Demonstration of an Automated Mass Flow Control System for Condensable Propellant Hall-effect Thrusters

Mark A. Hopkins[*] and Lyon B. King[†]
Michigan Technological University, Houghton, Michigan,49931

An automated mass flow control system for condensable propellant thrusters was demonstrated. The control system has the ability to arrest thermal runaway in a direct-evaporation feed system and stabilize the discharge current during voltage-limited operation of a magnesium-fueled Hall-effect thruster. The system supplemented plasma discharge heating at the evaporative anode with a resistive heater located behind the anode. Steady-state operation at constant voltage with discharge current variations less than 0.35 A was demonstrated for 60 minutes. A thrust of 44 mN was measured at a discharge voltage of 300 volts at 6 Amps, yielding a thrust-to-power of 24.4 mN/kW. A thrust of 50 mN was measured at a discharge voltage of 300 volts at 7 Amps, also yielding a thrust-to-power of 23.8 mN/kW. For a thruster operating at 2.1 kW, the steady-state supplemental heater power was 136 watts representing only 6% of the total system power.

Nomenclature

ε = difference between measured discharge current and discharge current set point
$I_{AnodeHeater}$ = anode heater current
K_c = proportional gain
T_d = derivative time
T_i = integral time

I. Introduction

STATE-of-the-art Hall thrusters operate using xenon gas as propellant because, of all the inert gases, it enables the most efficient operation. Inert gases, such as xenon, are easily delivered to the thruster using well-established gas feed technologies, making them the most convenient propellants for Hall thrusters. Condensable propellants, that is, propellants which are solid at ambient temperatures offer benefits over inert gases for certain missions. Because condensable propellants are solid at room temperature, they condense on the walls of the vacuum facility after being expelled from the thruster, and for this reason are often referred to as "self-pumping"; this reduces the need for expensive pumping systems – a cost benefit that becomes especially significant when developing high-power thrusters. Bismuth, zinc, and magnesium are three of the most practical condensable propellants, though others have been explored by Soviet researchers.[1] Bismuth, for example, has a lower ionization potential than xenon and has the highest atomic mass of the non-radioactive elements allowing for a higher achievable thrust-to-power than xenon. Zinc and magnesium also have lower ionization potentials that xenon, and their lower masses allow for a higher specific impulse than xenon at lower discharge voltages. Magnesium is a particularly promising Hall thruster propellant. It has a low molecular mass compared to xenon allowing for attainable specific impulses on the order of 4000 seconds at 300 volts discharge. Missions using magnesium as a fuel have the possibility of in-situ refueling as magnesium is found in both Martian and Lunar regolith.[2,3]

The biggest difference between condensable propellants and inert gas propellants is the mass flow control system. Inert gas propellants can be delivered to the thruster using well established gas feed technology. Condensable propellants are solid at ambient temperatures and must therefore be vaporized before being delivered to

[*] Doctoral Candidate, Mechanical Engineering-Engineering Mechanics, 815 R. L. Smith Building, Student.
[†] Ron and Elaine Starr Professor in Space Systems Engineering, Mechanical Engineering-Engineering Mechanics, 815 R. L. Smith Building, Member AIAA.

the thruster discharge chamber. The vapor mass flow rate must be controlled to enable efficient thruster performance and it is this control mechanism that comprises the most difficult subsystem of a condensable propellant thruster. Past experiments using condensable propellant Hall thrusters employed several different mass flow control systems. High-power bismuth Hall thrusters developed by TsNIIMASH in the 1960s-1980s used a propellant reservoir that was mechanically separated from the thruster head and delivered hot vapors to the thruster via heated propellant lines.[4] This propellant feed system was sufficient to allow for thruster operation but was not practical for a flight application. Because the supply lines were conductive the propellant reservoir and feed system could not be isolated from anode potential. In 2005 NASA researchers attempted to resurrect the TsNIIMASH thruster in the Very High Isp Thruster with Anode Layer (VHITAL) program.[5] As part of the program, a feed system was developed which used an electromagnetic pump to feed liquid bismuth into a porous carbon vaporizer.[6] This method was demonstrated by Polzin et al and was able to provide up to 6 mg/s of bismuth vapor, but the results were not reproducible and the mass flow control system was never integrated with a Hall thruster.

Massey and King studied an alternative flow control system that did not rely on a mechanically separate evaporator. In 2004 Massey et al[7] began work developing a 2-kW bismuth-fueled thruster which would be self-sustaining during operation; no additional power would be needed. In his experiments Massey developed an anode that acted as the propellant reservoir, gas distributor, and ion accelerator.[8-10] The anode was hollow with a porous face, such that liquid bismuth would reside in the anode while allowing the vapors to escape through the pores. The heat required for propellant vaporization was supplied directly from the thruster discharge due to Joule heating at the anode face from the plasma current, and so the method was aptly named the "direct evaporation method." Unfortunately, the temperatures needed for suitable bismuth evaporation strained the material limits of the thruster and the method proved unreliable for use with bismuth.[8] Magnesium and zinc, which both require much lower temperatures than bismuth to produce necessary vapor flow, proved to be ideal propellants for the direct evaporation method.[11] The experiments performed by Makela et al demonstrated the world's first Hall thruster operating on zinc, and the first operation of a Hall thruster on Magnesium since the end of Soviet research on condensable thrusters. Continuing the work started by Makela, Hopkins et al studied the relationship between anode design and thruster operation and eventually attained stable operation of the thruster and was able to measure performance.[12-14] While Hopkins was able to measure performance on a stable thruster, stabilization was achieved by actively adjusting the thruster magnetic field, and therefore the magnets were not properly tuned and stability was impossible to automate.

