer shim, inner shim, magnets, cathode mount, main propellant line and thruster mounting plate. Figure 5 is a photo of the thruster completely wired just before a test. An electrical schematic also showing the location of three of the thermocouples is shown in Figure 6.

All tests were performed in the Isp Lab's Xenon Test Facility (XTF) on the campus of Michigan Technological University. The facility is comprised of a 2m-diameter by 4m-long vacuum tank. Rough pumping is accomplished by a two-stage rotary oil-sealed vacuum pump with a Roots blower, capable of pumping at 400 cubic-feet-per-minute. High vacuum is achieved through a 48-inch-diameter cryopump, capable of pumping 60,000 liters-per-second on Nitrogen. Background pressure of 4.2×10^{-5} Torr (corrected for xenon) was maintained during testing.

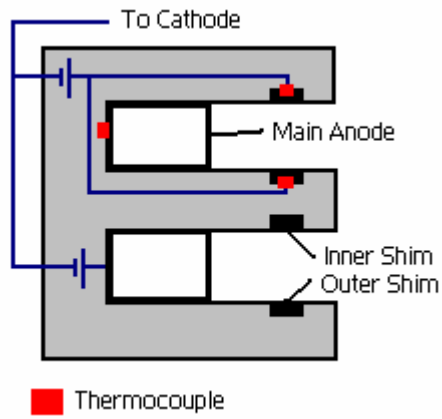

Figure 6 – Electrical Schematic of the segmented hall thruster. The red areas indicate the locations of the thermocouples.

3.2 Results

To evaluate the capability of sharing discharge current between the shims and main anode, the thruster was operated at 3.2 mg/sec of xenon with the main anode at 300 V. With the shims also held at 300 V, it was discovered that 100% of the discharge current (3.24 A) attached to the inner shim with no observable current on the main or outer shim. As the shim voltage was reduced, current sharing with the main anode was observed at approximately 290 V. As the shim voltage was further reduced controlled current sharing was observed until all of the discharge was attached to the main anode. As seen in Figure 7, 30 V change in shim potential was sufficient to induce 100% current transfer.

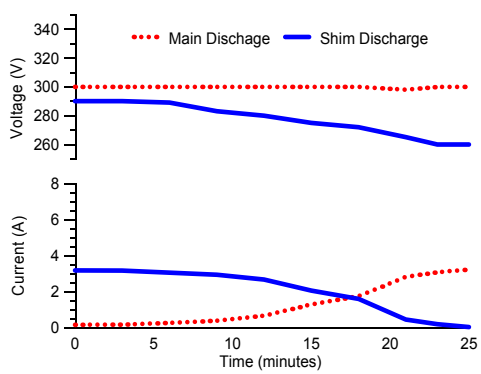

Figure 7 - Plot of discharge characteristics of a segmented anode thruster. A difference of only 30 volts is enough to cause complete crossover in discharge current.

To verify thermal control, the thruster was operated at 5.4 mg/sec of xenon with the main anode at 400 V. Initially, the shim voltage was reduced to 366 V, which was sufficient to ensure almost 100% current attachment to the main. A thermal soak was performed, with steady-state temperatures observed after about 100 minutes. At this point, the shim anode was increased to 400 V, whereupon the discharge current attached to the shim. Shim temperature then increased while main anode decreased, reaching a new equilibrium after another 25 minutes. The test results are shown in Figure 8.

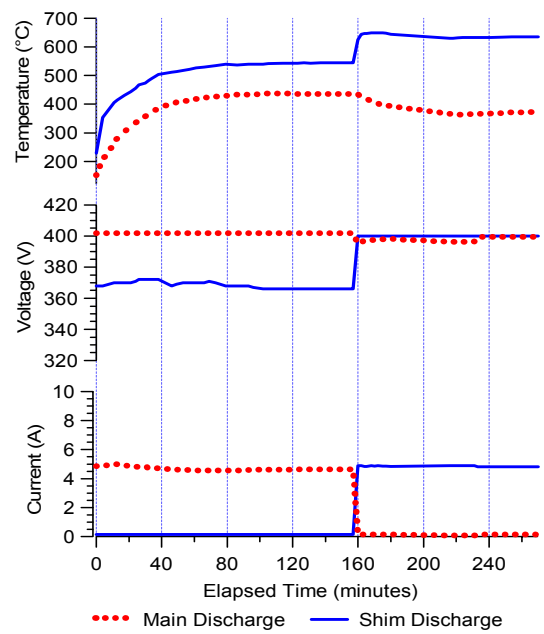

Figure 8 - Plot of the thermal response of the segmented hall thruster during a change in attachment. As expected, the inner shim anode heats up much faster and achieves significantly higher temperature then the main anode. Only a small voltage difference was required to induce the change.

4 DISCUSSION

Table 2 summarizes the electrical and thermal properties illustrated above. As before, a small change in voltage is all that is required to shift the discharge. Also listed are the steady-state temperatures. In summary, 33 volts creates a 66 and 81 degree difference in main anode and inner shim temperature respectively. Translating this back to mass flow rates, such a change in temperature would easily change mass flow by an order of magnitude.

