Thermal Characterization and Modeling of a Low-Power Laboratory Model TAL

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A low-power TAL was constructed and tested at Texas Tech University. The laboratory model's structure is similar to conventional designs. Initial operational characterization of the thruster was performed at power levels between 100 Watts and 1 kW. Thermocouples imbedded in the structure were used to monitor temperature rise due to resistive losses in the magnet coils alone, and temperatures during thruster operation. The relationship between the output power level and thruster temperatures was recorded. Thruster operation was compared at typical operating points before and after the thruster reached thermal equilibrium. A 3D thermal model of the thruster was developed based on the empirical measurements. The application of this data and thermal model to thruster structural design and materials selection is explored.

Introduction

Increasing interest in smaller satellites is pushing the development of small low-power electric thrusters. When modifying a mid-power Hall effect thruster design to operate on lower input power, the diameter of the acceleration region must be reduced.[1, 2] As the anode diameter becomes smaller, it becomes more difficult to dissipate heat from the thruster structure.[2] Thermal modeling and measurements have been performed on Texas Tech University's low-power TAL (Thruster with Anode Layer) to investigate this problem. Figure 1 shows the low-power TAL.

The thruster has a conventional TAL layout. It has been tested at power levels from less than 100 W to

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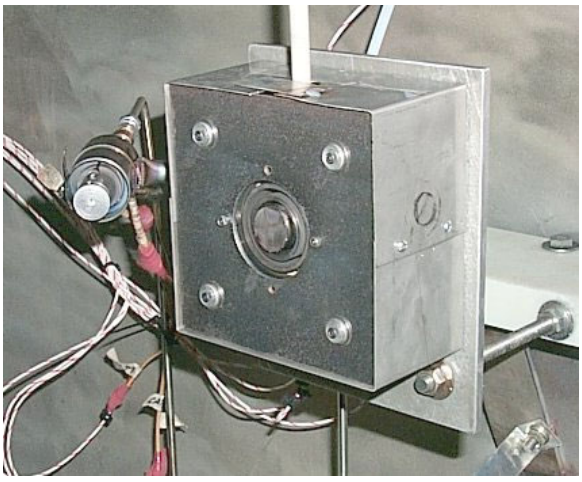

Figure 1: The low-power TAL: Average anode diameter is 1.5 inches; the width of the thruster is 5.5 inches. On the left is a NASA hollow cathode assembly. The presented testing utilized a hollow cathode system from Heatwave.

over 1 kW. Four solenoidal coils around the perimeter of the thruster and one in the center are used to create the needed magnetic field. The magnetic circuit of the thruster was constructed out of mild steel.

All of the thruster testing was carried out in Texas Tech's Space Simulation Facility. The facility consists of an 8-foot diameter by 14-foot long stainless steel chamber and the vacuum pumping systems needed to take the chamber down to the thruster's operational pressure. Using two large (36" diameter) diffusion pumps and six cryo-pumps, the system is able to maintain the pressure less than $1x10^{-5}$ Torr during testing. The facility is computer controlled, and the status is available on a website for remote monitoring. The facility currently lacks a thrust stand. Figure 2 shows a picture of the test facility.

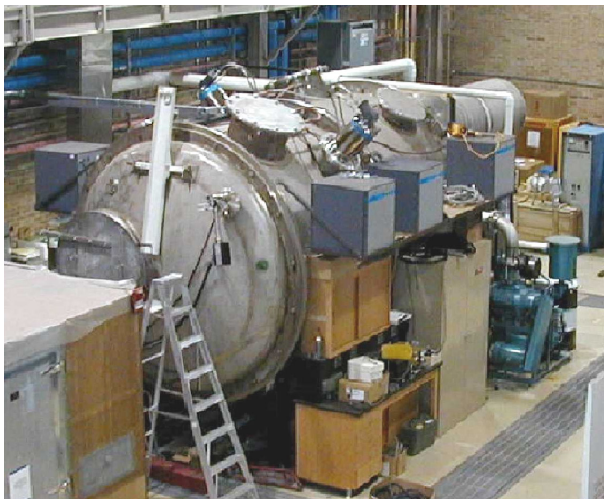

Figure 2: The Texas Tech Space Simulation Facility

Motivation

Thermal design is an important issue especially for low-power Hall thrusters, but it is also valuable in higher-power designs. The current laboratory model thruster has stability problems during operation, and variation in operational parameters from cold startup to when the thruster reaches thermal equilibrium. One current theory is that the Curie temperature is exceeded in portions of the magnetic circuit during operation (from earlier measurements showing extreme temperatures in certain locations), changing the carefully designed magnetic field profile. It was decided to investigate the thermal characteristics of the thruster both to improve the current device, and to assemble tools to aid in future designs.

