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Mass Flow Control in a Magnesium Hall-effect Thruster

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The research reported in this paper examined methods of operating a Hall-effect thruster on solid magnesium propellant at discharge voltages in excess of 200 volts. Mg vapors were supplied through evaporation of propellant feedstock within the thruster anode. A constant-current discharge was used to achieve steady evaporation from three different anodes, each having a different vapor escape area. It is shown that the stable discharge voltage can be increased by reducing the vapor escape area of the source. It was shown that by decreasing the open area of the anode from 2.77 x 10^{-4} m^2 to 6.93 x 10^{-5} m^2 the maximum discharge voltage of the thruster increased from 184 volts to 341 volts. The ability of inert (non-evaporative) shim anodes to stabilize the thruster by increasing or decreasing heat flux to the main anode was also shown.

Nomenclature

A_{open}	=	open area
I_{sp}	=	specific impulse
m	=	mass of atom
$\dot{m}$	=	mass flow
P_v	=	vapor pressure
T	=	temperature in Kelvin

I. Introduction

IN early 2009 the Ion Space Propulsion lab at Michigan Technological University began performing experiments using magnesium and zinc as propellants for a Hall-effect thruster[1]. These propellants are desirable for several reasons including that they are solid at room temperature. This means that the room-temperature walls of the vacuum facility itself can be used to pump the propellant, as the vapors will condense on the walls of the vacuum chamber. Magnesium is a particularly interesting prospect; it has a very low mass, allowing for a high theoretical specific impulse on the order of 4000 seconds at 300 volts. It is also found on the surface of both the moon and Mars[2,3] which may allow for in situ refueling. Research into condensable propellants started at MTU with the use of bismuth as a propellant[4,5,6,7,8]. Later experiments performed by Makela et al demonstrated the potential of magnesium and zinc. At the same time similar research into light metals was being performed by Busek[9]. All of this work followed initial Soviet research into magnesium and zinc for use as Hall-effect thruster propellants[10].

A challenge when using any solid metal propellant is the design of a feed system: the metal must be vaporized in an energy-efficient process and these vapors must be delivered to the thruster discharge chamber. Pathfinding experiments were performed by Makela et al[1] using solid anodes that were fabricated from the propellant stock itself – specifically Mg and Zn. The heat deposited into the anode from the plasma discharge current was sufficient to sublime vapor from the anode at a sufficient rate to sustain the thruster operation. This method proved that discharge plasma could be produced via direct sublimation of zinc and magnesium, but it lacked the ability to control the mass flow of the propellant. In later experiments a design was demonstrated that employed a hollow anode made of stainless-steel with a porous face which served as the propellant reservoir, gas distributor, and ion accelerator. The

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anode was filled with solid propellant and long-duration magnesium tests were performed using shim anodes to control the temperature of the main anode. The results of these tests proved the ability to control mass flow through heating and cooling of the main anode by sharing current between it and the shim anodes[1,11]. A magnesium Hall thruster implementing the use of a porous anode is shown below in Figure 1.

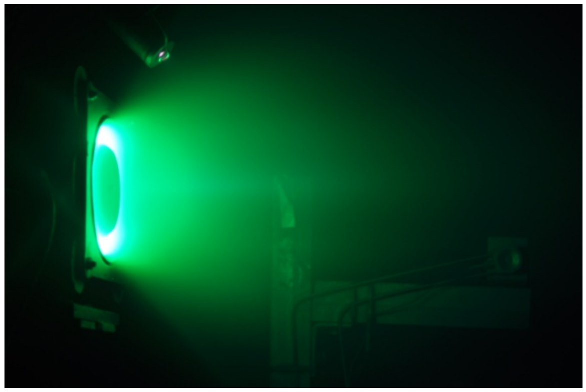

Figure 1. Hall-effect thruster operating on solid magnesium propellant contained in a porous anode.

Because it is the temperature of the main anode – which contains the solid propellant – that controls the mass flow of the thruster in Makela's experiment, the MTU team discovered that such thrusters are best operated using power supplies in current-limited mode. This is entirely different than gas-fed thrusters which are operated in voltage-limited mode. When operating in current-limited mode, the discharge voltage is dictated by the impedance of the plasma which is affected by, among other things, the propellant mass flow rate. Hall-thruster behavior in current-limited mode can be understood in terms of well known I-V characteristics, like those shown in Figure 2, where it can be seen that for a given discharge current an increase in mass flow causes a decrease in voltage. Therefore, when operating a thruster in constant current mode, like that used in Makela et al, with all other parameters constant, a change in mass flow rate will cause a corresponding change in voltage.

