THERMAL MODELS FOR A 3 CM MINIATURE XENON ION THRUSTER

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ABSTRACT

Thermal Models for a 3 cm Miniature Xenon Ion Thruster

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In order to support UCLA's development of the 3 cm Miniature Xenon Ion (MiXI) thruster, Cal Poly has a 3 cm thruster under development. This version, called MiXI Cal Poly Version 1 (MiXI-CPv1), is complete and has been utilized in vacuum chamber thermal validation testing. Testing on this version was used to check the validity of heat transfer simulations modeled in SolidWorks. Investigations of the 3 cm ion thruster configuration were intended to discover the driving factors affecting the thermal behavior of the discharge chamber and surrounding design space.

Numerical simulations indicate that the heating of the samarium cobalt permanent magnets can be mitigated through the implementation of two proposed modifications. The first modification is to implement a 2% thoriated tungsten filament cathode. This design exhibited maximum permanent magnet temperatures of 325°C, twenty-five degrees below the maximum upper temperature of 350°C. Since some magnetic degaussing effects have been observed at temperatures above 300°C, the aforementioned solution can be combined with a thruster design modification to achieve a reduced permanent magnet temperature of 298°C. This modification would involve increase the anode wall thickness from approximately 0.7 mm to 2 mm below the permanent magnet ring, creating a stepped anode design. Additionally, less effective solutions were proposed and modeled and are presented for completeness.

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Chapter I: Introduction

There is an increasing need in satellite missions for thrusters that are efficient, have a high specific impulse, and deliver thrusts on the order of milli-Newtons (mN). The electric propulsion (EP) class of thrusters can produce high specific impulses, more than 3000 seconds, versus solid rocket propellants (approximately 250 seconds) and liquid bipropellants (up to 450 seconds). A specific subset of electric propulsion, micro ion thrusters, is capable of delivering continuous, low thruster, high efficiency, and precision spacecraft control. These thrusters have applications for a variety of missions. Some spacecraft could use them for self-disposal maneuvers. Their high specific impulse also makes this class of thrusters attractive for interplanetary travel. In addition, due to size and mass constraints, microsatellites can use these thrusters as a primary propulsion source.

In addition to the aforementioned applications, one of the most intriguing uses of low thrust, high specific impulse thrusters is for constellation formation maneuvers and precision spacecraft placement. Earth and space-based science missions using precision formation flying will utilize high precision interferometer metrology gauges with nanometer resolutions. These gauges will fill in data previously unavailable between existing fine and course sensor readings using Modulation Sideband Technology for Absolute Ranging (MSTAR). MSTAR will increase the accuracy of space-based ranging technology by four orders of magnitude.¹

Ion Thruster Principles

Ion thrusters represent a form of electrostatic propulsion, meaning that a beam of positive ions from a propellant are accelerated by the direct application of electric body forces.² Figure 1 shows the typical operation of an ion thruster. Neutral propellant gas atoms (commonly xenon) are bombarded by electrons with enough energy to knock off or release an electron from the valence shell, thus ionizing the atom. The electrons are provided by an electron source, a cathode. A magnetic field is used to confine the electrons, prevent the loss of ions and electrons to the anode surface and allow a significant fraction of ions to preferentially migrate to the grids for extraction to beam.² The magnets are arranged so that the magnetic field lines primarily terminate at the grids and cathode or at cusps on the anode surfaces. Magnetic cusps are placed at anode surfaces to allow lower energy electrons to be lost along the field lines to carry the discharge current and maintain discharge stability. Since thruster performance is determined primarily by plasma confinement efficiency and discharge stability, optimal magnetic field topography is essential. Once confined these ions diffuse (or migrate) towards the screen grid at the exit of the discharge chamber and are then accelerated by the electric field established between the plasma generator and space ground. The accelerator grid is used to prevent electron backstreaming into the discharge chamber and neutral losses from the discharge chamber. The voltage applied between the discharge plasma (beam) and space ground potential (0 V) determines the final velocity of the ions. Once these ions are accelerated, a neutralizer cathode positioned outside of the discharge chamber of the thruster, provides electrons at the same rate as the extracted ions to prevent the spacecraft from becoming negatively charged.^{3, 4, 5}

Figure 1. An overview of ion thruster operations and geometry.⁶

The Miniature Xenon Ion Thruster

Current flight qualified propulsion technologies are not capable of delivering the precision necessary for the above mentioned science missions without requiring a high cost (measured in mass, power, propellant, etc.) to the satellite. This led to the development of the Miniature Xenon Ion (MiXI) thruster under the direction of Dr. Richard Wirz.^{7,8} MiXI is capable of delivering less than 0.1 mN to over 1.5 mN of thrust with efficiencies of greater than or equal to 50% with a specific impulse between 2500 - 3500 seconds. The low thrust levels of the MiXI allows for very precise position of spacecraft relative to each other within a satellite fleet. In addition, these low thrust levels make MiXI an attractive option for precision orbit control of medium sized spacecraft (approx. 100 - 1000 kg).⁸ For large spacecraft (>10,000 kg), MiXI could also be considered for attitude control. In addition, pico-satellites could use MiXI as a primary

propulsion source for orbit raising, control and disposal. Other possible uses for MiXI would be as the primary propulsion source for a scaled-down asteroid rendezvous mission or to provide a continuous thrust “artificial gravity” for an inspection and repair robot for a very large spacecraft.⁸ With MiXI delivering a high specific impulse, there is a significant mass savings to the satellite due to a lowering in the necessary propellant for a given mission. In addition, each MiXI requires less than 50 watts of power. For comparison, NSTAR (NASA Solar Technology Application Readiness), NASA’s 30 cm ion thruster requires up to 1.94 kW of power. This decrease in required propellant and power allows for less of the satellite design space to be consumed by the main propulsion and its necessary support systems. For missions that require lower thrust ion propulsion, a miniature ion thruster system will reduce thruster system volume and mass, thus allowing for an increase in payload, a huge advantage in science instrumentation based satellites. The MiXI thruster uses xenon, a non-reactive, inert, low contamination propellant. This reduces the contamination risks to the satellites systems, making MiXI attractive to missions that will use sensitive optical lenses and equipment. Finally, the small size of the MiXI thruster (3 centimeter diameter) allows for a greater flexibility in thruster placement and has low beam divergence to reduce concerns of thruster plume impingement on spacecraft surfaces.^{1,7}

MiXI Mission Candidates

Prior to MiXI’s development, there was a technology gap in low noise, low contamination thrusters operating between 0.01 and 1.0 mN of thrust. MiXI’s unique thrust range makes it an ideal candidate for precision formation flying, precision repeat path orbit control, and continuous, low disturbance, solar torque compensation. With this

in mind, the following paragraphs provide brief descriptions of some potential mission candidates for the MiXI thruster.⁷

TPF-Emma

The Terrestrial Planet Finder (TPF) is a space interferometer mission concept that is currently being studied by NASA. TPF would study numerous aspects of exoplanets from their formation and development in disks of dust and gas around nearly formed stars to their suitability for sustaining life.⁹ The Emma design of TPF has five separate spacecraft flying in formation: Four telescope spacecraft and a beam-combiner spacecraft form the interferometer.¹⁰ These spacecraft must maintain one centimeter accuracy in their formation while being spaced apart as far as 1200 meters.⁷ This formation is shown in Figure 2. The thrusters for this mission must be able to provide 3-axis attitude control and translation, exhibit minimum plume interaction with the spacecraft, and have minimum contamination of scientific instruments. In addition, the thruster must be able to operate in the milli-Newton and micro-Newton ranges, cause minimal spacecraft vibration, perform all mission functions if one thruster is lost.¹⁰ Four thruster pods on each spacecraft with each pod containing five MiXI thrusters can meet these requirements.⁷

Figure 2. An artist's rendition of the TPF-Emma design consisting of a five spacecraft formation.⁷

GRACE Follow On

The Gravity Recovery and Control Experiment (GRACE) is a formation consisting of two satellites that take detailed measurements of Earth's gravity field in an effort to make discoveries about gravity and Earth's natural systems.¹¹ This spacecraft formation is shown in Figure 3. In their current configuration the two spacecraft are allowed to drift naturally. Their position is measured by GPS and the drift between the spacecraft is used to determine changes in gravity. The proposed GRACE Follow On (GFO) formation could execute precision repeat orbit paths using the MiXI thruster to compensate for atmospheric drag.⁷

Figure 3. A representation of the GRACE twin spacecraft formation.¹¹

CubeSat

CubeSat has become the picosatellite standard for lower cost and quicker access time to space technology development. Early picosatellite development highlighted the need for a consistent and safe method of deployment. The response to this need was a collaborative development between Cal Poly and Stanford University of the Poly-Picosatellite Orbital Deployer (P-POD) in 1999. Since that time, Cal Poly's CubeSat program has been on the forefront of picosatellite development. A standard CubeSat is 10 cm cube weighing no more than 1 kg.¹² A Cal Poly CubeSat is shown in Figure 4.

Figure 4. A photograph of CP1, Cal Poly's first CubeSat.¹²

Once launched, CubeSats orbit naturally without performing orbit maneuvers or deorbiting. This is because they do not have a means of propulsion onboard. As single CubeSat with body mounted solar panels cannot supply the necessary power to operate a MiXI thruster. However, a combination of three CubeSats, known as a 3U, could provide more power. This is because a 3U can utilize deployable micro-satellite solar panels and more advance power processing units, like the ones developed by Clyde Space.¹³ Some 3U configurations are capable of producing between 50 and 60 W of power¹⁴, more than the 43 required for MiXI making the thruster a viable option for CubeSat propulsion. Figure 5 shows CubeSat 3U solar panels from Clyde Space.

Figure 5. A photograph of a 3U solar panel by Clyde Space.¹³

MiXI Thruster Versions

MiXI has undergone numerous design changes over the years in an effort to optimize the thruster. This section is intended to provide a brief overview of each MiXI version and highlight the differences between each thruster.

Micro Ion Thruster

The Micro Ion thruster was the first 3 cm thruster that was developed by Dr. Wirz.^{15,16,17,18} This version of the thruster was the first working test model of the MiXI design series. Key design features of this version included outwardly flanged

anodes and a threaded rod system supporting the grids. The Micro Ion thruster is shown in Figure 6. This thruster implemented a plethora of different anode length-to-diameter (L/D) ratios and magnet configuration combinations.⁸

Figure 6. A picture of the 3 cm Micro Ion thruster developed by Dr. Wirz.⁸

MiXI & MiXI-II

The development of the 3 cm Miniature Xenon Ion (MiXI) thruster represented a huge leap forward in the optimization of this thruster series. MiXI is a much more compact and lightweight thruster than its Micro Ion predecessor, with the thruster head weighing only 200 grams (with magnets). These versions built on lessons learned from the performance and testing of the Micro Ion thruster. With that in mind, MiXI has an anode L/D of 1 and utilizes a ring cusp magnetic geometry. The thruster represents a “flight-like” configuration, but was designed to accommodate various discharge cathodes, grids, and neutralizer cathodes. This version is shown in Figure 7.⁸

MiXI-II was a built by Caltech students to experimentally analyze the behavior of thruster beamlets for MiXI grids over a wide range of operating conditions, including

wide variations in discharge plasma density and extraction voltage. MiXI-II was similar to the original MiXI thruster, but was built on a very small budget. Therefore, many of the important design features of the original thruster could not be copied. Most importantly, MiXI-II's magnetic field configuration is different from that of the original MiXI thruster. Ultimately, the MiXI-II thruster performed well as a test bed for grid performance analyses, but did not achieve the impressive discharge performance and thermal performance of the original MiXI thruster.¹⁶

Figure 7. A picture of the MiXI thruster.⁸

MIXI-CPv1

Once the collaboration between Cal Poly and UCLA was formed, it became clear that Cal Poly would require its own version of a 3 cm thruster. As a result, the MiXI Cal Poly Version 1 (MIXI-CPv1) was fabricated. This version was mostly patterned after Dr. Wirz's Micro Ion thruster. The idea behind the MIXI-CPv1 design was to create a 3 cm

ion thruster that would allow for rapid assembly and disassembly to begin testing in Cal Poly facilities. Since the basis of this thesis is thermal testing and modeling, easy thermocouple access to critical locations was an absolute necessity. Modularity was also a primary focus in the MIXI-CPv1's design. The base of the thruster was selected to accommodate nearly any discharge cathode. The subsequent paragraphs detail the design and fabrication of each component. A fully assembled MIXI-CPv1 is shown in Figure 8 .

