Thermal Analysis of the 100-kW class X3 Hall Thruster

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Nomenclature

TDU	=	Test development unit
WCH	=	Worst Case Hot
WCC	=	Worst Case Cold
ARRM	=	Asteroid Redirect Robotic Mission
HERMeS	=	Hall Effect Rocket Magnetically Shielded
JPL	=	Jet Propulsion Laboratory
GRC	=	Glenn Research Center
IR	=	Infrared
UM	=	University of Michigan
TC	=	Thermocouple
AA[X]-[Y]	=	Coil location designation, X = Channel designation(Inner, Middle, Outer) and Y = Inner, Outer of specified channel

I. Abstract

Electric propulsion has generated significant interest recently as a mass efficient thrust option for deep space missions. This increased interest has drawn a renewed focus on improving the efficiency of electric propulsion thrusters, specifically Hall thrusters. Hall thrusters are a specific subset of ion engines that accelerate charged particles using a Hall current. Recent research into the 12.5 kW HERMeS (Hall Effect Rocket with Magnetic Shielding) for use on the proposed Asteroid Redirect Robotic Mission (ARRM) has shown the desire to use these devices on flight missions outside of earth orbit. This paper will focus on another Hall thruster, the X3. The X3 is a 100 kW class Hall effect thruster used for laboratory technology development. What makes the X3 unique, relative to more contemporary Hall thrusters beyond the order of magnitude increase in discharge power, is that the X3 is a 3 channel, nested Hall thruster. Common Hall thrusters typically have one annular channel where the plasma is constrained and used to charge the fuel and accelerated. The X3's 3 channels are nested in a concentric format, with each channel fitting in a single plane. This presents very unique thermal modeling challenges with respect to quantifying the impact of plasma thermal loading and cross talk between the power dissipating components for each channel. This work will discuss the development of the X3 thermal model and the efforts to validate it with experimental data. Furthermore, some of the unique challenges that appear when trying to model high power components will be discussed. The X3 represents a challenging and interesting example of the issues affecting thermal modeling of high power electric propulsion thrusters which will become more prevalent as their use becomes more common.

II. Introduction

The X3 thruster is a three channel, nested Hall effect thruster, which is a specific type of electric propulsion ion engine. The XR-100 system is part of NASAs Human Exploration and Operations Mission Directorate (HEOMD), Advanced Exploration Systems (AES) Next Space Technologies for Exploration Partnerships (NextSTEP) program, which seeks to develop advanced space travel technologies. One of the key components of the XR-100 system is the X3 thruster, on which this work is primarily focused.

An ion engine, a form of electric propulsion, is appealing for this application as it has a very high specific impulse, which can generally be understood as it requires less fuel mass to achieve the required impulse to accomplish a mission. In general, electric propulsion uses electrical and magnetic fields in order to accelerate charged particles (ions), thereby transferring momentum to a spacecraft. These charged particles exist as a plasma that is contained in the thruster. The charged particles are accelerated from the anode to the cathode in the thruster. The DAWN mission was the first human-made space craft to visit two interstellar bodies on the same mission, which was enabled by its use of electric propulsion. The 2.3 kW thruster on DAWN used a pair of gridded electrodes in order to accelerate ions into space.

NASA has conducted extensive testing of ion engines, prior to the DAWN mission, including Deep Space 1 and the 7 kW NEXT ion engine [1,2,3]. These tests sought to quantify a number of properties of the thruster, including performance and the wear behavior of the thruster on long duration missions. Ion engines can be run at a variety of different conditions and typically have power throttling ratios about 5-10.

In a Hall thruster, magnetic fields are used to constrain the plasma necessary to ionize the fuel gas. A cross section of a typical Hall thruster can be seen in Figure 1.