Thruster Operating Points					
Anode Voltage(V)	Anode Current (A)	Shim Voltage(V)	Shim Current(A)	Anode Temp(C)	Shim Temp (° C)
402	4.63	366	0.15	436	554
400	0.15	400	4.81	373	635

Table 2 – Selected operating points and temperatures

In order to ascertain plume changes, a significant amount of Faraday probe data was also taken during operation. Overall, shifting current from the shims to the main anode had little effect on the shape of the plume but did impact the overall beam current. These results are subject of another paper presented at this conference.[4]

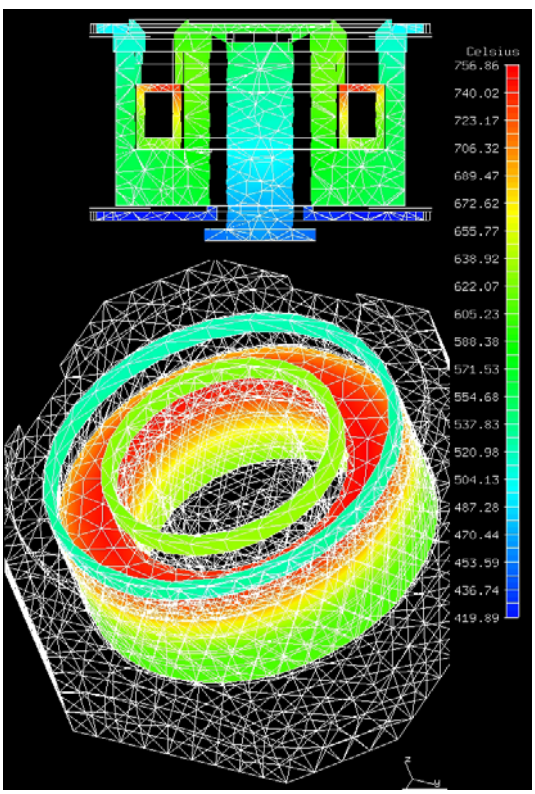

Figure 9 - Thermal simulation results with 500 watts into the anode. The additional power allows the main anode to achieve the desired operating point.

While the laboratory tests proved the ability to vary the main anode temperature over sufficient range to control evaporation, the absolute temperatures achieved in the test were not high enough to produce the desired mass flow. Comparing Figure 2 with Table 2, the maximum main anode temperature of 436 deg C is much lower than the required 750 deg C for ~ 5 mg/sec of evaporation. Recalling Figure 4, the experimental results match the thermal models quite closely which also precluded the possibility of reaching the required temperatures when the thruster is operated near 2 kW. A straightforward solution to this problem is to operate the thruster at higher power such that the power density on the main anode is sufficient to reach 750 deg C.

Figure 9 shows the thermal simulation of the thruster running at a higher power level. The simulation concluded that approximately 500 watts into the anode is needed to achieve the temperatures required. On the assumption that 10% of thruster power is input to the anode as heat, this equates to operating the Hall thruster at 5 kW for Bi, instead of the 2 kW intended for xenon. Generalizing to an arbitrary thruster size, power density becomes the most important design item for a bismuth Hall thruster with an evaporative anode. Based on anode face area, power density of 1 watt/mm^2 is required to reach evaporative temperatures.

5 CONCLUSION

Laboratory experiments verified the possibility to change the anode temperature in a Hall thruster using segmented anodes to share the discharge current. Temperature variation of approximately 50 C was

achieved with a transient time constant of tens of minutes. Such a system should be straightforward to implement in a closed-loop controller for evaporation of bismuth directly within the Hall thruster discharge. Such a system would avoid the difficulties associated with high-temperature gas supply, propellant isolation, and flow control while utilizing zero non-propulsive power for propellant evaporation.

While current sharing and temperature control was shown to be possible, the effect on thruster performance has not been directly measured at the time of this writing. Faraday probe sweeps of the plume indicate little effect on divergence, but no testing has been completed to quantify the affect that segmented electrodes have on specific impulse and efficiency.

Thermal models and laboratory tests show that typical design strategies for xenon Hall thrusters are not directly compatible with bismuth systems. Specifically, the conventional wisdom with xenon devices has been to minimize the temperature of thruster components. Since a bismuth system necessarily requires high temperature, future thrusters will likely require anode power densities about two times greater than their xenon counterparts, or about 1 watt/mm^2 based on anode face area. The Isp lab is in the process of testing such a device on bismuth.

Concurrently, the Isp Lab has completed construction of a dedicated bismuth thruster testing facility. The centerpiece of the test-bed is a 2-m-diameter by 4-m-long stainless-steel vacuum chamber evacuated through three 2,000-liter-per-second turbomolecular pumps. The chamber is equipped with automated probe positioning systems and performance diagnostics. Follow-on bismuth thruster development will proceed in 2005.

6 ACKNOWLEDGEMENTS

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