Figure 8. A picture of Cal Poly's Micro Ion Thruster (MIXI-CPv1) fully assembled.

The base of MIXI-CPv1 is a 2 ¾ inch standard ConFlat flange. This component was chosen because it is easy to integrate with the thruster stand and is made of stainless steel, a standard vacuum rated material. A SolidWorks model of the thruster base is shown in Figure 9.

Figure 9. A solid model of the MIXI-CPv1 thruster base.

The selection of a ConFlat flange as the thruster base drove the design of the anode. The anode is made of stainless steel and has a discharge chamber diameter and length of 30 mm. The anode flange is design to accommodate the six ConFlat bolt pattern coming from the thruster base and is 8 mm thick. In addition, the anode flange has four through holes on its edge for integration with the outer shell mounting structure. A solid model of the anode is shown in Figure 10.

Figure 10. A solid model of the MIXI-CPv1 anode.

The cathode mounting plate was designed to fit inside of the discharge chamber while simultaneously integrating with the thruster base. This plate is made out of a disc of stainless steel and has a press-fitted 1/8 inch stainless steel fuel pipe inserted in it. In addition a 3 inch piece of 1/8 inch diameter double bore alumina, used for separating the cathode leads, is ceramic cemented into the center of the plate. An additional hole opposite the fuel pipe entry was made to accommodate a thermocouple. This hole is threaded and nominally sealed with a screw if no thermocouple is used during the test. The entire fuel and cathode mount assembly is shown in Figure 11.

Figure 11. A solid model of the cathode and fuel mount assembly.

The outer shell mounting piece was design to interface with the anode flange and the cap piece and provide consistent, level spacing between the grids and the discharge chamber. The outer shell is made of aluminum and has eight evenly space tapped holes to integrate the cap piece and anode with screws. The outer shell is the piece that joins the

grid assembly with the discharge chamber and base of the thruster. This component is shown in Figure 12.

Figure 12. A solid model of the outer shell mounting piece.

The cap piece was designed to accommodate the MACOR grid mount and create proper component spacing and fastener clearance. The cap piece is made of stainless steel and has an eight hole pattern that mimics the hole pattern of the molybdenum grids. Each hole is counter sunk to integrate the MACOR shoulder washers and grid screws. The cap piece is shown in Figure 13.

Figure 13. A solid model of the MIXI-CPv1 cap piece.

The MACOR shoulder washers were designed to isolate the grid mounting screws from the cap piece and hence the discharge chamber. The shoulder washers were designed to two different lengths to accommodate different grid mounting screws. These washers are shown in Figure 14.

Figure 14. A solid model of a MIXI-CPv1 MACOR shoulder washer.

The MACOR grid mount was designed to isolate the thruster grids from the cap piece and discharge chamber. The grid mount has a shelf that fits snugly to the anode and has an eight hole pattern to match the grid hole pattern. This component is shown in Figure 15.

Figure 15. A solid model of a MIXI-CPv1 MACOR grid mount.

An exploded view of all of the MIXI-CPv1 components is shown in Figure 16.

Figure 16. A solid model of an exploded view of MIXI-CPv1 with all of its components.

MiXI CP

The latest version of the thruster is MiXI Cal Poly (MiXI CP). At the time this thesis was written, this version of the thruster was entering the preliminary fabrication phase. This version is not the primary focus of this thesis but is mentioned because its design is based on the results of this investigation. The purpose of MiXI CP is to provide Cal Poly with an optimized version of the 3 cm thruster. While MIXI-CPv1 served as an excellent initial test bed, it is not an optimal design for a flight worthy thruster. MiXI CP will combine the optimal nature of MiXI with the lessons learned in this thesis about

thermal design to create a reliable, streamlined thruster. Thermal design suggestions for this thruster are discussed in Chapters II and IV.

Motivation

The motivation for writing this thesis is to investigate thermal challenges at the MiXI scale and to explore some possible solutions to these issues. MiXI I did not experience any thermal complications. MiXI II however, has had some thermal issues. It is crucial to understand the design space of MiXI I and II and the factors that can cause undesirable operating temperatures in a thruster of this scale. The motivation of my work is to better understand the thermal properties of MiXI to ensure consistent thermal design and integration with spacecraft systems. To that effect, the thrusters built at Cal Poly were patterned after MiXI and redesigned but only in the context of better understanding thermal phenomena in micro ion propulsion. All design modifications are intended to isolate the analysis of particular thermal issues and are not baseline changes to the MiXI thruster.

Chapter II: Thermal Testing

In order to establish a baseline understanding of the effects of cathode radiation on thruster temperatures, thermal validation testing was performed. The following sections describe the facilities and apparatus associated with these tests as well as the results for the validation testing performed on MIXI-CPv1. Full procedures are available in Appendix A.

Experimental Facilities

Thermal validation testing was conducted at two separate facilities on the Cal Poly campus: Aerospace Laboratory 137 and CubeSat's thermal vacuum chamber facilities. Aero Lab 137 is dedicated to the study aerothermodynamics, space environments, thermal control, and electric propulsion. This is the primary facility at which testing for MIXI-CPv1 is and MiXI CP will be conducted. This lab has at its disposal one 30" HVEC bell jar vacuum chamber, one Veeco VE 747 vacuum evaporator bell jar chamber and two 18" LACO Technologies stainless top-loading vacuum chambers. Currently the HVEC bell jar chamber is designated for MiXI testing with the two LACO Technologies chambers dedicated to undergraduate lab experiences. The Veeco VE 747 vacuum evaporator will be designated for additional electric propulsion and thermal testing once refurbishment is complete. The HVEC vacuum chamber in Aero Lab 137 is shown in Figure 17 below.

Figure 17. A front view of the HVEC 30" bell jar vacuum chamber in Aero Lab 137.

During a period of maintenance in Lab 137, Cal Poly's CubeSat program made their thermal vacuum chamber facilities available for MIXI-CPv1 testing. This facility consists of a 30" diameter, front-loading vacuum chamber inside of a clean room. Since this experimental setup does not have fuel feedthroughs all testing conducted in this chamber was with the cathode running only. Temperatures were collected pertaining to the radiation heating from the cathode with no plasma being created and no beam being pulled. This was an acceptable result, however, since it was necessary to validate the radiation portion of the model separately from the plasma heating. The CubeSat thermal vacuum chamber is shown in Figure 18 below.

Figure 18. A front view of the 30" thermal vacuum chamber operated by CubeSat.

Lab 137 Apparatus

The subsequent paragraphs detail the apparatus associated with the operation of the Aero Lab 137 HVEC 30" bell jar vacuum chamber. The vacuum chamber currently has a base pressure of 2.1×10^{-5} torr. It is believed that with minor changes to the numerous feedthroughs around the baseplate this chamber can reach the 10^{-6} torr range however, a vacuum rating of 3.5×10^{-5} torr is sufficient for thruster testing based on previous MiXI testing. Modifications are in progress to reach the full potential of this chamber. A schematic of this vacuum system and an operational timeline are shown in Figure 19 and Figure 20, respectively. Complete experimental procedures for operating this system can be found in Appendix A.

Figure 19. A schematic showing the operational components of the HVEC bell jar vacuum chamber.¹⁹

Figure 20. The timeline used during the operation of the HVEC vacuum chamber.¹⁹

Roughing Pump

A Welch 1397B mechanical pump is used to pump the vacuum chamber and cryopump down to their respective operating pressures. This pump is capable of pulling vacuum in the 10^{-4} torr range however, a pressure of 50 microns is sufficient for cryopump operation. This pump is also used when servicing the compressor and is shown in Figure 21 below.

Figure 21. A photograph of a Welch 1397 DUOSEAL belt-drive two stage high vacuum pump used to pull low vacuum in the HVEC chamber.

Cryopump

A CTI Cryogenics CryoTorr 8" model cryopump pulls the vacuum chamber down to the high vacuum range. Cryopumps use a two technique capture process to reduce chamber pressure. The first technique is called cryoadsorption and it captures helium and neon molecules by trapping them on a charcoal absorbing array. Cryoadsorption is the process of cooling gases to the point that they lose sufficient energy and accumulate on a surface. The second technique is called cryocondensation and it captures air gases and water vapor in condensing arrays. Cryocondensation is the process of cooling gases to the

point that they condense and freeze on a surface. The CryoTorr 8 uses the Model SC helium compressor to turn the cold head and reduce the temperature in the cryopump. High vacuum operations can commence once the temperature indicator reads 20 K or below. Once the cryopump is ready for operation, the chamber must be pumped down to the crossover pressure.

Compressor

A CTI Cryogenics Model SC helium compressor is used to operate the cryopump cold head. This compressor is air cooled and requires 208/230 V, 60 Hz, 3 phase power. It is charged with 99.999% pure helium to 250 psig static and has a running pressure of 285 psig.²⁰ This compressor is shown in Figure 22 below.

Figure 22. A photograph of CTI Cryogenics Model SC helium cryopump compressor.

Fuel Flow

The rate at which thruster propellant, either argon or xenon, flows into the chamber is controlled with an Aalborg 171 mass flow meter. Fuel flows from the propellant tank, through a needle valve and flow meter, into a high vacuum fuel feedthrough and a fuel isolator before being connected to the thruster fuel pipe. The fuel isolator ensures that the propellant is not charged prior to being injected into the discharge chamber. Figure 23 shows the fuel isolator and flow meter with the needle valve.

Figure 23. Photographs a) of the fuel isolator and b) Aalborg flow meter for the HVEC chamber.

Monitoring Equipment

The temperature inside the cryopump is monitored using a CTI temperature indicator. This indicator can observe temperature ranging from 10 – 320 K. The pressure inside of the vacuum chamber and cryopump is monitored with the Convector gauge function of a Granville-Phillips 316 vacuum gauge controller. This gauge can observe chamber pressure until the 10^{-4} vacuum range is reached. The temperature indicator and 316 vacuum gauge controller are shown in Figure 24 and Figure 25, respectively. Once the

10^{-4} Torr vacuum range is reached, the pressure is monitored using a Granville-Phillips ionization gauge and a 307 vacuum gauge controller. The ion gauge and 307 vacuum gauge controller are shown in Figure 26 and Figure 27 respectively.

Figure 24. A photograph of a CTI Cryogenics temperature indicator reading the cryopump temperature while in operation.

Figure 25. A Granville-Phillips 316 vacuum gauge controller showing readings of the cryopump pressure on Convectron Gauge 2 (CG2) and chamber pressure on Convectron Gauge 3 (CG3).

Figure 26. A photograph of a Granville-Phillips ionization gauge used in conjunction with a Granville-Phillips 307 vacuum gauge.

Figure 27. A photograph of a Granville-Phillips 307 vacuum gauge controller reading chamber pressure with an ionization gauge.