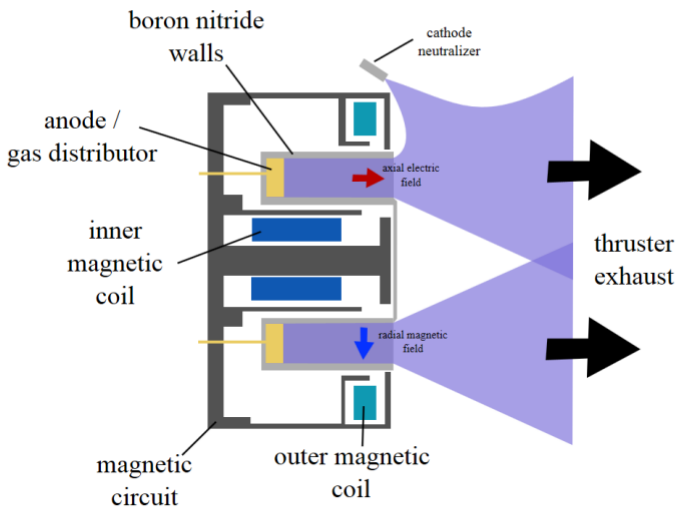

Figure 1: Cross section of typical Hall thruster

Note that unlike the ion engine on the DAWN mission, there are no grids to accelerate the ions in a Hall thruster. Instead, the discharge channel is open and while some ions will strike the side and front faces of the thruster, the exhaust plume proceeds largely unimpeded downstream of the thruster.

A detailed study of thermal steady state Hall thruster behavior done exclusively by IR was performed by Mazouffre [7]. This study was primarily looking at plasma-surface interactions but was useful in understanding some of the features of steady state Hall thruster operation. Even during the NEXT testing, NASA was looking into Hall effect thrusters, such as the work by Jacobson [6]. While this paper is primarily a review of Hall thruster testing in 2004, it does provide some insight on the transient heat up behavior of a few Hall thrusters from a room temperature like condition. The thrusters mentioned in this work typically heated to steady state within approximately four hours. Thermal and structural modeling of Hall thrusters was done by Yim [5] to help understand temperature response of the thruster. However, in this test, an analytical method was used to estimate the steady state behavior since the collection of temperature data was secondary as an experimental goal. Still their work showed good agreement with the temperature data collected and was useful as reference for this work.

The X3 will operate at 100 kW as part of the NextSTEP program, but has been designed to operate up to 200 kW. The discharge power of the thruster is determined by the discharge volage and current settings. Thrusters like the X3 are advantageous for future deep space missions because of their high specific impulse. Also, nesting channels tends to be the most mass efficient way to increase the total power capability of a Hall effect thruster.

However, the tremendous energy dissipation presents some unique thermal challenges. Typical Hall thrusters only have a single channel and so there is only one set of plasma loads to deal with. With three channels, as in the X3, the plasma loads from each channel dissipate heat into the thruster and interact with one another. The two inner channels also have more restrictive heat rejection boundaries since they can not radiate efficiently in the radial direction.

The modeling effort discussed in this work was created to support the testing of the X3 thruster, which is taking place at the University of Michigan. The testing is primarily designed to evaluate design improvements in the X3 thruster as well as new cathode designs being provided by JPL.

In this paper, we detail the development and calibration of a thermal model of the X3 thruster. This model will primarily be used to support testing of the X3 at 100 kW for NextSTEP and to evaluate future design trades in order to accommodate the thruster's operation at power dissipations approaching 200 kW. The results of modeling of the

X3 thruster test will be shown and analyzed with some rough comparison to X3 steady state data. Hall thrusters are unique amongst spacecraft components in that they maintain relatively high temperatures (~500 C) for extreme durations, compared to other spacecraft components. This work is intended to highlight some of these issues for use in future work.

III. Model Description

This model was built from CAD models provided by the University of Michigan. An image of the X3 thruster can be seen in Figure 2. Due to ITAR restrictions, it is difficult to show the internal structure of the thruster. This paper will go into as much detail as is possible but more detailed questions about the layout of the thruster should be directed at the authors.