At the same time Makela was performing his experiments, researchers at Busek Co. were independently developing another mass flow control system for condensable propellant thrusters. By employing long wires of zinc and magnesium, Szabo et al,[15] were able to demonstrate a wire propellant feed/mass flow control system. Zinc and magnesium wires were fed into a heated vaporizer tube. This system was able to produce zinc flow rates of greater than 1 mg/s at ~40 watts heater power, and magnesium flow rates of 0.8 mg/s at 80 watts heater power.[15] No literature is available showing the system in use with an operating thruster.

The external feed systems developed by the VHITAL program and Szabo have many strengths. They allow for instantaneous mass flow rate control since the evaporation rate is fixed by an independently controlled electrical heater and thus flow rate is uncoupled from thruster operating conditions (unlike the direct evaporation method). However, neither of the external feed systems has been demonstrated to work with a thruster. The direct evaporation method of Massey has been demonstrated to produce a stable discharge with multiple Hall thruster propellants, but the propellant flow rate is coupled to the discharge conditions and is difficult to control. In particular, constant-voltage operation of a Hall thruster with a steady discharge current was never demonstrated with Massey's approach, and, instead, an unconventional constant-current mode was employed.

II. Goal of Study

The goal of this study is to demonstrate an automated mass flow control system that combines the best features of prior systems to enable stable constant-voltage operation of a Hall-effect thruster using magnesium as propellant. The method utilizes waste heat from the thruster discharge to minimize the amount of non-propulsive electrical power required to evaporate the propellant, while also largely uncoupling discharge conditions from mass flow rate and thus permitting constant-voltage operation of the thruster in the manner of conventional gas-fed HETs.

III. Experimental Design/Description of Apparatus

The mass flow control system used in the experiments presented here will utilize the waste heat of the thruster discharge, as done in the direct evaporation method, but will also include a supplemental heater located behind the anode to provide fine temperature control. The most critical component of the design is the anode. The anode must be hollow and able to store enough propellant for each test. Also, the anode open area, that is, the area through which vapors can flow through the porous face, must be chosen carefully. If the open area is too great then the ambient anode temperature during operation will cause excessive mass flow and constant voltage mode will be impossible (e.g. it is not possible to actively cool the anode). If the open area is too small then an excessive amount of supplemental heater power will be required to sufficiently increase the anode temperature over its ambient value to achieve the desired evaporation. Based on previous experiments,[12] a hollow anode with open area 14.8 x 10^{-6} m^2 was fabricated.

The thruster described here is a modified Aerojet BPT-2000 Hall-effect thruster. The magnetic circuit design has been preserved, but the boron nitride body has been modified to allow the addition of a resistive heater composed of tungsten wire, located behind the anode. Figure 1 shows a cross-section of the thruster highlighting the location of the anode heater. Figure 2 shows the modifications to the boron nitride body to house the anode heater. Because several amps of current must be applied to the anode heater, the tungsten is wire is wrapped with alternating coils to ensure that the heater does not induce an axial magnetic field.

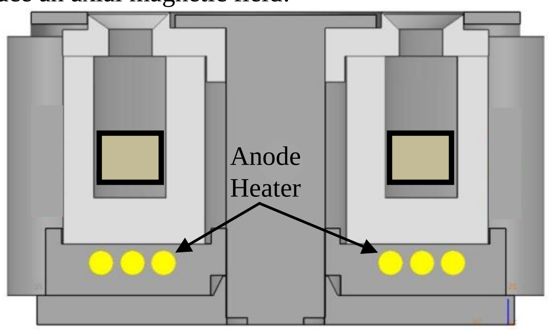

Figure 1. A cross-sectional view of the BPT-2000 Hall thruster is shown, highlighting the location of the anode heater.

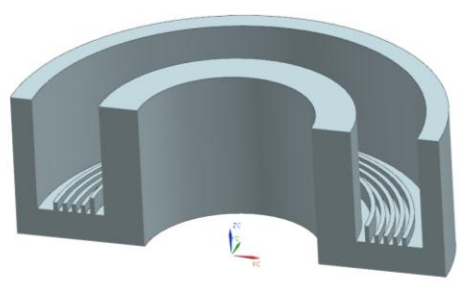

Figure 2.The boron nitride body with groves machined to allow for the addition of a tungsten heater behind the anode.

All experiments were performed using a laboratory LaB_6 hollow cathode operated using a 10-sccm flow of argon gas. The thrust stand used in the experiments was a NASA-Glenn style, inverted-pendulum, null-displacement thrust stand. The vacuum facility used was a 2-m-diameter by 4-m-long vacuum facility with a pumping speed of 6000 liters-per-second provided by three turbomolecular pumps.[9]

IV. Experimental Results and Discussion

For each of the experiments reported in the following sections the same testing procedure was followed. First the anode was preloaded with propellant, and the thruster assembled. The thruster was then mounted in the vacuum facility. Once at vacuum the thruster was pre-heated by passing 400-450 Watts to the supplemental anode heater. The anode potential was set to 300 volts when the heater was powered. After ~30 minutes the thruster ignites – usually in a current-limited mode with discharge voltage less than 300 V. The magnet current is then increased until the thruster switches to voltage-limited operation. During thruster operation, most, but not all, of the heat needed to vaporize the magnesium stored in the anode was provided by joule heating from the plasma discharge, i.e. the direct evaporation method; additional heat was provided by the anode heater to control the mass flow rate of the thruster.