Power Supplies

The beam supply used when running thruster tests will be a Glassman Series FC high voltage power supply, operating in the range of up to 1000 V and 120 mA. The discharge supply is a GW Model 30H10D laboratory DC power supply, capable of operating at 300 V and 1 A. The cathode heater supply used with the coiled tungsten filament cathodes is an EXTECH 382202 DC power supply operating at 18 V and 3 A. The Glassman supply is shown in Figure 28. The GW and EXTECH supplies are shown in Figure 29.

Figure 28. A photograph of a Glassman FC Series high voltage power supply used as the beam supply source.

Figure 29. A photograph of a GW power source used as a discharge supply and EXTECH power source used as a cathode heater supply.

CubeSat Apparatus

The subsequent paragraphs detail the apparatus associated with the operation of the CubeSat thermal vacuum chamber. This vacuum chamber is currently capable of sustaining a vacuum rating of 5.0×10^{-4} torr. This system is incapable of providing fuel directly to the thruster inlets; however, fuel can be provided by flooding the chamber through a valve. The power supplies, fuel flow and monitoring equipment are the same as those used in Lab 137. Figure 30 below shows the control panel for the CubeSat thermal vacuum chamber.

Figure 30. A photograph of the control panel for the CubeSat thermal vacuum chamber.

Roughing Pump

The CubeSat thermal vacuum chamber is roughed down to low vacuum using a Leeson B Series mechanical pump. Its performance characteristics are identical to the previously mentioned Welch 1397B mechanical pump. The Leeson pump is shown in Figure 31 below.

Figure 31. A photograph of a Leeson B Series mechanical pump used for roughing the CubeSat chamber.

Diffusion Pump

The CubeSat thermal vacuum chamber is pumped down to high vacuum using a Varian VHS-4 Series diffusion pump. Diffusion pumps are type of fluid entrapment pump. A heater sits just below a reservoir of oil. Oil vapors then rise up the center of the pump exciting a nozzle near the inlet. Any air molecules that contact the oil vapors are captured. Once the oil vapors make contact with the cooled walls of the diffusion pump they move downward towards the reservoir, releasing the trapped air molecules into an outlet as they go. Upon reaching the reservoir, the oil has been completely cooled and the process repeats itself.³⁶²¹ This pump is separated from the chamber by a gate valve and can pump down to 10^{-4} range. Figure 32 below show the Varian diffusion pump.

Figure 32. A photograph of a Varian VHS-4 Series diffusion pump used to pull high vacuum in the CubeSat vacuum chamber.

LN₂ System

The CubeSat shroud and diffusion pump use Varian 362-4 LN₂ cold trap to run thermal and high vacuum operations. The CubeSat LN₂ tank is shown in Figure 33 below.

Figure 33. A photograph of the CubeSat liquid nitrogen tank during shroud operation.

Experimental Setup

To conduct even the most basic testing on MIXI-CPv1, the thruster must have a stable, accessible, and isolated base as well as mounting and isolation structures for the cathode. The subsequent paragraphs describe this apparatus.

Thruster Stand

During testing the thruster is placed in a stand that consists of a 1 ¼ inch 304 stainless steel piping T-joint. While this is a simplistic choice for a test stand it is very effective at achieving our primary selection goals. The T-joint is very stable due to its heavy mass. Since it is stainless steel it is not coated so it will not exhibit outgassing effects and therefore its presence during testing does not poison the vacuum environment. In addition, it provides easy frontal access to the cathode leads and fuel connections. The T-joint stand is shown in Figure 34 below.

Figure 34. A photograph of the stainless steel T-joint thruster stand used in validation testing with MIXI-CPv1 mounted to the top of the stand.

Thruster Base & Isolator

The base of the thruster is a 275 straight reducing ConFlat flange. It has a three inch 133 port for protecting the cathode mount. The six 1/4-28 bolts screw directly into the anode. The inner diameter reduction provides seating for the cathode base. The thruster base is electro-isolated from the T-joint stand using a 1/2 inch thick ring of MACOR. The ConFlat flange and MACOR ring are shown in Figure 35 below.

Figure 35. A photograph of the ConFlat flange thruster base and MACOR isolator ring used in conjunction with MIXI-CPv1.

Cathode Base & Isolator

The coiled tungsten filament cathode requires its own base to ensure stability and correct cathode position in the discharge chamber. This was achieved by placing a 3 in long piece of double bore alumina into a 21.5 mm diameter stainless plate. The alumina slides into a center hole in the plate and is attached with ceramic cement. The leads of the cathode are stabilized at the exit of the alumina with Kapton tape. The cathode base and double bore alumina are shown in Figure 36 below.

Figure 36. A photograph of the stainless steel cathode base and double bore alumina isolator from MIXI-CPv1.

Thermocouple Locations

Once the thruster is properly set up and the vacuum chamber is ready for testing, thermocouples must be attached. The thermocouples used in both the Lab 137 and CubeSat facilities are OMEGA K type thermocouples with an operating temperature range of -200°C to 1250°C .³⁷²² A representation of the thermocouples used is shown in Figure 37. Figure 38 shows the thermocouple locations chosen during thruster testing.

Figure 37. A photograph of an OMEGA K type thermocouple used in validation testing.

Proper selection of these locations is crucial in validating certain aspects of the thermal models. Three thermocouples are placed at the anode wall in order not only to determine the temperatures at the current magnet locations but also to determine if the anode wall temperature profile exhibits the same behavior as displayed in the thermal models. The thermocouple at the base of the cathode mount is intended to determine if the maximum temperature of porous aluminum is exceeded and if the models can properly predict radiation aft of the cathode. The thermocouples located inside the anode and MACOR cap are optional for MIXI-CPv1 testing but will become much more crucial in MiXI CP testing. These locations will determine if predicted reductions in temperature due to increasing anode wall thickness and/or grid mount thickness truly exist. The thermocouple on the inside wall of the anode pole piece is necessary to determine if moving the permanent magnets will actually reduce their thermal load significantly. The anode pole piece is the ferrous steel ring that the permanent magnets attach to. Figure 39 below shows the experimental setup with some thermocouples attached.

Figure 38. A depiction of the thermocouple locations used during validation tests.

Figure 39. A photograph of the MIXI-CPv1 experimental setup with thermocouples attached at the anode wall locations.

Testing Results

The thermal baseline test was run using MIXI-CPv1 and a coiled tungsten filament cathode. The input power to the cathode was 24.7 W and the test was run for twenty-four hours (sufficient to achieve steady state). Temperatures at three locations along the anode wall were recorded. The heating experienced by the thruster during this test was from cathode radiation only. No plasma was created during this testing due to chamber limitations in delivering fuel to the discharge chamber. This setup is sufficient however, since the goal of this testing is to determine heating from cathodes as a heat source in a 3 cm thruster. The results of this test are shown in Figure 40.

Figure 40. A figure of thermal results for MIXI-CPv1 testing

Chapter III: Thermal Modeling

This chapter provides an overview of the thermal environment for small ion thrusters and possible modifications that could be used to minimize heating of the SmCo permanent magnets. In addition, detailed descriptions of past and present thermal modeling techniques are provided.

MiXI Thermal Considerations

The 3 cm MiXI has a number of design topics that bear investigation and provide a plethora of research opportunities. One such issue pertains to the thermal behavior of this thruster and is the motivation for this thesis. In the design of MiXI II, thermal considerations were not the priority therefore MiXI II is not as well designed thermally as MiXI I. At high operating conditions, the MiXI II variant of the thruster experiences higher magnet temperatures that were not present in previous versions of the thruster. It is imperative to know what changes cause these thermal variations and what consequences these thermal issues can have.

The primary thermal concern is degaussing of permanent magnets. The permanent magnets used in ion thrusters are made of samarium cobalt. This material has a maximum operation temperature of 350°C. At this point thruster performance may degrade significantly. In addition, any temperature above 300°C will begin to weaken the magnets.²³ Magnetic field topography is a significant research topic in electric propulsion, so any alteration in the performance of these magnets would defeat the purpose of their exact placement. The effectiveness of the magnets is of concern since

they confine electrons. Their presence and optimization increases the electron residency time and prevents electrons from settling on the anode. This has a direct impact on performance since thruster efficiency is determined by the minimum anode area necessary to maintain a stable discharge.³ The prevalent causes for permanent magnet failure are thought to be excessive heating due to cathode radiation, the physical configuration of the thruster and the direct placement of magnets on the anode walls. Proposed solutions for each of these causes are discussed in subsequent paragraphs and the majority of the remainder of this thesis is dedicated to finding the occurrence of permanent magnet thermal failures.

There are several additional concerns when running a thruster at higher temperature. First is the degradation of the molybdenum grids. Prolonged exposure to high temperatures can warp the grids and cause the grid spacing to change considerably, which may cause undesirable beam ion trajectories that could increase grid erosion. . This is particularly concerning since significant efforts are made to optimize the grids for nominal thermal loads.¹⁷ Specific solutions to this problem are not discussed in the thesis, however; the hope is that steps taken to mitigate other thermal failures will help eliminate this concern.

The second thermal concern is the outgassing of the electro-isolation components. These components separate the thruster pieces that are meant to be at different electric potentials. The materials used in these situations are typically machinable glass-ceramic (MACOR) and alumina. In cases where Vogel-mounted hexaboride cathodes were implemented some poisoning effects were observed. Since MACOR is comprised of 96% oxide compounds, it is possible that sputtering effects due to the discharge conditions

could cause elevated oxygen presence on the cathode emission surfaces.¹⁸ While this is cause for concern, the total mass loss percentage (TML) of 0.01% for MACOR and 0.028% for alumina (96% grade), which is not significant when compared to most materials.²⁴ As with the grid degradation this outgassing is not investigated specifically in this thesis, however; special attention is paid to temperatures at these locations.

The third thermal concern for small ion thrusters is heating of the spacecraft. This is especially important when integrating with a pico-satellite like CubeSat. In addition, spacecraft that intend to utilize numerous MiXI thrusters on the same spacecraft, like TPF-I, would prefer to minimize thermal loads from the MiXI thruster pods.

Initial Thermal Modeling & Results

An initial thermal investigation was performed in September 2009 for the 31st International Electric Propulsion Conference in Ann Arbor, Michigan.²⁵ This paper is available in its entirety in Ref. 25. The study used Thermal Desktop²⁶, a SINDA/FLUINT²⁷ and AutoCAD²⁸ based thermal analyzer, to model several MiXI configuration and cathode operating conditions. The investigation examined five thermal cases. The first two cases were numerical simulations of MiXI-II using Ba-W dispenser and LaB₆ hexaboride cathodes. These cases were examined since they were not expected to yield high magnet temperatures, according to previous investigations.¹⁸ The third case is a worst case scenario, in which MiXI-I used a high temperature coiled tungsten filament cathode. The final two cases approximated the MIXI-CPv1 geometry and were used to juxtapose two methods of anode modeling. These cases are summarized in Table 1 while their results are shown in Table 2.

Table 1. A summary of the cathode operating conditions examined in Thermal Desktop.

Case Number	Thruster	Cathode Material	Cathode Temperature	Cathode location from base plate
1	MiXI II	Barium-calcium aluminate impregnated porous tungsten	1373K	1.8 cm
2	MiXI II	Lanthanum hexaboride	1673K	1.8 cm
3	MiXI I	Coiled tungsten filament	2623K	1 cm
4	MIXI-CPv1	Coiled tungsten filament	2623K	1 cm
5	MIXI-CPv1	Coiled tungsten filament	2623K	1 cm

Table 2. Maximum temperature for each thruster component in Kelvin.²⁵

Case
1	376	412	453	460/435
2	460	493	516	553/526
3	551	593	607	634/616
4	552	N/A	610	635/616
5	553	N/A	619	617/578
Case
1	N/A	N/A	396	467/430
2	563	N/A	470	571/523
3	N/A	N/A	569	614/540
4	N/A	589	575	636/540
5	N/A	585	576	636/541

These models predict overheating at the permanent magnet locations in all three cases where a coiled tungsten filament cathode was implemented (cases 3-5). In addition, the models did not show overheating at the magnet locations when the more advanced cathodes were implemented. All five cases showed increased heating moving downstream of the cathode on the anode walls. This result drove future examinations of heating at this location.