Figure 2: X3 thruster (dark areas are plasma channels)

The thermal modeling software NX-SST was primarily used due to the ease of incorporating mechanical drawing files into the thermal model. Typically, mechanical drawing files of individual components were imported into NX and their geometries were idealized and simplified to facilitate mesh generation. The meshed idealized parts were then put into an assembly FEM where they were assembled in the configuration of the thruster.

Once the desired geometry was established, the material and optical properties were put into the model as well as contact conductances between the components. Most interfaces are mechanically attached without any thermal interface material and so were generally modeled as bolted interfaces, with respect to contact conductance. This yielded several areas in the model where contact conductances were quite low, specifically with ceramic components that interfaced with metal parts.

While there is some variation in the optical properties of thruster components as a function of temperature, in practice, this variation has not been observed to be significant. Most of the high temperature components did not appear to undergo significant optical or thermophysical property changes. However, carbon deposition can have a tendancy to alter the external surfaces' emissivity the longer the thruster was run. This is because of the presence of carbon targets that protect the vacuum chamber from high energy ions by absorbing their impact, sputtering carbon into the chamber in the process. This is a contributing factor which makes thermal modeling of all Hall effect thrusters difficult in large scale tests.

Typically, to validate the thermal model of a Hall thruster, the contact conductances, optical properties, and plasma thermal loads are adjusted (within reasonable bounds) to bring the temperature response of the model to reflect the temperature response in test. This is because it is possible to estimate the heat loads based on plasma modeling but there is variability. This variability is what is used to validate the thermal model since the researchers verified that their validated thermal loads were reasonable with respect to the plasma modeling.

This was more challenging with the X3 because the thruster has more mass than is typical. As a result, achieving thermal steady state throughout the thruster is more difficult. The data provided by UM to JPL included 4 runs; 3

seperate runs where each channel was running independantly, and a single run with only the magnet coils running (no channel was ignited). After extensive study of the data, it was determined that the runs where any channel was firing did not demonstrate sufficient temperature stability to serve as a representation of thermal steady state. However, the run with the magnets active and no channel firing did actually reach steady state and so this run was used for validation purposes.

Since the thermal model is also used to dial in the variability of the plasma loads, the researchers believe that validating against this case is sufficient in order to produce a credible thermal model. This will allow the researchers to use the model when assessing the impact of simulated plasma loads beyond those seen in test.

IV. Modeling Results

In this section, the results of the validation effort for the X3 thermal model will be discussed. First, an explanation as to why the current thermal model was validated only against a test run where only the thruster's magnet coils were operated. As discussed previously, data was provided for each individual channel running independently but it was determined through analysis that these runs were not at thermal steady state. A list of the TC's with their descriptions is seen in Figure 3.

TC #	TC Description
1	Outer Front Pole 6:00 connector Top
2	Outer Front Pole 6:00 connector outisde
3	Back Pole 6:00 connector
4	OFP 6:00 top
5	OFP 6:00 outside
6	Back Pole 6:00
7	Back Pole inner 4:00
8	Back Pole inner face outer ring 6:00
9	Back Pole inner face 6:00 outer ring
10	Back Pole back face 6:00 inner ring
11	Inner Cup
12	Mid Cup
13	Outer Cup
14	AAI-I wire turns
15	AAI-O wire turns
16	AAM-I wire turns
17	AAM-O wire turns
18	AAO-I wire turns
19	AAO-O wire turns
20	AAI-O bobbin
21	AAI-O Bobbin
22	AAI-O Bobbin downstream
23	AAM-O bobbin upstream
24	AAM-O bobbin midline
25	AAM-O bobbin downstream
26	AAO-O bobbin upstream
27	AAO-O bobbin midline
28	AAO-O bobbin downstream
29	Front Pole Cathode Channel BP interface AAI
30	Front Pole Cathode Channel Midline 1" from int
31	Front Pole Cathode Channel Midline 0.5" from int
32	Back Pole Cathode Channel midline

Figure 3: TC locations(AA[X]-[Y]) = Coil location designation, X = Channel designation(Inner, Middle, Outer) and Y = Inner, Outer of specified channel

The testing that generated these results was not done primarily for the purposes of establish thermal steady state. This was the reason for the definitions of thermal steady state being inadequate for all components. A comparison of the individual channel results with model estimates are shown in Figure 4 through **Error! Reference source not found.**.