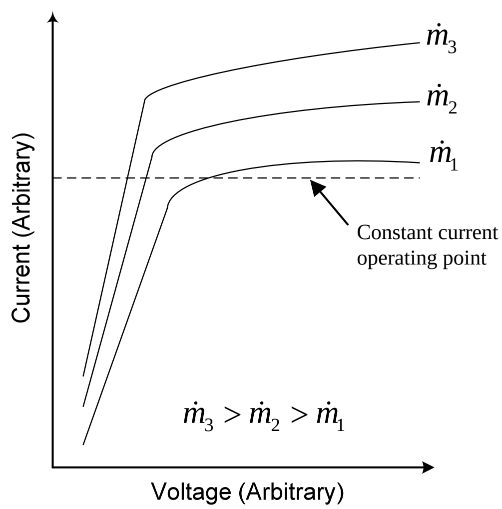

Figure 2.Typical Hall thruster I-V characteristics (for example see Haas[12]).

The mass flow rate of an evaporative metal thruster is governed by the propellant feedstock temperature (essentially the anode temperature) and the area of the evaporative surface, which is some fraction of the anode face area defined by the design of the porous surface. If the mass flow rate increases at constant current then the discharge voltage will decrease. This causes a decrease in discharge power which reduces the amount of heat transfer into the anode, which in turn reduces the anode temperature and with it the evaporative mass flow rate. This effect, while not necessarily stabilizing, acts to arrest runaway in the evaporative mass flow. In a similar manner when the mass flow rate decreases at constant current the discharge voltage will increase, which also increases the power, the heat deposited into the anode, and in turn the evaporative mass flow rate. It was shown in Makela et al, that there are stable operating conditions where this self-correcting process happens for long durations. The stable operating points are controlled by the thermal design of the thruster and the effective evaporative surface area of the anode.

In practice the evaporative surface area of the system is defined by the openings in the anode that allow vapors generated inside the hollow electrode to diffuse into the discharge chamber. In this approximation, the mass flow can be determined using the following equation:

$$\dot{m} = \frac{P_v(T)}{\sqrt{\frac{2\pi k_B T}{m}}} A_{open} \tag{1}$$

where $P_v(T)$ is the temperature-dependent vapor pressure of the propellant feedstock and the open area, A_{open}, is the surface area through which vapors enter the discharge chamber (the total area of holes in the anode face). In order to design such an evaporative propellant feed system for a Hall thruster, the temperature of the anode must be known a-priori so the anode can be fabricated with the correct value of A_{open}. Uncertainty in the thermal models will result in anodes with either too large or too small open areas. While the shim temperature control scheme demonstrated by Makela[1] enables some degree of control over the anode temperature and thus some ability to vary the mass flow through a fixed A_{open}, it is of course necessary to choose an open area that is within the control range. In the experiments performed by Makela et al, the desired mass flow rate was 1 mg/s for magnesium. Based on thermal models the open area of the anode was chosen to be 7.13 x 10^{-4} m^2. This particular open area was chosen because it allowed the thruster to operate at the relatively low temperature of 444 ˚C while still maintaining a mass flow of 1 mg/s.

As demonstrated in the experiments performed by Makela et al, stable operating points – that is points where the constant-current operation method results in steady, constant thruster voltage for long periods of time – can be found by changing the amount of the discharge current attached to the shims verses the main anode. Changing the amounts of current on the shims and on the main anode causes a change in heat flux to the main anode. When this happens, the mass flow rate and voltage also change proportionally. Because of this, the discharge voltage can be manipulated to a small degree for a given open area while still maintaining stable operation of the thruster. Due to the open area chosen for the anode used in the experiments, the range of achievable discharge voltages was only in the 100-150 volt range for stable operation. Higher voltages were attainable, however, but only on the order of 200 volts and only for periods of time less than one minute. When higher voltages were achieved, the total power of the thruster increased, which added to the heat flux of the anode, effectively increasing mass flow above the design point and decreasing voltage.

By inspecting Equation 1 it can be seen that if one reduces the open area of the anode, the anode temperature required for a particular mass flow will rise. If the temperature required for operation increases, then more heat flux to the main anode will be required for sustained discharge. This heat flux must be provided by operating the thruster at higher power, which means higher discharge voltage at constant current. Thus, the stable operating voltage of the Hall thruster is directly affected by the open area of the evaporative anode: a reduction in open area should result in an increase in the discharge voltage at the stable operating point(s).

The goal of this study was to determine whether the stable operating voltage, and thus the nominal Isp, of an evaporative Mg Hall thruster can be selected by varying the evaporative open area of the anode propellant feed surface. Previous research demonstrated stable thruster operation for discharge voltages on the order of 150 Volts[1]. The objective of work reported here was to increase the stable voltage and thus the Isp by reducing the open area. To achieve this, three anodes with varying open area were fabricated and tested within a Mg Hall thruster.

II. Description of Apparatus

The thruster used for the experiments reported here was a modified Aerojet BPT-2000 Hall-effect thruster. While the overall geometry and magnetic circuitry of the BPT-2000 was preserved, the interior boron nitride (BN) body and anode structure were modified to accommodate the inner and outer shim anodes as well as a porous anode. The main thruster components and anodes are shown in Figure 3.