While these results provided an excellent baseline for subsequent thermal investigations, there were a few important limitations in these modeling techniques. First, each cathode was modeled as a point source node since, at the 3 cm scale; geometrically accurate cathodes could not be modeled. Each cathode is differentiated by its initial temperature and by the method in which the conductor paths were created. This method of cathode modeling does not truly reflect the differences in thermal behavior between each cathode. In addition, the hexaboride and dispenser cathodes were modeled by simulating radiation from a flattened 3 mm disc. This also is not an accurate model of these cathodes. However, these results provided a good first order approximation into the effects of heat transfer through the discharge chamber. The most important limitation, however, was the minimum anode wall thickness that could be modeled in AutoCAD while using thermal objects. Modeling an accurate MiXI anode length-to-diameter (L/D) ratio of one, the minimum anode thickness that could be rendered was 4 mm. This is nearly six times thicker than an actual MiXI anode wall. To mitigate this L/D limitation a stacking technique was implemented; four shorter sections with L/D of 0.25 allowed the anode wall thickness of 0.7 mm to be achieved. These sections were then placed on top of each other to achieve a full length anode. The limitations in modeling small objects in

Thermal Desktop made it clear that different numerical modeling software would be necessary to accurately reflect the complexities of MiXI's design, especially those pertaining to the miniature nature of this thruster.

Proposed Solutions

To improve the thermal margin for the MiXI thruster, two main solutions are proposed. Each solution described in the following paragraphs and are listed below. The hope is that one or all of these modifications will be both effective and able to coexist with normal thruster operation.

1. Alternative cathode selection
2. Minor physical modifications to enhance thermal design

Cathode Selection

The cathode implemented in the operation of MiXI has a significant effect on the heating at the permanent magnet locations. MiXI has been operated with a number of cathodes ranging from coiled tungsten filament to lanthanum hexaboride (LaB_6). Table 3 below shows each of these cathodes with their respective maximum operating temperatures.

Table 3. A summary of cathode material and operating temperatures¹⁸

Cathode Material	Maximum Operating Temperature (°C)
Ba-W Hollow	1190
Ba-W Dispenser	1190
LaB_6	1675
CeB_6	1675
Regular Tungsten Filament	2350

Thoriated Tungsten Filament	1900
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The barium-calcium aluminate impregnated porous tungsten (Ba-W) hollow cathode has the advantage of a low maximum operating temperature but has xenon flow requirements that are significantly higher than the MiXI range. This cathode can be run at lower currents but limits the lowest discharge flow rate of the thruster.¹⁸ The Ba-W dispenser cathode also has the previously mentioned low temperature advantage but exhibits low current density and low critical poisoning pressure. The Vogel-mounted LaB₆ and cesium hexaboride (CeB₆) cathodes have high current densities and higher critical poisoning pressures but those come at the cost of high operating temperatures.¹⁸ In addition, only Applied Physics Technologies (AP Tech) is currently known to make hexaboride cathodes in miniature enough sizes for operation in a 3 cm MiXI, creating an availability problem. The coiled tungsten filament cathode has a maximum operating temperature that is well above the rest of the cathode candidates. In addition, these cathodes have been known to be unreliable and sensitive to heater current.⁸ These cathodes are used as lab test cathodes because they are simple to implement and calculate the emission parameters of. They would not be considered suitable for flight models.

A flight model cathode known as the Internal Conduction (IC) cathode has been developed by Dr. Wirz and was built by AP Tech specifically for the MiXI thruster. Initial discharge tests have shown that the cathode requires as little as 7W of heater power (at only 3.5A heater current) to provide the discharge current necessary for the maximum projected operating conditions of MiXI. The IC cathode has a cycling time on the order of several seconds. A prototype of the IC cathode is shown in Figure 41 below.

Figure 41. A picture of the Internal Conduction (IC) cathode developed by Dr. Wirz.⁸

Lab Model Cathode

Given the limitations of the cathode candidates discussed in previous section, a suitable lab test cathode needed to be found. Han Mao, a Ph. D candidate at UCLA working under Dr. Wirz and Dr. Goebel, investigated the use of 2% thoriated tungsten as a suitable lab model cathode replacement. The advantage of this material is that it has a lower maximum operating temperature (1900 K) than standard tungsten while still offering sufficient electron emission. To achieve this electron emission, however, the thorium in the filament must go through an activation process. This begins by flashing the filament at a temperature of 2900 K to turn the thorium-oxide into metallic thorium. The filament is then run at 2050 K for 30 minutes to bring the metallic thorium to the surface. Finally the filament is run at the maximum operating temperature of 1900 K to achieve the increased electron emission.⁷ Figure 42 below shows the thoriated tungsten

hook system developed by Mao and Figure 43 shows a comparison of the electron emission densities for the two tungsten types.

Figure 42. A picture of a thoriated tungsten filament attached to standard tungsten hooks.⁷

Figure 43. A comparison of emission current densities for thoriated and regular tungsten.⁷

Design Modifications to MiXI

Another proposed solution to increasing the thermal margin for small ion thrusters is to make design modifications to in order to enhance thermal design space understanding. The following paragraphs describe some proposed designs.

Anode Designs

The anode in a MiXI thruster is 3 cm in diameter with the cathode centered in the middle of it. This gives a radius of 15 mm (less if you consider the diameter of the cathode) between the cathode and the inside of the anode walls. The anode walls on MiXI II and MIXI-CPv1 are 0.7 mm thick stainless steel. The permanent magnets are in direct contact with the outer walls of the anode. This configuration is shown in Figure 44 where the cusp burns are in line with the magnet placement. In addition, the downstream portion of the anode makes contact with a piece of MACOR that the grids are mounted to, which will keep this portion thermally isolated. This means that the only non-critical direction the heat can conduct is to the steel pieces at the base of the anode. A 0.7 mm anode wall thickness, however, provides a very small conduction path. This current anode design ensures that nearly all of the heat internal to the discharge chamber is being conducted straight through the anode wall to the permanent magnets.

Figure 44. A photograph of permanent magnet placement around MiXI's anode.

The first design suggestion is to make the anode thicker. This would create a larger conduction path for heat to dissipate away from the magnet locations and into the thruster base. According to Dr. Wirz¹⁴, a thicker anode may help maintain discharge stability for some magnet configurations.

The second design suggestion is to make a stepped anode in which the portion of the anode containing the cathode is thickened but the downstream portion of the anode on which the magnets are placed remains at 0.7 mm. This stepped anode configuration is shown in Figure 45. The implementation of this configuration could be necessary if the weakened magnets do in fact require a thin anode wall in order to sustain a stable discharge. The stepped design would provide the desired larger conduction path on at least two thirds of the anode length.

Figure 45. A model of a stepped anode design with 2 mm wall thickness at the base and a 0.7 mm wall thickness at the downstream magnet locations.

The third design suggestion would be to implement a fined anode design. This configuration is preferable if larger conduction paths are desired along the entire length of the anode, however compared to the 0.7 mm thick anode wall, the added mass may be a concern. This configuration is shown in Figure 46.

Figure 46. A model of a fined anode design with thicker conduction paths along the entire anode length.

Radiation Shield

The final proposed design modification for MiXI is to implement a radiation shield that would protect the permanent magnet from higher temperatures. This configuration would utilize the stepped anode design. However, instead of placing the magnets against the thinner part of the anode wall, a shield ring would be put there instead. This shield would be made out of MACOR since its maximum continuous use temperature is 800°C.²⁹ In addition, MACOR has very low thermal conductivity. Although fragile, MACOR can be machined very thin. This means that the permanent magnets would not have to be moved more than 1.3 mm off the anode wall, however the consequence would be to reduce the electron confinement and may reduce discharge performance. The radiation shield design can be seen in Figure 47, where the shield itself is shown as the purple ring surrounding the anode at the downstream magnet location.

Figure 47. A modeled MACOR radiation shield (purple) around a stepped anode design.

Numerical Modeling Techniques

Given the limitations of the numerical simulation used in previous investigations, a new numerical thermal analyzer needed to be selected. The author chose to use SolidWorks Simulation³⁰ to create the current thermal models. SolidWorks was selected for a few reasons. First, SolidWorks is an excellent software package for modeling parts with very fine resolution, such as thruster grids and anode walls. This provided a significant advantage over Thermal Desktop which could not handle thin anode walls and miniature parts when they were converted to thermal objects. Second, Cal Poly's CNC machines are run off of SolidWorks. This allowed for design changes to be implemented from simulation into actual thruster components rapidly. Finally, SolidWorks Simulation has a built in finite element modeler making it a viable option for numerical studies. The following paragraphs give detailed descriptions of the techniques used to model key components. Figure 48 below shows a SolidWorks thermal simulation modeled with the same conditionals as the Thermal Desktop models. The SolidWorks results show a maximum magnet temperature of 380 K, which is 243 degrees below the maximum operating temperature of samarium cobalt. This result differs from the Thermal Desktop

maximum temperature by 250 degrees. The cathode models in thermal desktop did not properly reflect cathode behavior derived from experimental results. When the SolidWorks simulation used the same incorrect cathode radiation parameters the results at the magnet locations did not exceed maximum temperatures. This deviation from the experimental result shows that SolidWorks is a better choice for this particular numerical simulation.

Figure 48. A MIXI-CPv1 thermal model run in the same configuration as the Thermal Desktop investigation with a standard coiled tungsten filament cathode.

Cathode Modeling

The most important component to model correctly is the primary heat source, which is the cathode. In the previous investigation proper modeling techniques for cathodes were a primary limitation.²⁵ Using SolidWorks, all cathodes were modeled to their precise dimensions. The SolidWorks models of the Vogel-mounted hexaboride and dispenser cathodes are shown in Figure 49 and Figure 50, respectively, with their real life counterparts pictured next to them.

Figure 49. a.) A comparison of a) a simulated Vogel-mounted hexaboride cathode and b) an actual Vogel-mounted hexaboride cathode.

Figure 50. a.) A comparison of a) a simulated Ba-W dispenser cathode and b) an actual Ba-W dispenser cathode.

These cathodes were modeled but seldom used in thermal simulations and are not commonly implemented in the current MiXI configuration. Modeling the cathodes with their exact dimensions caused certain thruster configurations to fail in finding the radiation view factors between these cathodes and discharge chamber surfaces. This is likely because, while the cathodes are modeled to appear like real cathodes, certain portions of the assembly do not serve a purpose in the numerical simulation. This problem was lessened by modeling these cathodes as cylinders or cylindrical shells. In addition, the primary concern in the thermal simulations became the juxtaposition of

tungsten cathodes and the investigation of thruster design space. Incorporating the models of more advanced cathodes is left for future investigations.

An attempt was made to model coiled tungsten filament cathodes in their true-to-life form for use in the thermal simulations. While this attempt is aesthetically pleasing and functional since it represents the actual cathode used in testing, it too failed to resolve since the auto-mesher in SolidWorks could not create a mesh size small enough to capture the thin features of this cathode model. The cathode filament model is shown in Figure 51a), next to an actual coiled tungsten filament, Figure 51b).

Figure 51. a.) A simulated coiled tungsten filament, b.) A real coiled tungsten filament.

In simulations these cathodes were modeled as a tungsten cylinder whose dimensions match those calculated using a filament sizing spreadsheet designed by Dr. Wirz. In the thermal models, radiation parameters are set between the cathode cylinder and the discharge chamber. The emissivity of the cathode, ϵ , is provided in filament sizing spreadsheet calculations, but can also be determined by rearranging Stefan-Boltzmann law.^{31,32} This calculation yields an emissivity of 0.33 which is very close to value of 0.324 provided by the emissivity fit in the filament sizing spreadsheet.