A. Feasibility Test

In the pure direct evaporation mode of Massey, wherein all of the heat required for evaporation is supplied by plasma heating, there exists no stable operating point where mass flow would remain constant. If a perturbation caused a slight increase in mass flow rate (and thus discharge current) then the discharge power would increase. If the discharge power increases, the joule-heating of the anode would increase causing a temperature increase in the anode. The increase in temperature would then cause further increase in the mass flow rate. This increasing runaway effect will be referred to as “hot runaway.” If a perturbation is in the other direction and the mass flow rate decreased, then the discharge power would decrease. The decrease in discharge power would lead to a decrease in the joule-heating of the anode causing the anode temperature to drop. If the anode temperature drops then the mass flow rate would decrease again. This runaway decrease in mass flow rate will be referred to as “cold runaway.”

As described in section III the most critical component in the mass flow control system presented here is the open area of the anode. The open area of the anode dictates the temperature range at which sufficient propellant vapors can flow through the porous face. The supplemental anode heater easily arrests cold runaway since the heater power can always be increased to further heat the anode and deliver a corresponding increase in mass flow. In order to arrest hot runaway it is crucial that the anode is designed with an open area too small to provide adequate mass flow to the thruster when heated by the plasma discharge alone: some amount of supplemental heater power must be required for stable operation. In this fashion the supplemental heater can provide control authority to arrest hot runaway by decreasing the heater power.

The first experiments performed were to demonstrate the feasibility of using the anode heater to arrest both hot and cold runaway. For each of the experiments the discharge voltage was at a constant 300 volts and the current on the electromagnets was set at a constant 2.3 amps. Three experiments were performed to evaluate the ability of the anode heater to control the mass flow rate of the thruster. Experiment 1 demonstrated the ability of the anode heater to arrest hot runaway by lowering the power to the anode and reducing its temperature. Experiment 2 demonstrated the ability of the anode heater to arrest cold runaway by increasing the power to the anode and increasing its temperature. Experiment 3 demonstrates a manual bang-bang control system that demonstrates the ability to actively control mass flow by continually reversing the runaway conditions.

For Experiment 1, the thruster was already operating in voltage-limited mode at 300 volts and a constant electromagnet current of 2.3 Amps. Initially the discharge current was increasing – and along with it the total power to the anode – indicating that the total heat input to the anode was too high and the thruster was in a hot runaway mode. In an attempt to arrest the increasing discharge current and mass flow rate, the heater power was manually reduced from 450 watts to 280 watts at 0.5 minutes and then further reduced to 100 watts at 2.5 minutes. At 2.5 minutes the discharge current reached a maximum of 6.8 amps and began to decline, showing that hot runaway was arrested. The results of this experiment can be seen in Figure 3.

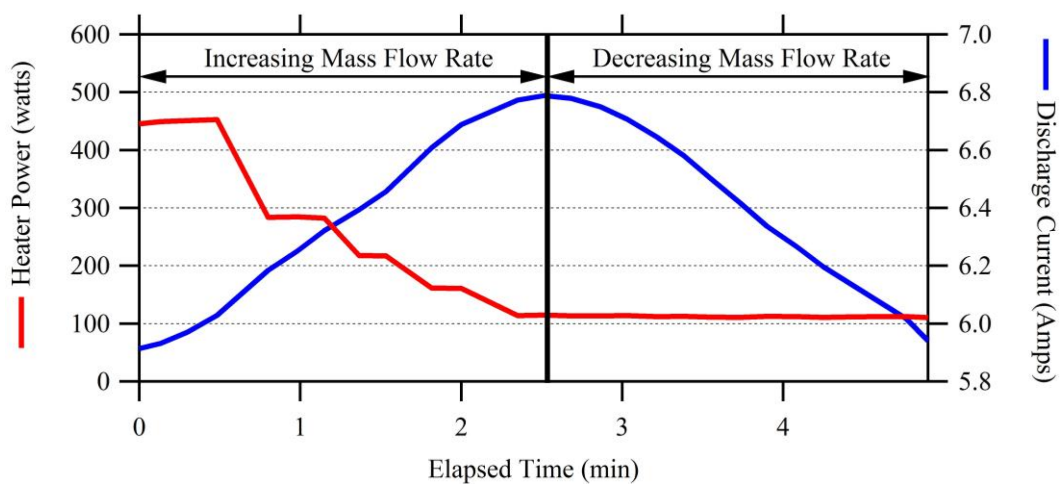

Figure 3. A graph of demonstrating the ability of the supplemental heater to arrest a hot runaway instability. Anode heater power is reduced at 0.5 minutes, cooling the anode and propellant. As the anode cools the discharge current eventually reaches a maximum of 6.8 amps at 2.5 minutes, and begins to decline. The discharge voltage was a constant 300 volts and the current on the electromagnets was a constant 2.3 Amps.

For Experiment 2, the discharge current and mass flow rate were initially decreasing, indicating that the thruster was in cold runaway. At 0.5 minutes the heater power was manually increased from 100 watts to 450 watts. The discharge current reached a minimum of 5.85 Amps at 0.8 minutes and began to increase indicating an increase in the mass flow rate. Figure 4 shows the results of Experiment 2 where cold runaway was successfully arrested.