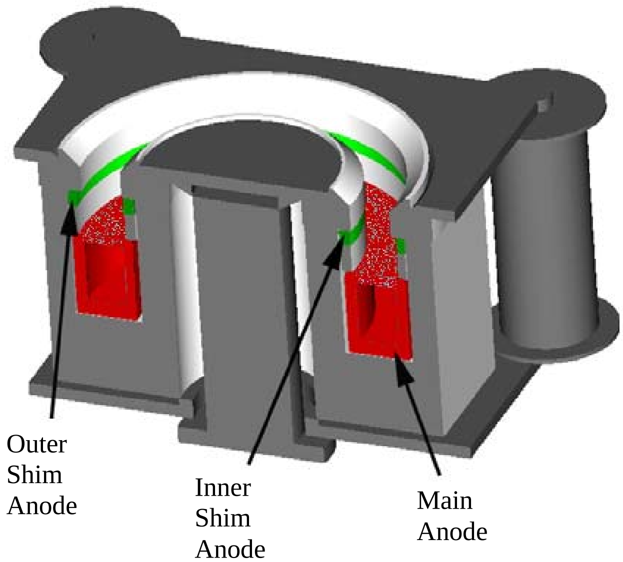

Figure 3. Cut-away view of a modified BPT-2000 Hall-effect thruster, showing the location of the shim anodes and main anode. The cavity within the main anode is filled with metal propellant feedstock, with the porous face allowing metal vapors to diffuse into the discharge chamber.

Three different porous anodes were used in this study. Anode 1, the anode used in the experiments performed by Makela et al, had an open area of 7.13 x 10^{-4} m^2; Anode 2 had an open area of 2.77 x 10^{-4} m^2; and Anode 3 had an open area of 6.93 x 10^{-5} m^2. Using Equation 1, the temperature required for operation at 1 mg/s is predicted to be 444 ˚C for Anode 1, 474˚C for Anode 2, and 522˚C for Anode 3. In order to pre-heat the thruster a length of tungsten wire was wrapped around the body as shown in Figure 4. This heater was designed to heat the thruster prior to ignition of the discharge current and was then unpowered during thruster operation. A thermocouple was attached to the back of the main anode to measure temperature. All experiments utilized a laboratory LaB_6 hollow cathode operating on argon.

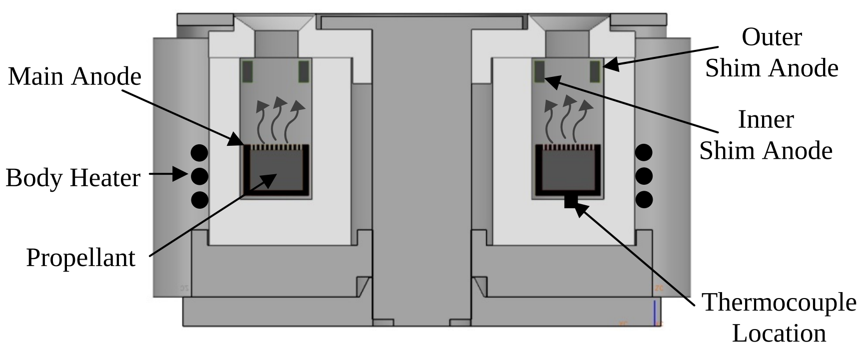

Figure 4. Cross sectional view of the experimental thruster showing the location of the main anode, shim anodes, body heater, and thermocouple.

III. Experimental Methods/Discussion

A) Shim Anode Operation

It has previously been shown that stable operating points can be achieved in an evaporative Mg Hall-thruster[1]. The conditions that dictate thruster operation are the main anode current and voltage, the shim anode current and voltage, and the magnet current. A stable operating point is a set of operating conditions which allow the thruster to operate in constant-current mode at relatively constant voltage for long periods of time, often greater than one hour. While a single stable operating point was shown in Makela's experiment, finding multiple operating points at higher voltages would increase the achievable specific impulse of the thruster. Results of further testing with Anode 1 show that multiple stable operating points can be achieved; this is shown in Figure 5.