Grid Modeling

In the current thermal simulations, grids were modeled with exact dimension and correct hole patterns.

While these grid models were used in some simulations, others failed to create a radiation view factor between the cathode and the screen grid due to the large number of individual holes modeled. To simplify the process, grids were modeled without hole patterns and were given a transmissivity value of 0.67, that corresponded to the open area grid fraction used in the plasma heating calculations. This method is commonly employed when modeling thruster grids.³³

Component Modeling

All other thruster components necessary for simulation were modeled to their exact physical dimensions. These pieces include the anode, anode pole piece, cathode mount, cathode pole piece, fuel diffusion plate, MACOR isolation pieces, and thruster base. Each of these pieces was assigned proper material characteristics in SolidWorks. Table summarizes these characteristics for the materials used. All thruster components were given an initial temperature of 323 K. In SolidWorks, assembled components automatically conduct to one another in simulation.

Table 4. The key material properties of MiXI thruster components.³⁴

Thruster Component	Material	Conductivity [W/m/K]	Specific Heat [J/kg/K]	Density [kg/m³]
Anode	303 Stainless Steel	21.5	500	8027
ConFlat flange	316 Stainless Steel	21.5	500	8000
Cathode lead separator	Alumina	35	880	3890
Grid mount	MACOR	1.46	790	2520
Grids	Molybdenum	138	250	10220

Propellant diffusion plate	Porous Aluminum	19	867	867
Magnets	Samarium Cobalt	10.5	370	8400

Plasma Heating

To incorporate the previously discussed plasma heating results, a thermal ring was modeled and placed on the inside of the anode wall. This ring was given a heat source power value equivalent to the total power deposition on the anode. The ring length was modeled to match the length of the permanent magnets, since power deposition on the anode has been known to pattern the magnet footprint on the discharge chamber wall.³⁵ Ring thickness is negligible since the heat source is being applied directly to the inner anode wall. Figure 52 shows a plasma heating ring inside of the MIXI-CPv1 anode.

Figure 52. A model of the plasma heating ring (red) inside of a MIXI-CPv1 anode.

Configurations Modeled

Based on previous investigations and proposed thermal modifications, seven test cases were modeled using SolidWorks. These cases represent the most crucial comparisons for validation or most important predications for current and future thermal considerations for MiXI. The first case is a comparison to the cathode radiation validation test performed in CubeSat's thermal vacuum chamber facility. This case will be used to determine if the modeled cathode radiation heating properly approximates actual heating experienced by the MIXI-CPv1 thruster under these conditions. The second case is a comparison to the MiXI II thruster using a coiled tungsten filament cathode. This case will determine if the overall numerical solution can predict thermal inconsistencies when they might occur. The third case is an examination of the use of a thoriated tungsten filament in the MiXI II configuration. Cases 4 – 6 are simulations to determine the potential effectiveness of modifying the anode design of the MiXI thruster. Case 7 is an examination of MACOR as a potential anode radiation shield material. The results for these cases will be discussed in Chapter IV. Table below gives a summary of the thruster configuration and conditions modeled in this thesis.

Table 5. A summary of the simulation cases and cathode conditions modeled using SolidWorks.

#	Simulation Case	Thruster Version	Cathode	Maximum Cathode Temperature (°C)
1	Comparison to Validation Test	MIXI-CPv1	Tungsten filament	2350
2	Baseline thermal configuration	MiXI II	Tungsten filament	2350
3	Thoriated tungsten filament solution	MiXI II	Thoriated tungsten filament	1627
4	Thickened anode solution	MiXI CP	Tungsten filament	2350
5	Stepped anode solution	MiXI CP	Tungsten filament	2350

6	Fin anode solution	MiXI CP	Tungsten filament	2350
7	Anode radiation shield solution	MiXI CP	Tungsten filament	2350

Analytical Modeling Techniques

Prior to implementing improved numerical modeling techniques, analytical solutions for the power deposition on the anode from thruster plasma were derived. When combined with radiation solutions these equations can approximate the temperature conditions at the permanent magnet locations; however, numerical modeling provides a platform to make specific design changes to the thruster. Instead these analytical results are integrated into the numerical simulations for enhanced thermal approximations.

Plasma Heating

In order to obtain the heat transferred by the plasma in the discharge chamber to the permanent magnet locations, equations for approximating the power deposition onto the anode need to be derived. These equations include the power deposited from four sources: Primary electrons, Maxwellian electrons, ions, and the radiated energy from excited neutrals and ions. Each of these four contributors is discussed in the subsequent paragraphs. Van Noord derived these equations in his NEXT ion thruster thermal model.³⁵ The following equations were necessary to calculate power deposited and are included for completeness. For complete details please see Refs. 35, 36, 37 and 38.

Electron Velocities

In order to determine crucial plasma densities, it is necessary to calculate neutral, primary electron and Bohm velocities. The mean neutral velocity, v_o , in the discharge

chamber is shown in Eq. 1 and is driven by the neutral gas temperature, which is approximately 280°C for MiXI.⁸

$$v_o = \sqrt{\frac{8kT_n}{\pi M_{Xe}}} \quad (1)$$

where k is Boltzmann's constant, T_n is neutral gas temperature, and M_{Xe} is the mass of a xenon atom. To determine the primary electron velocity, v_{pe} , the primary electron energy, V_{pe} , must first be found. Equation 2 shows the primary electron velocity can be calculated by,

$$V_{pe} = V_D + V_A - V_C \quad (2)$$

where V_D is discharge voltage, V_A is the anode fall voltage and V_C is the cathode fall voltage (the voltage drop for a hollow cathode relative to ground). The cathode fall voltage is the voltage drop for a hollow cathode. In the case of a tungsten filament, this term isn't likely to exist due to a lack of local separate plasma.²⁴ Anode fall voltage is equivalent to the plasma potential plus the sheath potential relative to ground. Further discussion of these potentials can be found in Ref. 38. Once primary electron potential is found, the mono-energetic primary electron velocity can be calculated using Eq. 3.

$$v_{pe} = \sqrt{\frac{2eV_{pe}}{M_e}} \quad (3)$$

where e is the elementary charge and M_e is the mass of an electron. Equation 4 is used to calculate Bohm velocity,

$$v_b = \sqrt{\frac{kT_m}{M_e}} \quad (4)$$

where T_m is Maxwellian electron temperature. Determining T_m will be discussed in detail later in this section.

Densities

To find the neutral density, the mass utilization efficiency (η_m), must first be found. Mass utilization efficiency is defined as the ratio mass flow of ions leaving in the beam to the total mass flow of number of xenon atoms introduced into the discharge chamber, shown in Eq. 5;

$$\eta_m = \frac{I_B}{\dot{m} 4.5 \times 10^{17} e} \quad (5)$$

where I_B is the beam current and $\dot{m}$ is propellant mass flow rate in sccm. The neutral density, n_o , is found by equating the neutral influx and the atoms leaving the thruster through the optics in the form of neutrals and ions. This derivation is given in Ref. 38 and is shown in Eq. 6.

$$n_o = \frac{4I_B(1-\eta_m)}{v_o e A_g \Phi_{ago} \eta_c \eta_m} \quad (6)$$

where A_g is grid area, Φ_{ago} is the accelerator grid open area fraction, and η_c is a clausung factor. The clausung factor represents the reduced conductance of the grids for multiple grids of finite thickness. Ion thruster grids will typically have a clausung factor on the order of 0.5.³⁸ The primary electron density was derived through a combination of Refs. 37 and 38 and is shown in Eq. 7;

$$n_p = \frac{I_e}{en_oV\sigma_Tv_{pe}} \quad (7)$$

where I_e is emission current, V is the volume of the ion production region, and σ_T is total ionization and excitation cross sectional area. The Maxwellian electron density can be calculated using the equation for plasma ion density. This calculation is shown in Eq. 8;

$$n_m = \frac{2I_B}{v_b e A_g \Phi_i} \quad (8)$$

where Φ_i is grid transparency.

Maxwellian Electron Rate Factor

The previously mentioned Maxwellian electron temperature, T_m , can be found using an iterative method in which an educated initial guess for T_m is made when calculating Bohm's velocity (Eq. 4). This velocity, in addition to the densities derived in the previous section, is used to calculate the Maxwellian electron rate factor, Q_o , shown in Eq. 9,

$$Q_o = \frac{v_b A_i}{2n_o V} - \frac{n_p}{n_m} Pr_o \quad (9)$$

where Pr_o is the primary electron rate factor. This value is then compared to the chart shown in Figure 53 and a new T_m is found. Once this solution converges, this value is the final Maxwellian electron temperature. Equation 10 gives the calculation for ion loss area, A_i ,

$$A_i = A_k + A_g + A_{ha} + A_{sa} f_c \quad (10)$$

where A_k is the area of the keeper, A_{ha} is the hybrid anode area, and A_{saf_c} is the surface area of the anode exposed to the plasma times the ion confinement factor. For further details on these areas see Ref. 38. Since the neutral density parameter for MiXI is known from background references on the thruster, additional charts in Ref. 37 are available for use in finding T_m and Q_o .

Figure 53. A chart of xenon ionization reaction rate versus electron temperature²⁴

Currents

Two necessary current calculations are for the excitation of neutrals (I_n^*) and ions (I_i^*) shown in Eqs. 11 and 12;

$$I_n^* = I_e \left(1 - \exp(-\sigma_{p^*} n_o L_p) \right) \quad (11)$$

$$I_i^* = I_e \left(1 - \exp(-\sigma_{p+^*} n_i L_p) \right) \quad (12)$$

where $-\sigma_{p+^*}$ is the primary ion excitation cross sectional area, $-\sigma_{p^*}$ is the primary neutral excitation cross sectional area, and L_p is the average length a primary electron travels before it is collected on the anode.

The calculation for primary electron current to the anode, I_{an}^p , is

$$I_{an}^p = I_e \exp(-\sigma_T n_o L_p), \quad (13)$$

and the total ions produced current, I_{pl}^+ ,

$$I_{pl}^+ = e n_o V (n_m Q_o + n_p P r_o). \quad (14)$$

The calculation for ion current to the anode, I_{an}^+ ,

$$I_{an}^+ = I_{pl}^+ - I_B - I_k - I_{sg} \quad (15)$$

where I_k is keeper current and I_{sg} is screen grid current. The Maxwellian electron current to the anode, I_{an}^m , is calculated as

$$I_{an}^m = I_D + I_{an}^+ + I_B - I_{an}^p \quad (16)$$

where I_D is the discharge current.

Power Deposition

The preceding section described the processes for finding all of the necessary values for calculating anode power deposition. Figure 54 shows a flow chart of the overall process for arriving at solutions for anode power deposition.

Figure 54. A description of the process used to find the power deposition on the anode.

The average power used to ionize a beam ion and the average power used to excite a neutral or ion can be found by multiplying their respective currents, found in the previous section, by their threshold energies,

$$P_n^* = I_n^* U_{n^*} \quad (17)$$

$$P_i^* = I_i^* U_{i^*} \quad (18)$$

where the excitation of neutrals from ground state, U_{n^*} , is 8.3 eV and the excitation of ions, U_{i^*} , is 11.27 eV. In addition, to find the power deposition from ionization, and neutral and ion excitation, the total discharge chamber surface area must be calculated, given by

$$A_{dc} = A_{an} + A_g + A_k \quad (19)$$

The radiated power from the plasma deposited onto the anode surface area can now be calculated using

$$P_{an}^* = \frac{A_{an}}{A_{dc}} (P_n^* + P_i^*) \quad (20)$$

The power deposited on the anode from Maxwellian electrons can be calculated by

$$P_{an}^m = I_{an}^m \left(\phi_{an} + \frac{5}{2} T_m \right) \quad (21)$$

where ϕ_{an} is work function, which for tungsten is 4.55.