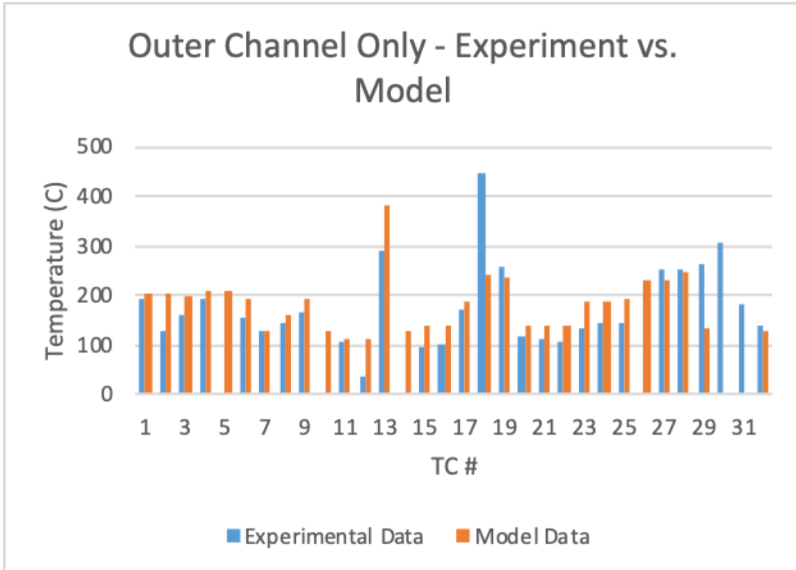

Figure 4: Outer Channel Only- Experiment vs. Model

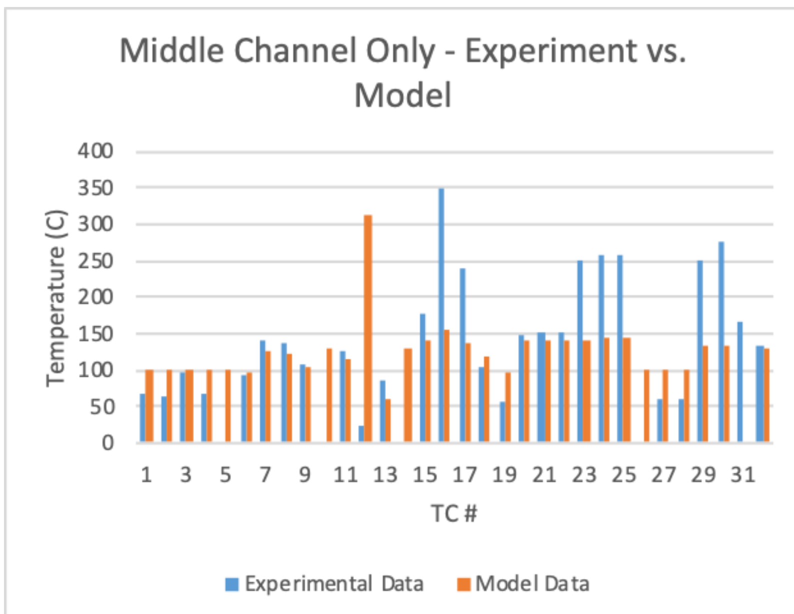

Figure 5: Middle Channel Only - Experiment vs. Model

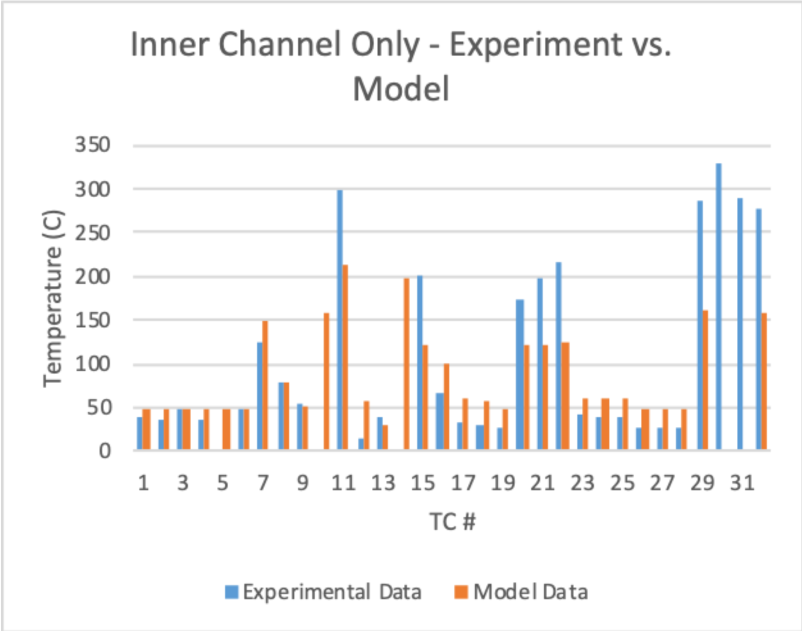

Figure 6: Inner Channel Only - Experiment vs. Model

The reason these runs were found to not be thermal steady state is due to substantial gradients that are not consistent with thermal steady state. Inspection of the experimental data of TC's 30-31 in the Middle channel only case, shows there is a gradient of 111 °C. These TC's are only roughly 0.5" apart and if these were actually based on geometry, there would be more energy flowing through these TC than the entire power dissipation of the thruster. As a result it was determined that validation of the thermal model would need to be focused on the magnet bakeout case.

That being the case, the model is reasonably close in most of the external components that are likely to reach steady state faster by virtue of increased exposure to the ambient thermal environment, such as the outer front poles and exposed areas of the backpole. In all three channels, the inner core is where the largest transient gradients were observed, indicating that this component still had not reached thermal steady state.

The magnet bakeout was conducted over a much longer time period than the channel runs and as a result, was observed to actually reach a reasonable thermal steady state. A comparison of the magnet bakeout thermal data with the model are shown in **Error! Reference source not found.**.