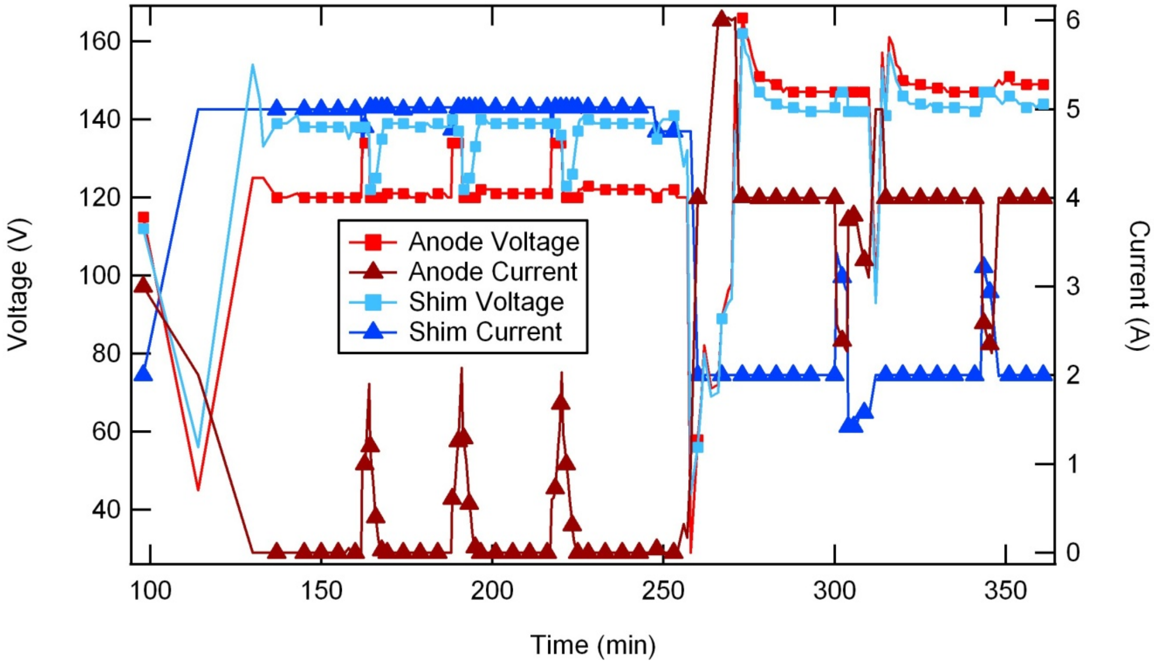

Figure 5. Voltage and current characteristics of the magnesium Hall-effect thruster operating with Anode 1. Note that the excursions at approximately 170, 190, 220, 300, and 340 minutes were intentional deviations from the stable operating point designed to test the ability of the thruster to return to the same stable point. In all cases the thruster returned to stability.

From Figure 5 it can clearly be seen that there are at least two distinct stable operating points. The conditions of Operating Point 1 are 120 volts 0 amps on the main anode and 138 volts 5 amps on the shims with 0.6 amps on the magnets. The conditions of Operating Point 2 are 147 volts and 4 amps on the main anode and 143 volts and 2 amps on the shim anodes with 0.73 amps on the magnets. Because mass flow as well as specific impulse are coupled to the operating conditions, finding multiple operating points shows that mass flow and I_{sp} can be varied for a particular anode with constant open area.

Currently, however, there is not a closed form method for predicting the conditions of a stable operating point. The known operating points were found by systematically transferring different amounts of current between the main anode and the shim anodes until stability was found. When the thruster was left at a particular set of anode and magnet currents, a decreasing voltage suggested that temperature and mass flow were rising. To cool the thruster and decrease mass flow, some of the current on the main anode was transferred to the shims and voltage was again monitored. A voltage rising unstably indicated that the anode was cooling and more current should be added to the main anode to increase mass flow. This method is demonstrated in the following experiment.

The perturbations in the data of Figure 5 are deliberate disturbances to the thruster caused by the investigators. In the experiments performed by Makela et al[1], it was shown that by transferring current from the shim anodes to the main anode, the main anode is heated and mass flow is increased. The three perturbations seen in Figure 5 are demonstrations of anode heating by sharing current with the shim anodes. After the thruster had stabilized at Operating Point 1, the power supply driving the main anode was put into voltage-limited mode. The power supply driving the shim anodes was left in current limited mode but the voltage limit was set to 140 volts. The voltage on the main anode was then increased to 134 volts. This caused an initial current of approximately 0.5 amps to attach to the main anode while simultaneously reducing the current on the shims to approximately 4.6 amps. The added current heated the propellant reservoir, causing several effects to happen concurrently. First, the increased mass flow caused the current on the main anode to begin rising. Second, the shim anode current increased to the current limit of 5 amps after which the voltage on the shim anodes began to decrease, as they were then current-limited. Once the current on the main anode reached 2 amps the voltage on the main anode was again reduced to 120 volts, this was done to draw less current to the main anode and cool the propellant reservoir. The current on the main anode slowly dropped back to 0 amps and the voltage on the shim anodes slowly rose and stabilized at 138 volts. This process can be seen more clearly in Figure 6.