The power deposited on the anode from primary electrons can be calculated using Eq. 22 and the power from an ion neutralizing on the anode can be calculated using Eq. 23,

$$P_{an}^p = I_{an}^p (\phi_{an} + (V_D - V_C)) \quad (22)$$

$$P_{an}^+ = I_{an}^+ \left(V_A + \frac{5kT_n}{2e} + U_+ - \phi_{an} \right) \quad (23)$$

where the ionization threshold for xenon, U_+ , is 12.13 eV.

Plasma Heating Results

Table below shows the calculated results for the power deposition on a MiXI CP anode using a coiled tungsten filament cathode. Thruster specific inputs were taken from Ref. 18.

Table 6. The power deposition on the anode from each primary source.

Heating Source	Power Deposited (W)
Maxwellian electrons	0.43
Primary electrons	4.91
Ion neutralization	5.25

Excitation	1.36
TOTAL	11.95

To determine if the calculation of the total power deposited on the anode is reasonable a few cross checking, back of the envelope calculations can be made. First a power balance on the thruster can be performed since we know the input power and the power leaving the thruster. Any remaining power must be consider waste heat. Equation 24 shows this power balance,

$$\text{Waste heat} = \text{Input Power} - (V_B I_B) - (I_B U_+). \quad (24)$$

Inputting MiXI's operating conditions from Ref. 16 and a cathode input power of 24.7 W yields 12.24 W of waste heat. This implies that 97.6% of the total waste heat is deposited on the anode, with the remainder deposited on the grids. In addition, some of the waste heat may be comprised by local cathode heating from ions that originate in the discharge plasma. This is higher than NSTAR (81%) but still a reasonable assumption since the anode surface area comprises most of the discharge chamber area in the MiXI configuration. Another check that can be performed is to calculate the total heat loss to the discharge chamber and subtract the loss to the screen grid, P_{sg} , to obtain heat loss to the anode, given by

$$\text{Heat loss to the Anode} = [(V_D I_D) - (I_B U_+)] - P_{sg}. \quad (25)$$

Eq. 25 yields a heat loss to the anode of 11.06 W. This represents an error of 8.05%. This calculation is shown in Eq. 25. The power deposition calculations described in this section neglected the presence of doubles because it is a second order effect. It

should be noted, however, that the presence of a significant number of doubles can throw off Eq. 25. In addition, this balance does not include heating from the cathode. This is not a concern, however, since this is accounted for in numerical modeling.

Chapter IV: Results

This chapter presents the results for the cases described in Table 6 in Chapter II. The first two results provided are for comparison to previous tests in order to validate the models. The next seven results represent the proposed changes to MiXI's configuration and operating conditions. The final result is a combination design that is included as a recommendation for MiXI CP.

Comparison to Validation Testing

The results presented in this section are for comparison to the thermal validation test that was conducted in CubeSat's thermal vacuum chamber facilities. The model represents the MIXI-CPv1 setup with a coiled tungsten filament cathode. The plasma heating ring is excluded from analysis since this comparison is meant to determine if the thermal models correctly predict cathode radiation. These results are shown in Figure 55.

A grid independence analysis was conducted for the thermal model that approximates the cathode radiation heating tested experimentally on MIXI-CPv1. The goal of a grid independence analysis is to determine simulation order and error associated with numerical approximations. In addition, it is advantageous to determine an intermediate mesh size that optimizes simulation time while provided sufficiently accurate results. The maximum temperature at the outer wall of the anode was recorded for three separate numerical simulations, each using a different mesh size. The course mesh was determined by setting the auto-mesher in SolidWorks to the most course setting of 0.256 inches. The intermediate mesh was set to 0.18 inches since this value was

slight more fine than the medium setting. The fine mesh was set to 0.11 inches since this is almost the finest mesh SolidWorks can resolve. With the mesh size and results for each setting recorded, an apparent simulation order of 1.54 and an approximate relative error of 0.67%. The extrapolated temperature for an infinitely small mesh size was 286.9°C. Since the intermediate mesh size was used for all of the numerical simulations, its relative extrapolated error of 0.92% was determined. Table 7 summarizes the key terms of the grid independence analysis.

During the MIXI-CPv1 validation test, three temperatures were sampled along the outside of the anode wall using K type thermocouples. The error for a K type thermocouple is 0.75%, or approximately ± 2.5 °C for the tests performed. This combined with the error associated in measuring the location of a thermocouple gives a maximum relative experimental error of 0.79%. A summary of the modeling and experimental results are shown side by side in Figure 56, where the error bars for the experimental values are taken from measurement uncertainty and thermocouple error and the numerical error bars are taken from the grid independence analysis. The temperature at the very top of the anode wall was measured at 284.2°C after the thruster reached steady state (twenty-four hours of testing). In the numerical simulations results the temperature at this same location is 284.3°C. This is a very encouraging result since this represents an error of only 0.035% from the measured value and the results are well within the error bars. The temperature measured at the center of the anode wall during the test was 251.1°C. In the model above this temperature is 254.0°C. Once again this result differs from the validation test by only 2.9 degrees and is within the error bars. During the test the temperature where the anode wall meets the flange was 216.5°C. The results have this

location at a temperature of 209.0°C. Of all the results this represented the greatest disparity at an error of 3.5% and the results are just outside of the error bars. All of these results confirm that cathode radiation is represented well in the thermal models, lending credibility to later models that approximate the use of a coiled tungsten filament cathode.

Figure 55. MIXI-CPv1 thermal model with a regular tungsten cathode and no plasma heating.

Table 1. The key terms and results for the grid independence study.³⁹

Term	Value
Cell size – Fine mesh	0.11 inches
Cell size – Intermediate mesh	0.18 inches
Cell size – Course mesh	0.256 inches
☐ fine	285.7°C
☐ intermediate	284.3°C
☐ course	282.4°C
Apparent simulation order	1.54
Extrapolated ☐	286.9°C
Approximate relative error	0.67%
Extrapolated relative error for intermediate mesh size	0.92%
Fine-grid convergence index	0.54%

Figure 56. A summary of the radiation modeling results versus the chamber testing results.

Baseline Thermal Case

It has been suggested that the MiXI II configuration has higher magnet temperatures than MiXI-I when a standard coiled tungsten filament cathode is implemented. The following simulation is of a MiXI II configuration with a coiled tungsten filament cathode, neglecting plasma heating. This result is shown in Figure 57 below. The temperature of the outer anode wall is at its maximum at the location most downstream of the cathode. In subsequent paragraphs this location will be referred to as the top of the anode. Also, the anode is the only component shown in all result plots since this is the design space of most concern. Including all thruster components tends to clutter the results and make temperature variations along crucial components difficult to detect visually. In this configuration, the maximum temperature at the magnet ring location was 635 K. This result is twelve degrees above the maximum operating point of samarium cobalt magnets.

Figure 57. The anode thermal plot of MiXI II with a regular tungsten filament without plasma heating approximations.

This configuration was also run including the plasma heating approximated in Chapter III. These numerical simulations are included for all cases in order to approximate the temperatures that would likely be experienced by the thruster during nominal operating conditions when plasma is being generated. These results have not been validated experimentally and are intended to examine worst case thermal scenarios during operation. With plasma heating included the maximum temperature at the magnet ring location was 673 K. This is fifty degrees above the maximum operating temperature of samarium cobalt magnets. This result is shown in Figure 58 below. This is the expected result and validates that the model can be used to predict cases where a thruster may overheat. All of the results for proposed modifications will be compared to this baseline result to determine if any thermal benefit is gained by making suggested modifications.

Figure 58. The anode thermal plot of MiXI II with a regular tungsten filament including plasma heating approximations.

Results for Proposed Modifications

This section provides results and discussion for the six proposed thermal enhancements to MiXI CP. The scales for the plots differ so please refer to maximum and minimum temperature values for each case. A standard color scale would have been implemented; however, SolidWorks cannot resolve differences over the range of temperatures that were explored. A standard color scale would eliminate the ability to visualize thermal differences along the length of the anode walls.

Suggestion 1: Thoriated Tungsten Cathode

The first Suggestion examined was the use of a thoriated tungsten cathode in a MiXI II configuration. This cathode was differentiated from the standard coiled tungsten filament cathode by altering the heat source input in the thermal model. The temperature input along the cathode was reduced from 2350°C to 1900°C. In addition, modifications

were made to the plasma heating calculations in order to better reflect the use of this cathode. These modifications included changing the work function of the cathode and reducing the maximum operating temperature. These changes resulted in a decrease in plasma heating of approximately 10%. The result at the top of the anode was 560 K and is shown in Figure 59. This is sixty-three degrees below the maximum temperature for the permanent magnets and thirteen degrees below the lower end of the degaussing range.

Figure 59. A thermal plot of MiXI II using a thoriated tungsten filament cathode without plasma heating.

The maximum observed temperature at the permanent magnet locations is 598 K. This result is shown in Figure 60 below. This result is twenty-five degrees below the absolute maximum operating temperature for samarium cobalt magnets indicating that the use of a thoriated tungsten filament cathode could mitigate persistent thermal variations. Since magnetic degaussing can still occur in temperatures ranging from 573 – 623 K, this result cannot be viewed as a guaranteed solution to thermal variations. However, given that the use of this cathode represents a 75 degree temperature savings

over a standard coiled tungsten filament, suggesting this result is an encouraging cathode substitution to the standard tungsten filament cathode.

Figure 60. A thermal plot of MiXI II using a thoriated tungsten filament cathode including plasma heating.

Suggestion 2: Thickened Anode

As discussed in Chapter II, a thicker anode is an easy design modification to implement in MiXI from a machining standpoint. For this study, an anode thickness of 2 mm was chosen and placed on the MiXI CP configuration. This thickness was chosen because an increase of up to 2 mm will not interfere with the current grid mounting structure components. The resulting temperature at the magnet locations is 603 K. This result is twenty degrees below the maximum temperature of the permanent magnets and is show in Figure 61.

Figure 61. A thermal plot of MiXI CP with a 2mm thick anode wall excluding plasma heating approximations.

This case was also examined including plasma heating approximations. This result is shown in Figure 62 below. The maximum observed temperature at the outer anode walls for this case was 643 K. This result indicates that if this was the only thermal modification to the thruster, the permanent magnets would be 20 degrees above their maximum operating temperature. This does, however, represent a 30 degree temperature reduction over the baseline case. The reduction in temperature comes at a cost of 32 grams of additional thruster head mass. While this design does not offer as favorable of a result as the previously discussed cathode modification, it is significant enough to recommend that a 2 mm thick anode be fabricated and investigated with the future MiXI CP configurations. In addition, this suggestion is a valid flight level modification since it can coexist with flight model cathodes as opposed to a lab level substitution.

Figure 62. A thermal plot of MiXI CP with a 2mm thick anode wall including plasma heating approximations.

Suggestion 3: Stepped Anode

In the event that the thickening the entire anode is prohibitive for the magnet field topography, a stepped anode could be implemented. The anode modeled in this study is 0.7 mm thick at the magnet locations and 2 mm thick elsewhere. This result is shown in Figure 63 below, where temperature on the downstream portion of the anode walls is still the primary concern. The maximum temperature at the magnet locations is 629 K which is six degrees above the maximum operating temperature of samarium cobalt.

Figure 63. A thermal plot MiXI CP with a 2 mm thick stepped anode design excluding plasma heating approximations.