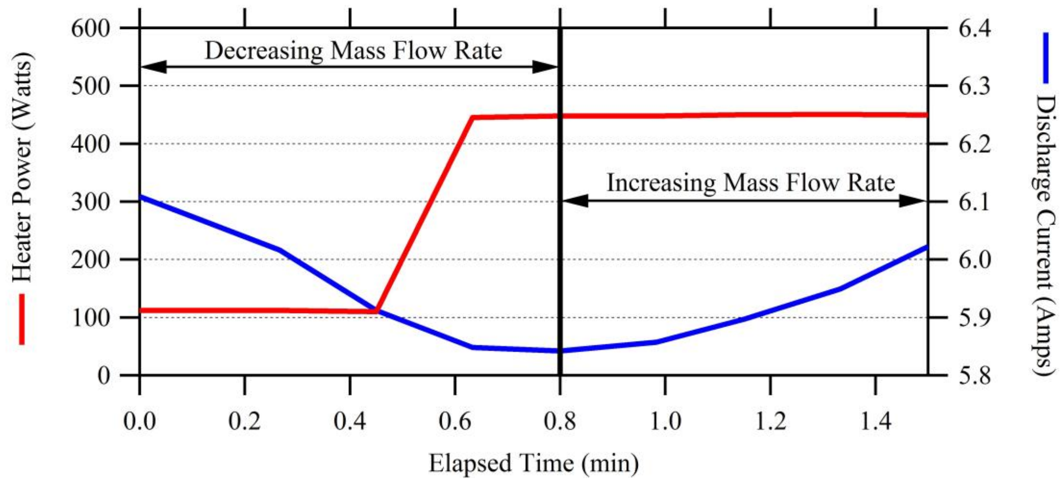

Figure 4. A graph demonstrating the ability of the anode heater to arrest a cold runaway condition. At 0 min the discharge current is decreasing, signaling a decreasing mass flow rate. At 0.5 minutes the anode heater power is manually increased to 450 watts. After the power to the anode heater increased the anode and propellant began heating as signified by the increasing discharge current and mass flow rate. The discharge voltage was constant at 300 volts and the current to the electromagnets was a constant 2.3 amps.

Experiment 1 and Experiment 2 demonstrated that the supplemental anode heater can be successfully used to prevent instability growth. Experiment 3 was an attempt to extend this concept and use the supplemental heater to actively control thruster mass flow (and thus current) to a desired value. To this end a manual "bang-bang" style control system was attempted wherein the thruster was alternately placed in hot and cold runaway. Results are shown in Figure 5. In the experiment, the discharge current was initially increasing, indicating hot runaway. As the discharge current increased past 6 Amps the power to the anode heater was reduced from 450 watts to 100 watts to cool the anode and decrease the propellant flow rate. As the anode cooled the discharge current decreased indicating cold runaway. As the discharge current dropped below 6 Amps, the power to the anode heater was increased to 450 watts to reheat the thruster and increase the mass flow rate and discharge current once more. This process was repeated to "stabilize" the discharge current to values within the vicinity of 6 Amps. After four cycles the power limits on the heater were adjusted to reduce the oscillation amplitude in the discharge current. The lower power limit was changed to 150 watts and the upper limit was changed to 350 watts. This successfully reduced the peak-to-peak amplitude of the current oscillations from ~1 Amp to less than 0.5 Amps.

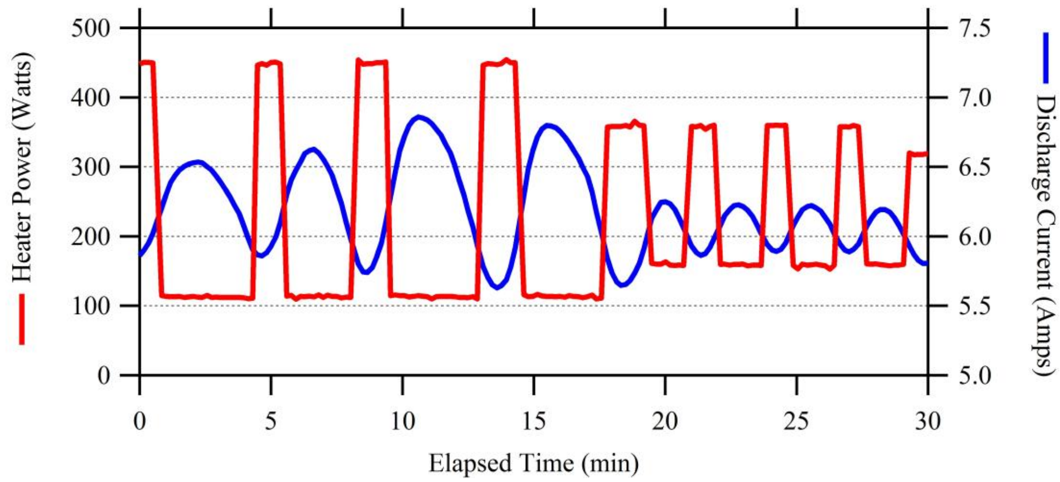

Figure 5. A graph demonstrating a crude manual bang-bang control system that alternatively places the thruster in hot and cold runaway. As the discharge current increases past 6 Amps the power to the anode heater is reduced. As the anode and subsequently the propellant cools the discharge current decreases. Once the discharge current falls below 6 Amps the power to the anode heater is increased, heating the propellant and increasing the mass flow rate. Decreasing the high power limit and increasing the lower power limit of the bang-bang scheme at 18 minutes reduced the amplitude of the current oscillations. The discharge voltage was constant at 300 volts and the current to the electromagnets was a constant 2.3 amps.