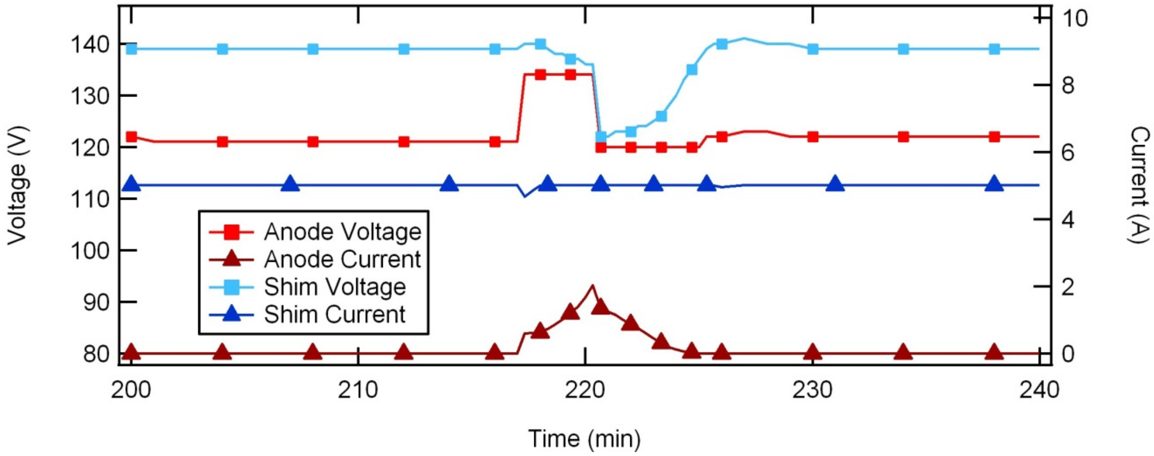

Figure 6. Graph of heating experiment with Anode 1. It can be seen that with increased heating on the main anode the voltage on the shims drops in a manner consistent with a decrease in mass flow.

The results of the heating experiment were two-fold. First, it explicitly demonstrates the relationship between mass flow and voltage; second it demonstrates that stable operating points are repeatable. As the mass flow increased due to heating of the main anode, the voltage on the shims decreased sharply. Once the voltage on the main anode was reduced and the extra heat began to dissipate, the voltage on the shims began to rise. Over the period of ten minutes the voltage on the shims stabilized again at 139 volts.

While the thruster was at Operating Point 2, cooling experiments were performed by transferring current from the main anode to the shim anodes. In order to do this, both power supplies were operated in voltage-limited mode. Then, by increasing the voltage on the shims current was drawn away from the main anode. As the main anode cooled, total current dropped due to loss of mass flow. To re-heat the thruster, the power supplies were then put back into current limited mode at their initial values. As the thruster was heated the mass flow increased and re-stabilized. The graph in Figure 7, an excerpt of Figure 5, shows the results of the cooling experiments.

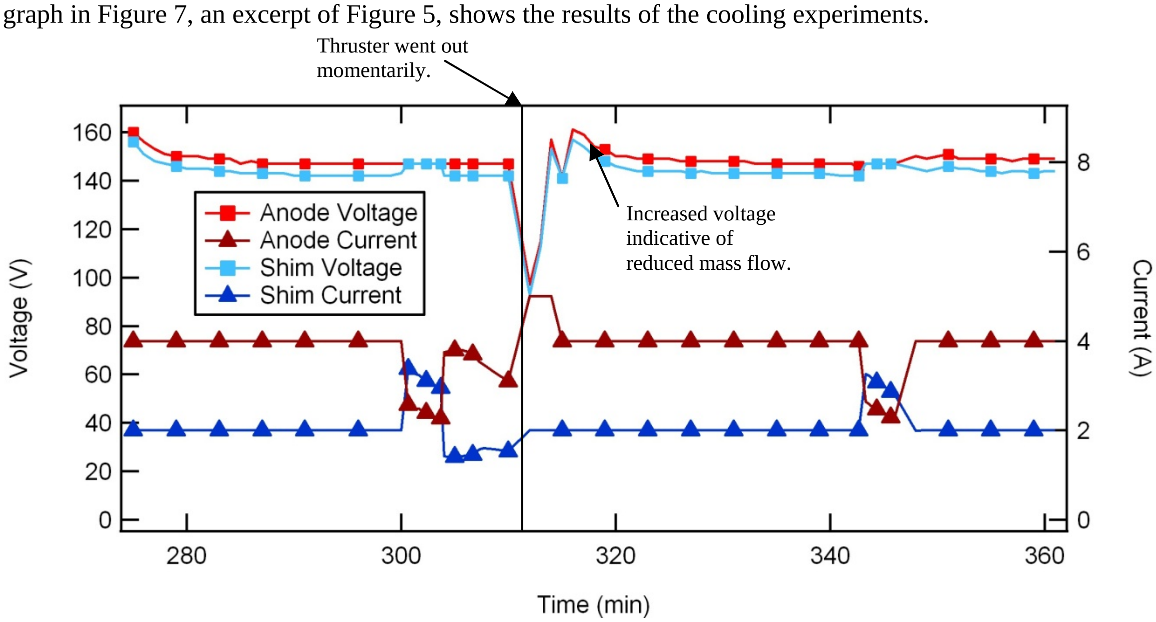

Figure 7. Cooling experiment performed using the shim anodes. Current is removed from the main anode and placed on the shims, effectively cooling the main anode and reducing mass flow. Main anode voltage was increased 11 volts from Operating Point 2 at 316 min which is consistent with a drop in mass flow due to the anode cooling. Because of the increased power, mass flow increased and the thruster stabilized back to the conditions of Operating Point 2.

In the first attempt at demonstrating anode cooling, 300 min to 310 min in Figure 7, thruster discharge was interrupted. This is not visible in the plot as the data were taken every minute and discharge was restored in a matter of seconds. Instead of setting the power supplies at the constant-current values of Operating Point 2, they were set to the constant voltage values. Because of this, the thruster did not re-heat; the mass flow continued to fall until thruster discharge ceased. For the second attempt (starting at 342 min) the constant current values of Operating Point 2 were used to stabilize the thruster.