The maximum temperature at the permanent magnet locations in this simulation was 665 K. This result is shown in Figure 64. This configuration would result in the samarium cobalt magnets being 42 degrees above their maximum operating temperature. The stepped design outperforms the baseline case by eight degrees at the cost of an additional 21.3 g of thruster head mass. This result experiences 22 degrees of additional heat when compared to the thickened anode design while only saving 10.7 g of mass. Pending results from an investigation in the magnetic field topography effects of implementing a thickened anode, this design could be considered a candidate for MiXI CP fabrication.

Figure 64. A thermal plot MiXI CP with a 2 mm thick stepped anode design including plasma heating approximations.

Suggestion 4: Fin Anode

Another alternate solution to thickening the entire anode was to create a fin design. This design would be preferential if thickening the entire anode creates a mass issue. The thickness chosen was 2 mm. The resultant maximum magnet temperature is 610 K which is thirteen degrees below the maximum operating temperature of samarium cobalt. This result is shown in Figure 65.

Figure 65. A thermal plot of MiXI CP with a fin anode design excluding plasma heating results.

The fin design has a maximum anode wall temperature of 650 K. This result would put the permanent magnets 27 degrees above their maximum operating temperature and is shown in Figure 66. The thickened anode design outperformed fin anode design by seven degrees, however, the fin anode design represents a mass savings of 14.6 g over a thickened anode. The fin design is 17.4 g heavier than a MiXI II anode. The result is a 23 degree improvement over the baseline case. While this anode is the most complex to machine, it may be a worthwhile option given that it is a compromise between increased mass and temperature savings.

Figure 66. A thermal plot of MiXI CP with a fin anode design including plasma heating results.

Suggestion 5: Anode Radiation Shield

One solution available, if significant anode modifications are infeasible and/or the use of a thoriated tungsten filament does not reduce temperature enough, is the placement of a radiation shield between the outer anode wall and the permanent magnets. As discussed in Chapter II, this shield would be made of MACOR which can be machined into thin configuration and can withstand constant thermal exposure up to 800°C. Two configurations of this solution were modeled. The first uses a 1.3 mm thick MACOR radiation shield. The second uses a 2.3 mm thick MACOR radiation shield. Both designs utilize a stepped anode platform. The 1.3 mm thick configuration modeled without plasma heating approximations exhibits a maximum magnet temperature of 613 K. This is ten degrees below the maximum magnet operating temperature. The 2.3 mm thick

configuration modeled without plasma heating approximations had a maximum magnet temperature of 600 K. This is twenty-three degrees below the maximum magnet operating temperature. These results are shown in Figure 67 and Figure 68.

Figure 67. A thermal plot of a stepped anode design with a 1.3 mm thick MACOR radiation shield excluding plasma heating.

Figure 68. A thermal plot of a stepped anode design with a 2.3 mm thick MACOR radiation shield including plasma heating.

The maximum temperature at the permanent magnet locations for the 1.3 mm thick radiation shield design including plasma heating approximations is 653 K. This result is shown in Figure 69. This is a disappointing result as it leaves the magnets 30 degrees above their maximum operating temperature. While this result represents an improvement over the baseline of 20 degrees, it comes at the cost of 20.1 g of additional mass. In addition, this design is outperformed by the simpler to implement thickened anode design.

Figure 69. A thermal plot of a stepped anode design with a 1.3 mm thick MACOR radiation shield including plasma heating.

The maximum anode wall temperature in the 2.3 mm thick MACOR radiation shield design including plasma heating approximations is 639 K and is shown in Fig. Figure 70. While this is a 14 degree improvement over the 1.3 mm thick radiation shield, it is still 26 degrees higher than the maximum working temperature of samarium cobalt magnets. This result also does not take into account the effect that a radiation shield this

thick would have on electron confinement. In addition, this result comes with an increase in mass of 39.2 g over the baseline case while providing only 34 degrees of temperature savings.

Figure 70. A thermal plot of a stepped anode design with a 2.3 mm thick MACOR radiation shield including plasma heating.

Recommendations

Based on the results presented in the previous section, the best course of action for enhancing MiXI's thermal margin is to incorporate a combination of solutions in the fabrication and set up of MiXI CP. This combination of solutions is shown in Figure 71 below. This design would utilize the 2 mm thickened anode configuration with a thoriated tungsten filament cathode. Both of these solutions offered a noticeable temperature reduction when compared with the baseline case. In addition, the only cost is 32 g of mass. The implementation of a thickened anode in the fabrication of MiXI CP is

the simplest anode modification for the machinist. Obtaining thoriated tungsten for MiXI CP may present a greater challenge but the implementation of this cathode is also simple when considering its similarities to the cathode used in MIXI-CPv1.

Figure 71. A model of the proposed thermal modifications to MiXI CP.

The maximum permanent magnet temperature in this design is 571 K. If implemented as a MiXI CP configuration, the permanent magnets would be 52 degrees below their maximum operating temperature. This combined design represents a 102 degree temperature improvement over the baseline design.

In addition to the configuration above, it is recommended that a stepped anode design with a 1.3 mm thick MACOR radiation shield be attempted in MiXI CP. Even though this configuration did not perform as well as other proposed solutions, its implementation in MiXI CP does not represent a high degree of difficulty, especially if a stepped anode design is to be attempted by the machinist. Lab 137 has a rod of MACOR

with sufficient diameter to attempt this design. This assembly could then be subjected to a thermal validation test to determine if the aforementioned numerical simulations fail to properly represent this solution. In the validation testing performed in CubeSat's thermal vacuum chamber, the MACOR ring that isolates the thruster stand from the thruster base performed well. When the thruster was being removed from the chamber, the anode and thruster base were still too hot to touch. The thruster stand however was room temperature to the touch. In addition, the thruster could be removed from the stand by lifting from the MACOR. This occurrence leads the author to believe that the MACOR radiation shield may perform better than anticipated in thermal validation testing.

Chapter V: Conclusion

Based on the results presented in this thesis, the SolidWorks thermal models provide a foundation for the creation of a more streamlined and thermally optimized version of MiXI. The numerical simulations presented represent significant progress in both methods and fidelity of results than those previously applied to this thruster. In addition, the vacuum chamber facilities acquired and repaired during the creation of this thesis should provide an excellent platform for the continued development of MiXI at Cal Poly.

Future Work

Moving forward in development of thermal models for miniature thruster will likely require the selection of an even higher fidelity thermal analyzer. The logical choice would be SINDA/G⁴⁰ since it can incorporate the plasma physics presented in Chapter II, and the associated references, directly into the numerical simulations. In addition, SINDA/G utilizes an advance lumped mass, resistance-capacitance network approach in conjunction with its finite difference numerical methods. The SINDA/G application suite can interface with most CAD systems, including SolidWorks.

In addition to the continued development of thermal models, mission thermal analysis for MiXI could be performed for the mission candidates discussed in Chapter I. Thermica³⁸, a Monte-Carlo ray tracing radiation program, is part of the SINDA family and would be an ideal candidate for analyzing spacecraft thermal conditions.

Appendix A: Experimental Procedures

The purpose of this section is to provide a detailed and repeatable order of operations for conducting MiXI thruster testing in the Lab 137 30" HVEC vacuum chamber.⁴¹ To minimize experimental test time observe the following procedures in the order they are written.

Lab 137 30" HVEC Procedures

Pre-Pumping Procedures and Safety Checks

1. Ensure that all vacuum control panel toggles are switched to the off position.
2. Make sure all service panels, especially the relay cover, are closed and secure.
3. Flip the 240 VAC breaker to the "on" position.
4. Open the ball valve to the pressurized air line.
5. Check the pressurized air regulator and ensure that it reads between 70-75 psi.
6. Turn on the "Main Power" on the vacuum control panel.
7. Turn on the Cryogenic Temperature Indicator.
8. Turn on the Granville-Phillips 375 Vacuum Gauge Controller.
 - a. Convectron gauge 2 (CG2) indicates cryopump pressure in torr.
 - b. Convectron gauge 3 (CG3) indicates chamber pressure in torr.

Cryopump Roughing Procedure

1. Turn on the "Mechanical Pump" on the vacuum control panel.
2. Check the sight glass on the back of the Welch 1397 roughing pump to ensure the oil level is acceptable. If it is not see manual for procedures.
3. Turn on the "Rough Interlock Valve" on the vacuum control panel.
4. Turn on the "Cryo Rough Valve" on the vacuum control panel.
5. Monitor the 375 Vacuum Gauge Controller and ensure that cryopump pressure is falling.
6. Once pressure reads 50 - 150 microns (5.0×10^{-2} to 1.5×10^{-1} torr) proceed to Cryopump Compressor Procedure.
 - a. Note: It is preferential for the cryopump pressure to be as low as possible. Beginning Cryopump Compressor Procedure at 50 microns has shown marked improvement in pumping speeds. However, if roughing pump performance has degraded, compressor procedures can commence at 150 microns.
7. If cryopump pressure never reaches 150 microns or pressure is decreasing at an unacceptable rate, proceed to Martin-Victor Cycling Procedure.

Martin-Victor Cycling Procedure

Only to be used when pressure ceases to decrease to the required vacuum or decreases at an extremely slow rate when using the roughing pump.

1. Close the roughing valve.
2. Immediately turn off the roughing pump.
3. Wait 30 seconds.
4. Turn on the roughing pump.
5. Wait 10 seconds.

6. Open the roughing valve.
 - a. The pressure will initially rise, but then lower below the previous threshold. Repeat these procedures as necessary to achieve the required vacuum.

Cryopump Compressor Procedure

1. Make sure that the compressor is plugged into the 208V, 3 phase outlet on the left side of the vacuum chamber.
2. Verify that the helium pressure on the CTI SC Series Compressor is 250 psi.
 - a. If the helium pressure is incorrect **do not operate the compressor**. If this is the case please refer to the Helium Addition Procedures.
3. Verify that the cover limit switch is depressed. The compressor will shut off if this is not actuated. Note: If the compressor ceases to operate at any point this is the first area the operator should check.
4. Make sure that the “Cold Head” and “Compressor” power switches on the front of the compressor are on.
5. Turn on the “Compressor” switch on the vacuum control panel.
6. Verify that the running helium pressure is 285 psi. The needle will oscillate by 5 psi. This is normal and not a cause for concern.
7. Observe the cold head motor to ensure that it rotates clockwise. Listen for any signs of seizing. It will sound like bad brakes on a car grinding and will be very loud.
8. Monitor the Cryopump Temperature Indicator. The temperature will begin to fall slowly until it reaches an operating point between 17 – 20 K. This process typically takes between 3 – 4 hours but can be faster or slower on given runs.
9. The pressure in the cryopump must remain at 150 microns or lower throughout operation. To ensure that this occurs leave the “Cryo Rough Valve” open and the “Mechanical Pump” on. These can be turned off, if desired, once the Cryopump Temperature Indicator reaches 150 K. At this point the pressure will remain below operating thresholds without the aid of a roughing pump.
10. Monitor the compressor throughout the procedure to ensure that overheating does not occur.

Experimental Loading Procedure

This process can be conducted at any time but is should be done during the first two hours after the Cryopump Compressor Procedure has been initiated. This will coincide with a cryopump temperature still above 100 K. Adhering to this policy will minimize experimental testing time.

1. Turn on the “Vent Switch” on the vacuum control panel.
2. Monitor the Granville-Phillips 375 Vacuum Gauge Controller to ensure that the chamber pressure rises to levels at or above atmospheric pressure (760 torr).
 - a. Note: Not observing this procedure is likely to result in catastrophic shifting of the entire vacuum system and will lead to extensive repair.
3. Raise the bell jar using the hoist controls
 - a. Use the “slow” buttons when raising or lowering the bell jar within four inches of the chamber.