B. Automated Control Tests

The results of the manual bang-bang control system test showed that the anode heater could control the inherently unstable direct evaporation system, however the crude test permitted discharge current variations of 0.5 Amps. In order for the control system to be viable as a flight control system, the control process must be automated, so a simple software PID control system was developed which used the discharge current as the measured, or process, variable and the current supplied to the anode heater as the control variable. The PID control equation is shown below in equation (1) where $I_{AnodeHeater}$ is the current supplied to the anode heater, K_c is the proportional gain, T_i is the integral time, T_d is the derivative time, and ε is the difference between the desired discharge current set point and the measured discharge current.

$$I_{AnodeHeater} = K_c \times \left\{ \varepsilon + \frac{1}{T_i} \int \varepsilon dt + T_d \frac{d\varepsilon}{dt} \right\} \tag{1}$$

LabView software was used in conjunction with data acquisition hardware to measure and control the output of the power supplies controlling the thruster anode and anode heater. The program measured the discharge current of the thruster and used equation (1) to set the output current of the anode heater. This measurement and calculation occurred at a frequency of 1 Hz.

The PID loop was manually tuned. The proportional gain was determined through several guess-and-check experiments while the effect of changing the integral and derivative times is shown in Figure 6. The controller performance was evaluated by commanding step changes in the discharge current and monitoring the dynamic response of the system. For each set of gains the first set point was 6 Amps and then after several cycles the set point was commanded to 6.5 Amps and allowed to settle again. Once a few cycles occurred at the higher set point the PID gains were then changed and the set point was reduced to 6 Amps to start a new cycle. The results of the experiment showed that the lowest settling time was achieved with the second set of gains tested: $K_c = 10$, $T_i = 3.00\,\text{min}$, and $T_d = 0.01$.

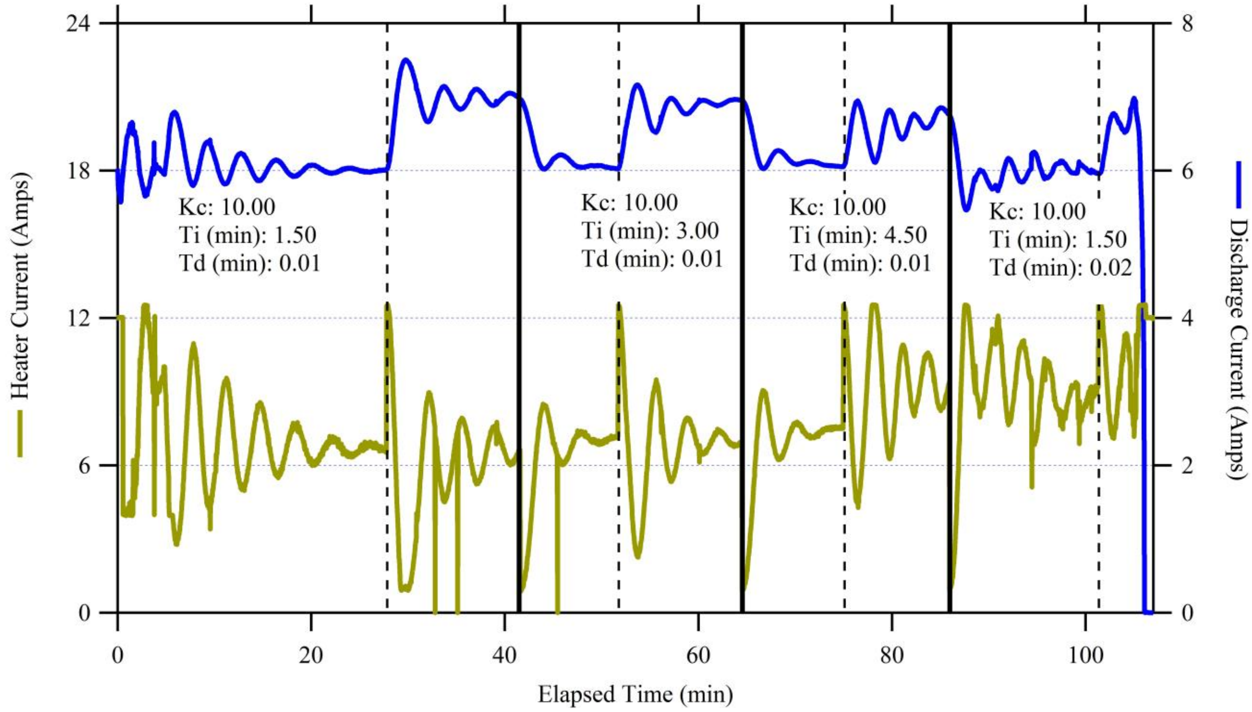

Figure 6. A graph illustrating the effect of PID gains on settling time. The set point for the discharge current is alternated between 6 Amps and 6.5 Amps. The vertical dashed lines in the graph indicate the times where the set point changed from 6 Amps to 6.5 Amps. The solid vertical lines occur at times where the set point was reduced from 6.5 Amps to 6 Amps. The PID gains were also changed at the time indicated by the solid vertical lines

Once the PID gains were chosen longer duration tests were performed to test the stability of the system. These tests were successful for discharge current set points below 7 Amps. At higher currents the oscillations in the discharge current were no longer damped with the gains as described above. This was rectified by one final change in the PID parameters. The derivative gain was increased by 600% to $T_d = 0.06$ forcing extra damping on the system. This extra damping eliminated the oscillations in the discharge current at all values of set point that were tested. Figure 7 shows the results of the experiment.