The results of the heating and cooling experiments prove that sharing current between the main anode and the shim anodes permits control of the thruster mass flow. The experiments also showed that multiple operating points are achievable using the shim anodes to control mass flow and temperature. No stable operating points were found above 150 volts for Anode 1. It was hypothesized that the open area of Anode 1 was too large and, when heated, the mass flow rate was greater than expected. For this reason Anode 2 and Anode 3 were fabricated with reduced open areas to explore operation at higher discharge voltage.

B) Open Area Comparison

In order to compare how open area affects achievable voltage and power, two experiments were performed. In both experiments the shim anodes were placed in the thruster, but no current was attached to them. Because the shims were not used, the only variable between the two experiments was the open area of the anodes. For each of the two experiments the thruster was heated with the body heater prior to ignition.

To characterize Anode 2, two trials were compared. Trial 1 had an anode current of 3 amps; Trial 2 had an anode current of 4.5 amps. These specific values of current were investigated as they were the limits of thruster operation. Lower values of current did not maintain the temperature of the propellant reservoir causing the mass flow to drop, extinguishing the discharge. Higher anode currents caused too much heating and mass flow, and the thruster voltage would not increase beyond 100 volts. Before entering each operating point, the thruster was heated to a slightly higher temperature than predicted for operation. This ensured that enough mass flow was available. The thruster was then current-limited, and the magnet current was set. Magnet current for the operating points was chosen by the response of the voltage. Initial experiments were conducted in which the magnet current was increased at a particular anode current until discharge was extinguished. 15-25 mA was subtracted from the maximum magnet current achieved before the thruster went out. The resulting current and was then used as the magnet current for that particular anode current. The thruster was then set at each operating point and the voltage was recorded. As the thruster cooled at a constant anode current and magnet current, the voltage increased due to the decreasing mass flow. The increased power added heat to the anode causing increased mass flow, and again lowering the voltage. This process repeated itself until the thruster stabilized or until thruster discharge extinguished itself.

In Trial 1, the thruster was heated by operating it at a very low magnet current and hence very low efficiency such that most of the discharge power was thermally deposited into the anode; the thruster was intentionally heated beyond the temperature that was estimated to be necessary for steady-state operation. The magnet current was then increased to 0.33 amps. The increase in magnet current also increased the thruster discharge voltage and, at constant current, increased the total power input to the thruster. However, the magnetic field also increased the efficiency of the Hall thruster so that the net thermal input to the anode was decreased, allowing the anode to cool. As the anode cooled the discharge voltage increased in response to the decreasing mass flow and approached a stable value. The results are shown in Figure 8.

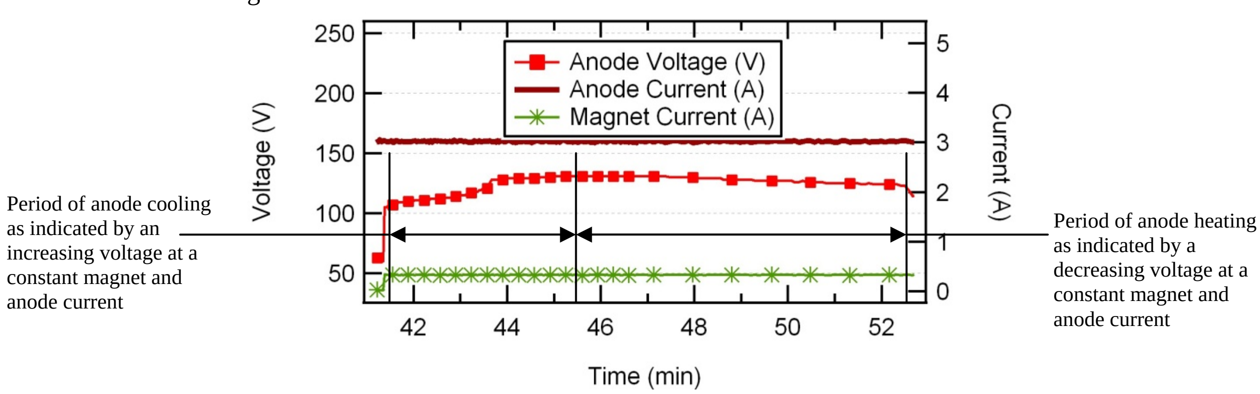

Figure 8. Results of the first experiment Trial 1. With three amps on the anode the voltage only reached a maximum voltage of 131 volts.

As can be seen from Figure 8, the highest voltage achieved with three amps on the main anode was 131 volts. At this voltage the operating point was stable to within 2 volts over several minutes, though a decreasing trend in the voltage is visible. The voltage dropped 10 volts from 44 min to 52 min, indicating a slow increase in mass flow over time due to anode heating. This type of slow variation is expected due to the thermal mass of the anode.

In Trial 2 the thruster was again operated at a low magnet current to heat the thruster, but this time the discharge current was set to 4.5 A. The magnet current was then set to 0.63 amps, and the thruster was allowed to cool and stabilize. The results are shown below in Figure 9.