- b. The “fast” buttons can be used to raise or lower the bell jar to loading heights.
4. Turn off the “Vent Switch” on the vacuum control panel.
5. Install the experimental setup according to the goals of your given test. Refer to procedures provided later in this section for connecting individual experimental equipment.
6. Ensure that all materials being placed in the chamber have acceptable outgassing levels. If unsure check Ref. 17 for this value.
7. Check the bell jar gasket to ensure a **complete coating** of high vacuum grease.
8. Ensure all pipe, cables and other equipment clear the shroud.
9. Lower the bell jar.
10. Check the perimeter of the bell jar to ensure a uniform seal.

Chamber Roughing Procedure

1. Turn on the “Mechanical Pump” on the vacuum control panel.
2. Turn on the “Chamber Roughing” on the vacuum control panel.
3. Monitor the chamber pressure on the Granville-Phillips 375 Vacuum Gauge Controller.
4. When the chamber pressure reaches less than 1 torr, shut off the “Chamber Roughing” on the vacuum control panel. This pressure can be lower but should be below or near the calculated crossover pressure for this chamber. Refer to Chapter III of this thesis for this formula. Operating the cryopump near this pressure ensures that the operating life of the pump is maximized.
5. The pressure in the chamber will rise so take this into account when roughing.

Cryotorr Pumping Procedure

These procedures can commence once the cryopump temperature is below 20 K and the chamber pressure is below the calculated crossover.

1. Turn off the “Chamber Rough” and “Cryo Rough Valve” on the vacuum control panel.
2. Turn off the “Mechanical Pump” on the vacuum control panel.
3. Turn on the “Pressure Interlock” on the vacuum control panel.
4. Open the high vacuum valve by turning on the “Gate Valve” on the vacuum control panel.
5. Within moments the chamber pressure on the Granville-Phillips 375 Vacuum Gauge Controller will read 0 microns. Once this occurs turn on the Ionization Gauge (IG) on the Granville-Phillips 307 Vacuum Gauge Controller.
 - a. Turning the ion gauge before the chamber pressure reaches 0 microns may result in the filament burning out.
6. Experimentation can commence once the pressure reaches 3.5×10^{-6} torr.

Experiment Removal Procedure

To be used when all experimentation is complete and the experimental apparatus needs to be removed.

1. Turn off the Granville-Phillips 307 Vacuum Gauge Controller.
2. Turn off the “Gate Valve” to close the high vacuum valve.

3. Turn off “Compressor” to power down the cryopump.
4. Turn off the “Pressure Interlock” on the vacuum control panel.
5. Turn on the “Vent Valve” to vent to chamber.
6. Deactivate all individual experimental equipment.
7. Once the chamber pressure reads 760 torr or higher, raise the bell jar.
8. Remove the thruster.

Shut Down Procedure

1. Turn off all switches on the vacuum control panel.
2. Turn off the Granville-Phillips 375 Vacuum Gauge Controller.
3. Turn off the air pressure main by closing the ball valve.
4. Turn off the 240 VAC power breaker.
5. Lower the bell jar.

Appendix B: Additional Thermal Plots

The following paragraphs are the thermal results for the MiXI CP configuration that involved repositioning the permanent magnets off of the anode wall. A complete examination of this modification is outside of the scope of this thesis. In addition, this configuration is not likely to achieve proper electron confinement. The modeling techniques and results are included for completeness and the sake of future work.

Repositioning of Permanent Magnets

Another proposed solution for preventing high temperatures for the permanent magnets is to change the ring location by using stronger, smaller magnets.. These magnets would be moved away from the anode wall eliminating the direct conduction path between the anode and the magnets. In this configuration, the magnets would only experience heating from radiation off the anode walls. In essence, the anode would be acting as a radiation shield between the cathode and permanent magnets. This configuration is suitable from a pure thermal standpoint but would need to be investigated to determine if suitable magnetic field topography and discharge stability can be achieved and to ensure that other performance characteristics are not compromised. Figure 72 shows the current magnet location on the left and the proposed magnet location on the right.

Figure 72. A model of a) the current downstream permanent magnet locations and b) of the proposed permanent magnet locations moving the magnets off the walls to effectively shield the magnets from a direction conduction path.

Magnet Repositioning Results

The results for the repositioned magnet design are shown in Figure 73. The maximum magnet temperature for this design was 523 K. This result is 100 degrees below the maximum samarium cobalt operating temperature. This design has the same thruster head mass (less considering the magnets) as the baseline case. While this temperature reduction is significant, an examination of magnetic field topography, which is outside the scope of this thesis, would have to accompany this result.

Figure 73. A thermal plot of the permanent magnets spaced off of the anode walls.

References

¹“DST-Precision Thrusters”, Jet Propulsion Laboratory,

[<http://dst.jpl.nasa.gov/thrusters/>].

² Jahn, R. G., Physics of Electric Propulsion, Dover Publications, Mineola, New York, 2006, Chaps. 1-5, 7.

³ Goebel, D. M., Katz, I., Fundamentals of Electric Propulsion, John Wiley & Sons, Hoboken, New Jersey, 2008.

⁴ Jameson, K., “Development and Testing of a 13 cm XIPS Thruster,” Master’s Thesis, Cal Poly State University, San Luis Obispo, CA, 2003.

⁵ “XIPS – The Latest Thrust in Propulsion Technology”, Boeing: Satellite Development Center, [<http://www.boeing.com/defense-space/space/bss/factsheets/xips/xips.html>].

⁶ “NASA Innovative Engines”, NASA Glenn Research Center,

[<http://www.nasa.gov/centers/glenn/about/fs08grc.html>]

⁷ Mao, H. S., “Miniature Xenon Ion Thruster (MiXI): An Overview,” Wirz Research Group, UCLA Advanced Propulsion Laboratory, University of California, Los Angeles, March 2010.

⁸ Wirz, R., “Discharge Plasma Processes of Ring-Cusp Ion Thrusters,” Ph.D. Dissertation, Division of Engineering and Applied Sciences, California Institute of Technology, Pasadena, CA, 2005.

-
- ⁹ “Planet Quest: Missions – Terrestrial Planet Finder”, Jet Propulsion Laboratory, Rodriguez, J., Lawshe, C., [http://planetquest.jpl.nasa.gov/TPF/tpf_index.cfm].
- ¹⁰ Martin, S., Wirz, R., “TPF-I Emma X-Array: 2007 Design Team Study,” Jet Propulsion Laboratory/California Institute of Technology, April 2007.
- ¹¹ “GRACE – Gravity Recovery and Climate Experiment”, University of Texas/NASA/DLR, [<http://www.csr.utexas.edu/grace/>].
- ¹² Nugent, R., Munakata, R., Chin, A., Coelho, R., Puig-Suari, J., “The CubeSat: The Picosatellite Standard for Research and Education,” AIAA, CubeSat, Cal Poly State University, 2008.
- ¹³ “CubeSat Solar Panels”, Clyde Space, [http://www.clyde-space.com/cubesat_shop/solar_panels].
- ¹⁴ “Small Satellite Solar Panel Datasheet”, Clyde Space, 2009.
- ¹⁵ Wirz, R., Polk, J., Marrese, C., Mueller, J., Escobedo, J., Sheehan, P., “Development and Testing of a 3cm Electron Bombardment Micro-Ion Thruster,” *International Electric Propulsion Conference*, Pasadena, CA, 2001
- ¹⁶ Wirz R., Sullivan R., Przybylowski J., Silva M., "Discharge Hollow Cathode and Extraction Grid Analysis for the MiXI Ion Thruster," *International Journal of Plasma Science and Engineering*, Vol. 2008, Article ID 693825, June 2008.
- ¹⁷ Wirz, R., Goebel, D., Polk, J., Marrese, C., Mueller, J., “Experimental and Computational Investigation of the Performance of Micro-Ion Thruster,” *AIAA Joint Propulsion Conference*, AIAA, Washington, DC, 2002, pp. 3

-
- ¹⁸ Wirz, R., Goebel, D., Marrese, C., Mueller, J., “Development of Cathode Technologies for a Miniature Ion Thruster,” *AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA, Washington, DC, 2003, pp. 1-12
- ¹⁹ Martin, O., Victor, A., “Operation of the HVEC Cryopump Vacuum Chamber and Resistojet Testing,” Senior Project, Cal Poly State University, San Luis Obispo, CA, June 2001.
- ²⁰ “Cryo-Torr® Pump Installation, Operation and Maintenance Instructions”, Helix Technology Corporation, Mansfield, Massachusetts, 2004.
- ²¹ “Diffusion Pumps”, Midwest Tungsten Service,
[<http://www.tungsten.com/Diffusion%20Pump.pdf>].
- ²² “Type K Thermocouple Reference Table”, OMEGA,
[<http://www.omega.com/temperature/Z/pdf/z204-206.pdf>].
- ²³ “Samrium Cobalt Magnets”, Adams Magnetics,
[<http://www.adamsmagnetic.com/pdfs/samariumcobalt.pdf>]
- ²⁴ “Outgassing Data for Selecting Spacecraft Materials”, NASA, Thomas, D. L., Viens, M. J., Waterbury, S., [<http://outgassing.nasa.gov/>].
- ²⁵ Younger, C., “Thermal Modeling of a Miniature Xenon Ion Thruster,” *International Electric Propulsion Conference*, Ann Arbor, MI, 2009
- ²⁶ Thermal Desktop, Software Package, C&R Technologies, Littleton, CO, 2005.
- ²⁷ SINDA/FLUINT, Software Package, C&R Technologies, Littleton, CO, 2005 .
- ²⁸ AutoCAD 2009, Software Package, Autodesk, San Rafael, CA, 2009.

-
- ²⁹ “MACOR – Machinable Glass Ceramic”, Corning,
[<http://www.technicalproductsinc.com/pdf/macor.pdf>]
- ³⁰ SolidWorks 2009, Software Package, Dassault Systèmes SolidWorks Corp., Concord, MA, 2009.
- ³¹ Incropera, F.P., DeWitt, D.P., Fundamentals of Heat and Mass Transfer, John Wiley & Sons, New York, NY, 1990.
- ³² Siegel, R., Howell, J. R., Thermal Radiation Heat Transfer, Hemisphere Publishing Corp., Washington D.C., 1992.
- ³³ Gilmore, D. G., Spacecraft Thermal Control Handbook Volume 1: Fundamental Technologies, The Aerospace Press, Reston, Virginia, 2002.
- ³⁴ “Properties of Common Solid Materials”, EFUNDA,
[http://www.efunda.com/materials/common_matl/common_matl.cfm].
- ³⁵ Van Noord, J., “NEXT Ion Thruster Thermal Model,” *AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA, Cincinnati, OH, 2007
- ³⁶ Van Noord, J., “Thermal Modeling of an Ion Thruster,” Ph.D. Dissertation, Aerospace Engineering Department, University of Michigan, Ann Arbor, MI, 1999.
- ³⁷ Brophy, J. R., Wilbur, P. J., “Ion Thruster Performance Model,” Ph.D. Dissertation, Colorado State University, Fort Collins, CO, Dec. 1984.
- ³⁸ Van Noord, J., “Analytical Ion Thruster Discharge Performance Model,” *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA, Sacramento, CA, 2006.

³⁹ Celik, I. B., “Procedure for Estimation and Reporting of Uncertainty Due to Discretization in CFD Applications,” Mechanical and Aerospace Engineering Department, West Virginia University, Morgantown, WV

⁴⁰ Overview of SINDA/G Thermal Analyzer, Network Analysis Inc., Arizona
[http://www.sinda.com/sinda_home.htm. Accessed 2/24/10.]

⁴¹ Yount, R., “Plasma Uniformity of XIPS Thruster,” Master’s Thesis, Cal Poly State University, San Luis Obispo, CA, 2005.