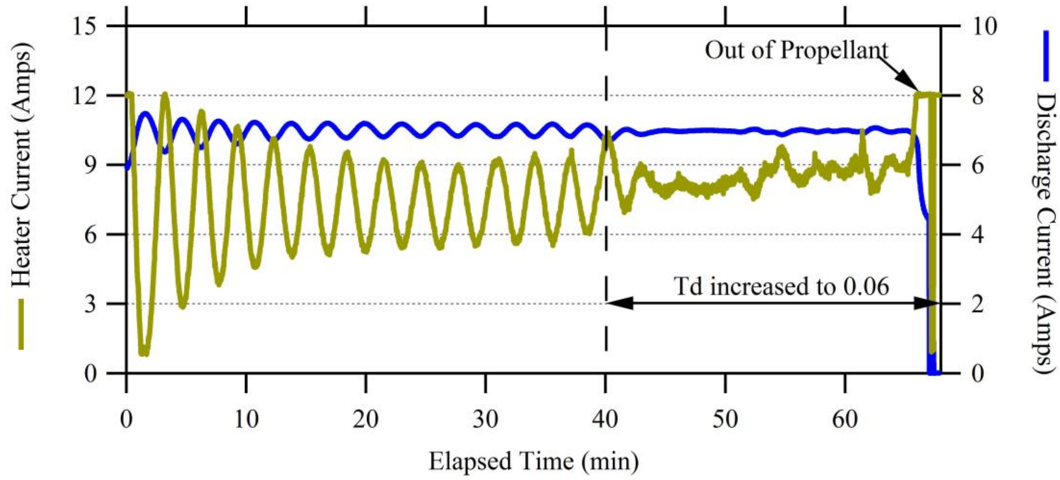

Figure 7. The results of a long-duration test with a discharge current set point of 7 Amps. For the first 40 minutes of the test the PID parameters were Kc = 10, Ti = 3.00, Td = 0.01. At 20 minutes, however, the oscillations in the discharge current reached steady state and were no longer damped. At 40 minutes the derivative time, Td, was increased to 0.06 minutes, at which point the current immediately settled on the set point.

To optimize HET performance at a given discharge voltage and mass flow it is necessary to tune the electromagnets such that the discharge current is minimized. In order to find the optimum magnet current, the discharge current was monitored as the current to the electromagnets was swept between 2.5 Amps and 2.1 Amps. Because the discharge conditions are slightly coupled to the mass flow rate of the thruster (e.g. changing discharge current will alter the total heat load to the anode) the PID control system was first turned off and the electromagnet current was swept quickly such that the thruster thermal response was negligible. The results of the test are plotted in Figure 8 and show that the optimum electromagnet current was 2.18 Amps.

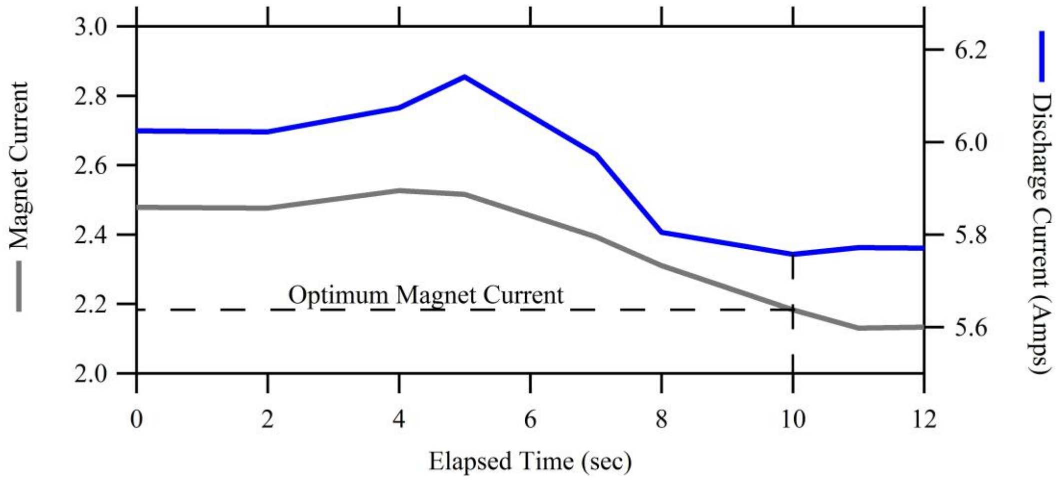

Figure 8. The electromagnet current was swept between 2.5 Amps and 2.1 Amps while recording the discharge current. The minimum discharge current occurred at 10 seconds, corresponding to an electromagnet current of 2.18 Amps. The discharge current was held at a constant 300 volts and the anode heater power was held at 130 watts.