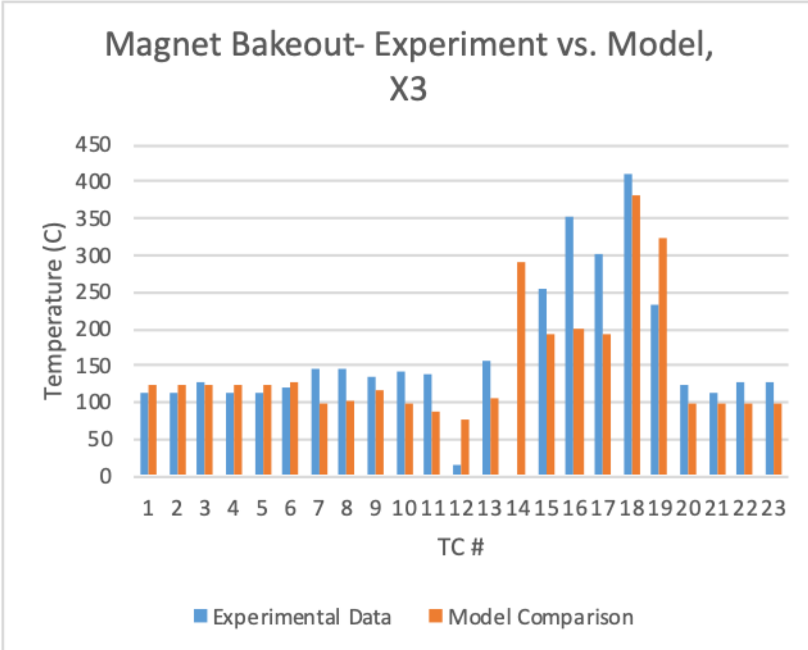

Figure 6: Magnet Bakeout - Experiment vs. Model

Note that in this case the gradient for the inner core, TC's 30-31 is less than 15 °C, which is consistent with the power dissipation of the thruster. The mean relative error between the experimental values and model predictions across the entire thruster is approximately 25%, which is consistent with prior Hall thruster thermal model development [8]. The main issues with accuracy are associated with the magnet coils and their bobbins. Part of the issue with the coils is that they are encased in a potting compound that makes estimating its optical properties and contact to the bobbins difficult. The potting compound does not have deterministically measured values for optical properties nor is it precisely known what the thermal conductivity of the wire/potting compound combination is. Also, the discrepencies noted in the coils led to the determination that the thruster actually has coil covers installed on the magnetic coils, that were not part of the original CAD model provided to JPL. This is likely why the model significantly underpredicts some of the magnet temperatures in the coil bakeout case.

When looking at the experimental data the model tended to under predict the temperatures in the bobbins (except in the outermost coil) even though the magnitude of the trend was fairly intact. However, it is difficult to discern a trend in the model predictions of the magnet coils. In these components, the thermophysical properties are much more difficult to ascertain. As they are wire coils buried in a brittle potting compound, its thermal conductivity is anisotropic and the optical properties can vary locally based on the state of the surface of the potting compound. All this is to say that more significant variation is expected on the surface of the coils.

Furthermore, test conditions of Hall thrusters are such that continuous carbon deposition to exposed surfaces means that surfaces tend to gradually gain higher emissivities as testing goes on. The relatively high constant temperatures also create large gradients across the massive thrusters.

A mesh independence study was conducted on the thruster in order to determine that there was adequate nodalization in the model. The mesh size of the components were doubled and a change of temperature was noted as less than 2.2°C, which is within the minimum thermocouple uncertainty (±2.2 °C for K-type thermocouples). This was deemed sufficient to demonstrate that original mesh of the thermal model was sufficient.

That being said, efforts are ongoing to improve the accuracy of the temperature measurements and property representations in order to drive the accuracy of the thermal model higher. Most of the current effort is focused on a better understanding of the thermophysical properties of the magnet coils. As the researchers gain a better understanding of the thermophysical and optical properties, even as they change, it is expected that a better thermal model will follow. This will be critical as the thermal model of the X3 is integral to assessing design trades for the thruster as well as evaluating the maximum operating conditions of the thruster.

V. Conclusion

In this work, the development of a thermal model of the X3 thruster, part of the XR-100 system was detailed. Some of the challenges of making this thermal model workable have been detailed. The effort to validate this thermal model against the magnet bakeout thermal data was also discussed and shown to have been reasonably close. However, certain temperature measurements are off by significant margins and are known to the authors. Efforts are being made to diagnose the coponents, primarily the coils. In the process of conducting this research, it was found that the coils have an insulating plate installed on them that was not in the original CAD model, which the thermal modeling exposed. In the future the researchers will continue to improve the accuracy of the X3 thermal model as more thermal steady state data is provided. Reasonable accuracy of the X3 thermal model is critical for the X3's development because the thermal model is used to help evaluate the accuracy of the plasma models. Also the thermal model will be used to evaluate the thruster components to determine their compatibility with future power dissipations up to 200 kW. The XR-100 system represents a potential step forward on the path to high specific impulse deep space transport.

Acknowledgments

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