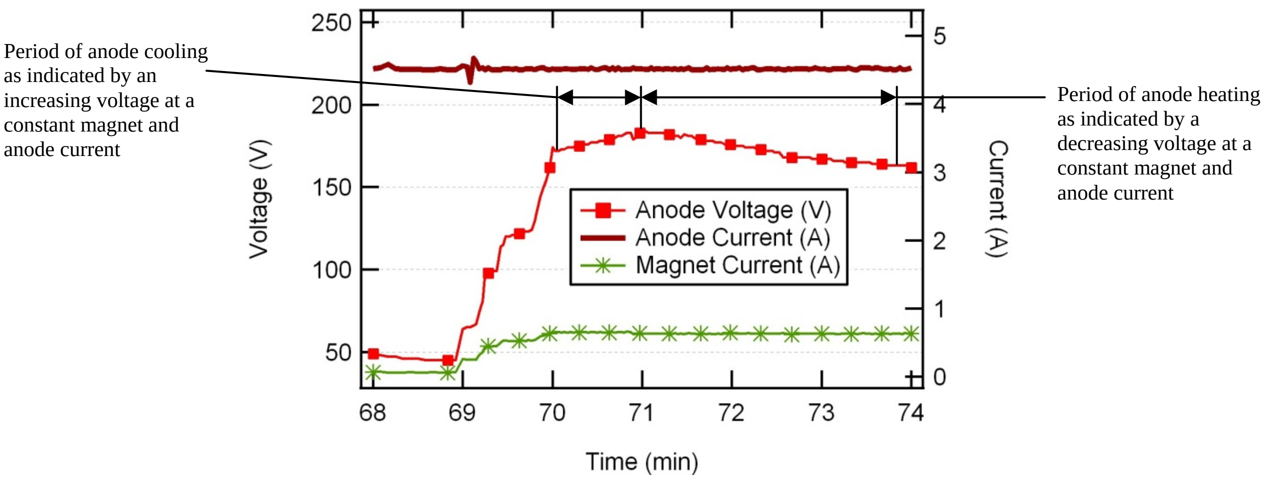

Figure 9. Results of testing Anode 2 Trial 2. At 4.5 amps the maximum voltage recorded was 184 volts.

In Trial 2, with 4.5 amps on the main anode and a magnet current of 0.63 amps, the maximum voltage recorded was 184 volts. The voltage on the anode was only maintained at greater than 180 volts for less than one minute. From its peak of 184 volts the anode voltage dropped 22 volts in 3 minutes, indicating a faster increase in mass flow than in Trial 1.

The results from Trial 1 and Trial 2 confirm that an increased power raises the main anode temperature and increases mass flow, causing a corresponding decrease in voltage over time. Additionally it was found that Anode 2 can achieve voltages of higher than 180 volts during operation, though not for long durations (at least in this open-loop scheme without shim anodes). This is likely due to the increase in maximum power from 393 W in Trial 1 to 828 W in Trial 2.

A second experiment was performed using Anode 3. Unlike Anode 2, Anode 3 was operated at currents of 5.75-6 amps to maintain proper heating of the propellant. Initial testing with Anode 3 revealed the ability of the anode to reach voltages as high as 341 volts. These voltages were not maintainable for more than 1.5 minutes, as seen in Figure 10.

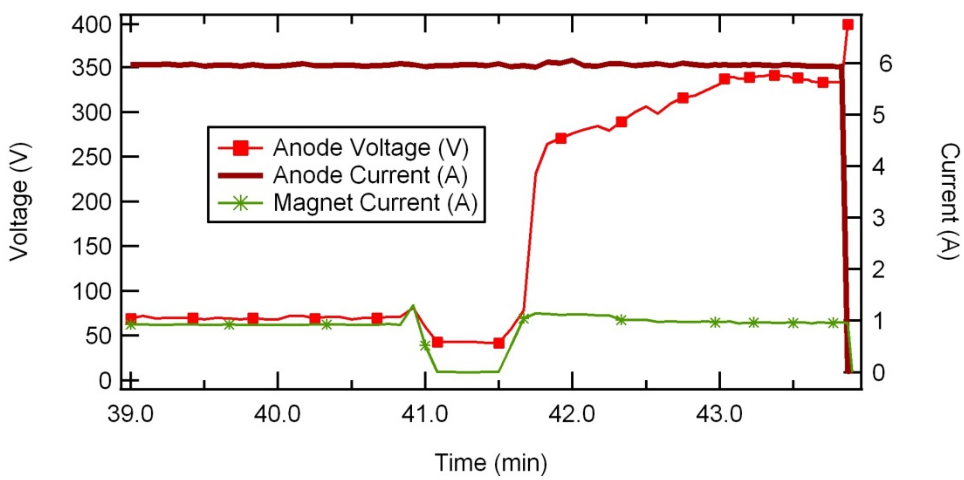

Figure 10. Results of initial test conducted with Anode 3. A maximum anode voltage of 341 volts was achieved, but only for 1.5 minutes. The sharp decrease in anode current occurred as the thruster went out.