C. Thrust Data

Thrust data were obtained using the automated PID control system during two tests: Test 1 and Test 2. The thrust stand was a NASA-Glenn style, inverted pendulum, null-displacement thrust stand. For Test 1, the thruster was operated at 300 volts discharge with a discharge current set point of 6 Amps. The data obtained from the test are plotted in Figure 9. The graph in Figure 9 shows the un-altered data from the experiment in its entirety. At 2 minutes into data collection the pre-heat was initiated. Unfortunately due to a malfunction in the anode heater power supply, the anode heater voltage was not recorded so only heater current data are available. The anode potential was set to 300 volts during the heating and the magnet current was varied between 0 and 0.8 Amps. After 25 minutes of heating the thruster ignited. The magnet current was then slowly increased to 2.15 Amps, driving the thruster into voltage-limited operation at 300 volts discharge. Once the thruster was voltage limited, at 27 minutes, the PID controller was turned on to a discharge current set point of 6 Amps and the thruster control was automated for the rest of the experiment. The results of Test 1 showed that the thruster produced ~44 mN of thrust after eliminating the linear thermal drift in the thrust measurement. This thrust measurement yields a thrust-to power of 24.4 mN/kW.

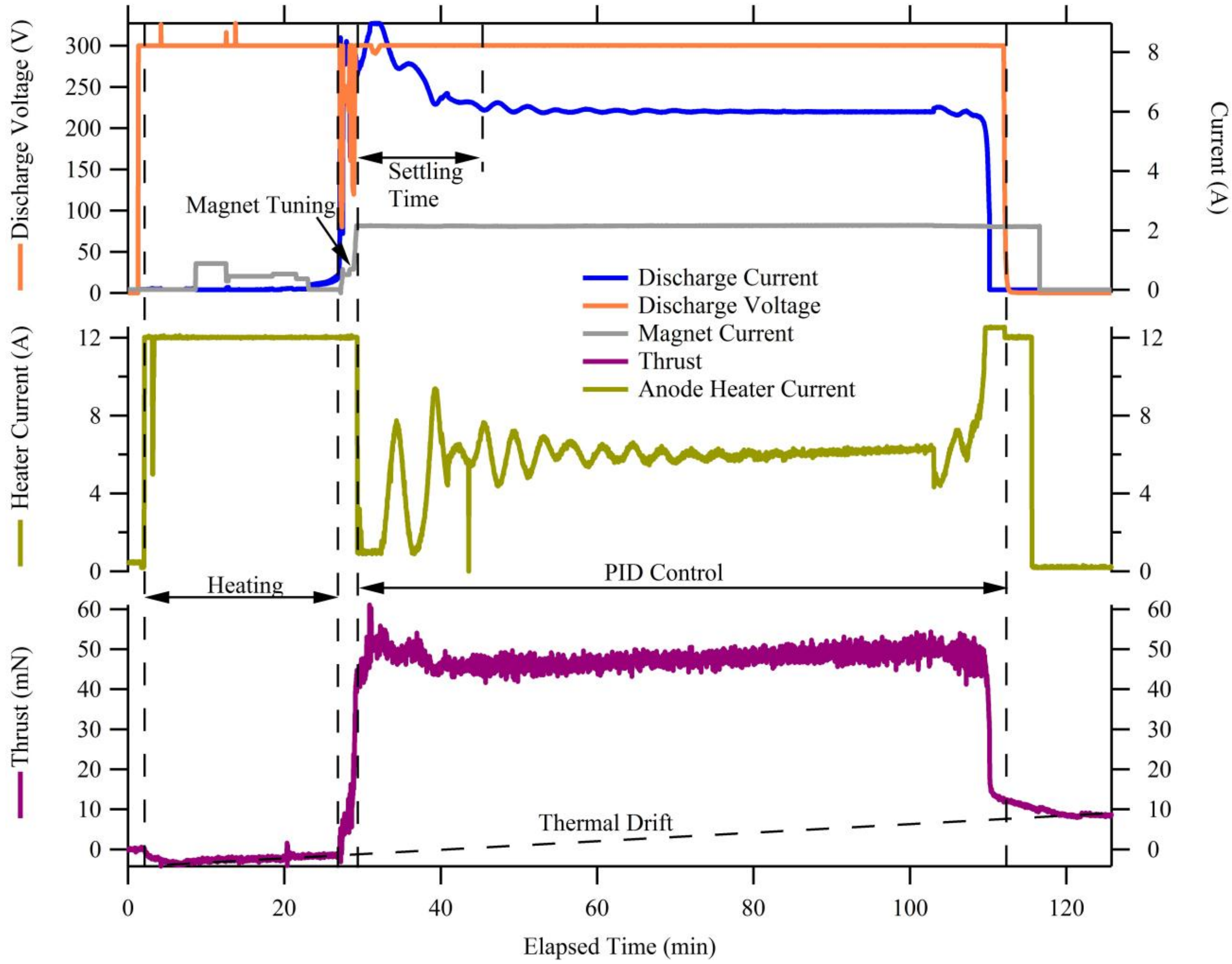

Figure 9. The results from Test 1. The thruster was first pre-heated for 25 minutes with the anode potential set to 300 volts. Once the discharge was established, the magnets were tuned and the PID loop was turned on at 27 minutes to a set point of 6 Amps. The discharge current settled within 15 minutes and thrust data were recorded for the duration of the test.

Test 2 was similar to Test 1. The thruster was again operated at 300 volts but at a discharge current set point of 7 Amps. The results of Test 2 are plotted in Figure 10 starting once the PID controller was engaged. Unlike Test 1, in Test 2 the power provided by the anode heater was known and recorded. Once the discharge current settled the power supplied by the anode heater oscillated near 136 watts; only ~6% of the total system power is used in the anode heater. Thrust data were also obtained. As with Test 1 there was a linear thermal drift in the thrust data. Accounting for the thermal drift yields ~50 mN of thrust and a corresponding thrust-to-power ratio of 23.8 mN/kW, which agrees well with the thrust-to-power of 24.4 mN/kW found in Test 1.

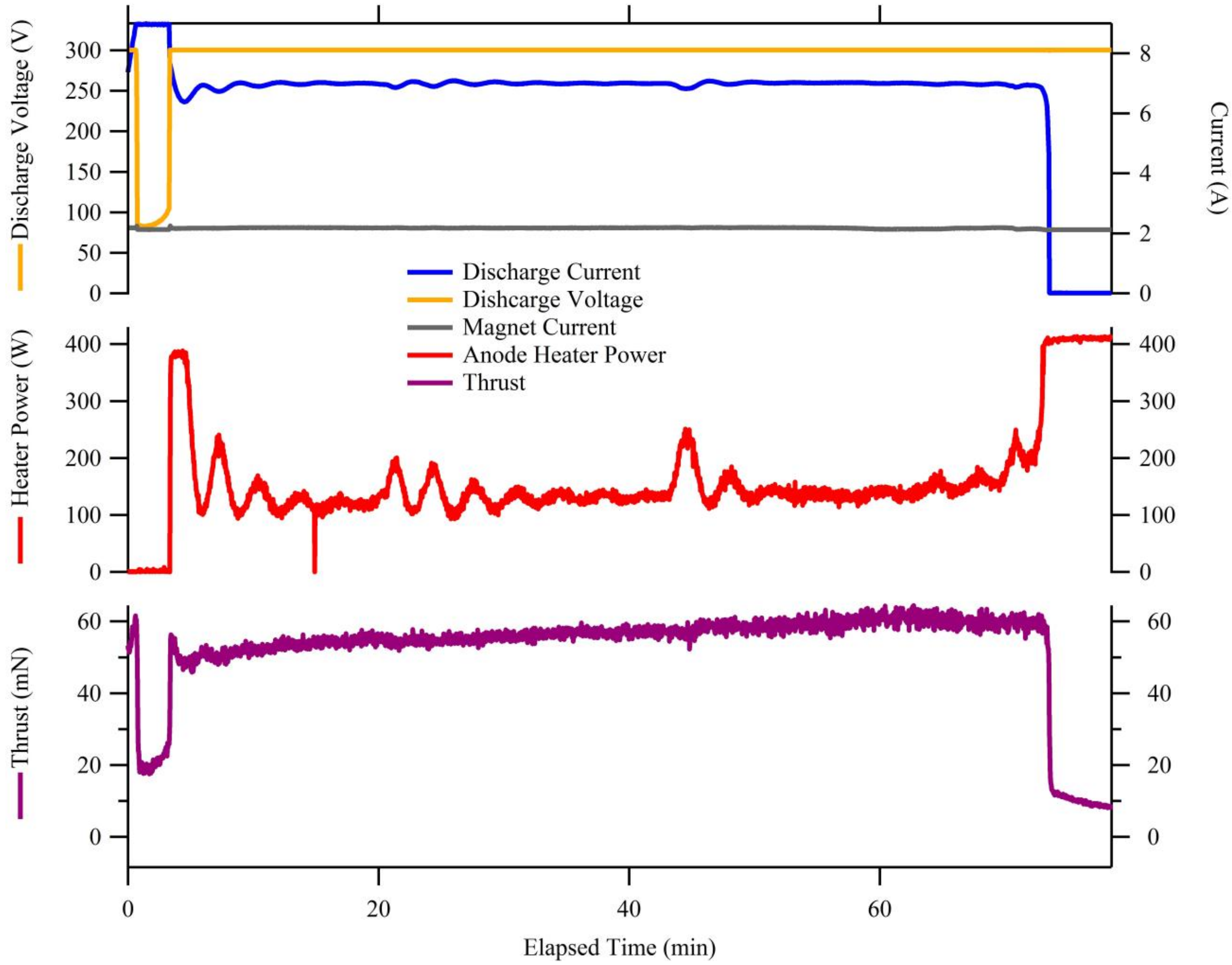

Figure 10. The results of Test 2. For the entire test the thruster was operated voltage limited except for a short period of current-limited operation at the beginning while the PID controller converged. As the discharge current approached the set point, the anode heater power settled near 100 watts, representing only 5% of the total power to the thruster. As with Test 1, there was a linear drift in the thrust data. Accounting for the drift yields a thrust of ~50 mN and a thrust-to-power of 23.8 mN.

V. Conclusion

By using the direct evaporation method supplemented with a heater located behind the anode, a thruster operating on magnesium propellant can be stably operated in constant-voltage mode. A PID control system was used to control the anode heater and automate the mass flow control system. It was found that during steady-state operation the anode heater only required 100 watts of power and so the mass flow control system only consumed 5% of the total system power. Multiple operating points were also demonstrated, and thrust data were obtained. With a discharge voltage of 300 volts and a discharge current of 6 Amps, the thrust-to-power ratio was 24.4 mN/kW at 44 mN of thrust. Increasing the discharge current to 7 Amps showed a thrust-to-power ratio of 23.8 mN/kW at 50 mN of thrust.

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