Using the results of the initial test conducted on Anode 3 an experiment was conducted at voltages between 200 and 260 volts to see if a stable operating point could be found. In this experiment the thruster was externally heated (using the resistive body heater) well beyond the temperature needed to maintain thruster operation with the magnet current already set to 0.75 amps. This value of magnet current was chosen as it was known to result in anode voltages in excess of 200 volts. After the thruster was sufficiently hot, the body heater was turned off. To encourage higher voltages, the anode current was then increased to 6 amps and the thruster characteristics were monitored. The results are presented in Figure 11.

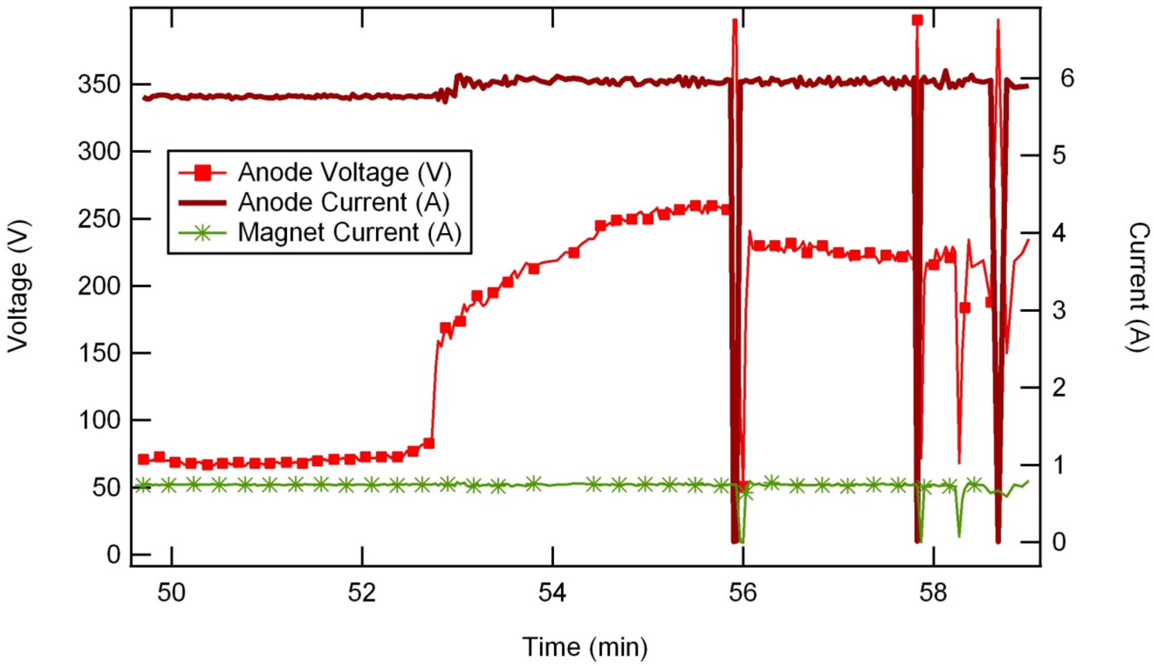

Figure 11. Results of attempting to stabilize the thruster at high voltage. First the thruster was heated using the resistive body heater (50-52.75). The body heater was then turned off, which caused the thruster to cool. Once the anode current was set to 6 amps the thruster was allowed to stabilize, only the magnets were adjusted and only to bring the thruster back on if it went out.

Figure 10 and Figure 11 show that the thruster achieved higher voltages with Anode 3 than with Anode 2. In total, with Anode 3, the thruster operated above 200 volts for five minutes at an anode current of 6 amps with 0.75 amps on the magnets. While the Anode 3 did allow for thruster operation for a longer duration of time at voltages above 200 volts than recorded previously, it was still unstable and went out several times during operation.

V. Conclusions/Future Work

It has been found that by implementing shim anodes a thruster operating on solid metal propellant has multiple stable operating points for an anode of a particular open area. Also, by using the shim anodes mass flow and temperature of the main anode can be increased or decreased, which allows for the stabilization of a thruster with increasing or decreasing mass flow and temperature. Having multiple operating points and the ability to stabilize thruster discharge allows for variation in discharge voltage and therefore I_{sp}. Experiments varying the open area of the anodes have demonstrated voltage as high as 341 volts. For reasonable acceleration efficiency this Mg thruster would be expected to have specific impulse greater than 4,000 sec. These experiments confirmed that by reducing the open area of the anode, the achievable discharge voltage is increased.

In the future, experiments will be performed using an open area between 2.77×10^{-4} m^2 and 6.93×10^{-5} m^2 in order to find an operating current lower than 6 amps that will operate at high voltage. These experiments will be coupled with a closed loop control system implementing the shim anodes. This is expected to enable temperature and mass flow control at the higher voltages available on the new anode, allowing for stable thruster operation at voltages greater than 300 volts for long durations.

V. References

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