Low-Power TAL Thermal Measurements

Temperature measurements were made on the thruster both with only the magnet coils turned on, and during operation. Measurements were made at three (and later eight) positions in and around the thruster structure. Thermocouples were wound into the inner coil and one of the outer coils, and also fixed in contact with the rear plate. Later, thermocouples were also attached to the rear anode mount, the back of the inner pole, and to three locations on the front plate. Readings from the thermocouples were taken every few seconds and recorded by the data acquisition computer. The current in the inner and outer windings was set at 6A for all testing.

One experiment performed was to give a reference point indicating how much of the temperature rise was generated by resistive losses in the windings. Temperatures were monitored with the coils energized, but without the thruster operating. Figure 3 shows an example plot of the temperature rise against time, and Table 1 shows the temperatures after reaching thermal equilibrium.

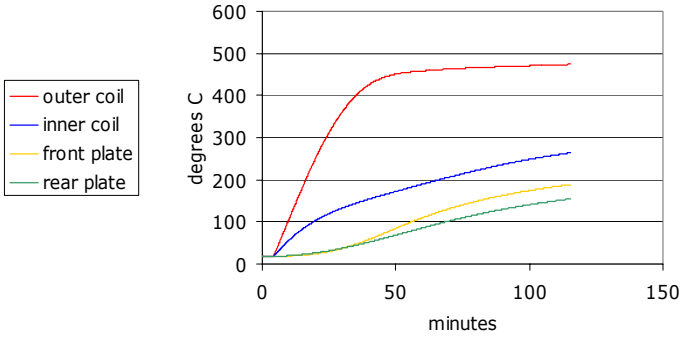

Figure 3: Example measured temperature rise, with only magnet coils energized

Temperature measurements during operation

The thruster was also left running long enough at several operating points to attain thermal equilibrium. (Thermal equilibrium was defined as being reached when the measured temperatures would vary no more than a tenth of a degree over a few minutes.) Figure 4 shows an example plot of the temperature rise against time, and Table 2 shows the tested operating points.

Table 1: Thermal equilibrium temperatures (degrees C), magnets energized only

Outer coil	Inner coil	Front plate-1	Rear plate	Front plate-2	anode support	Inner pole	Front plate-3
554.7	287.5	170	156	165	155	260	164

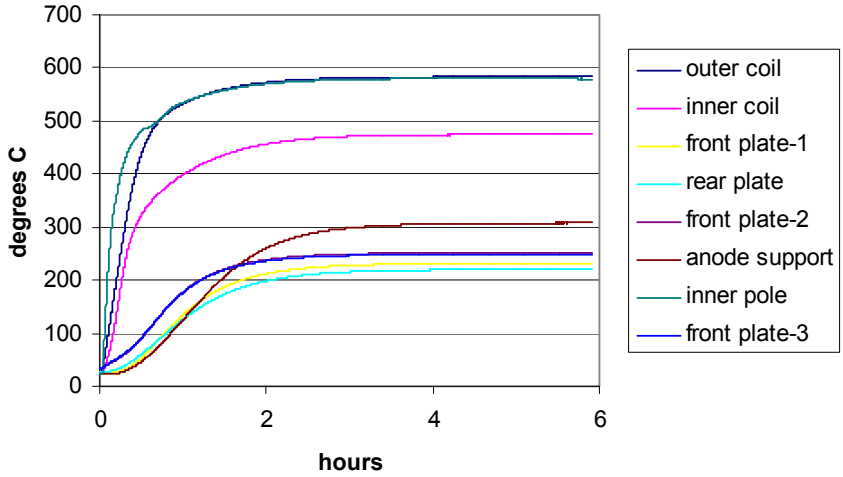

Figure 4: Example measured temperature rise during operation. Discharge voltage was 250V, anode flow was 0.7 mg/s, and the discharge current varied from 0.84A at startup to 0.66A at thermal equilibrium.

Table 2: Tested operating points vs. thermal equilibrium temperatures (degrees C)

Voltage (V)	Flow (mg/s)	Current (A)	Power (W)	Outer coil	Inner coil	Rear plate
200	0.8	0.88	160	577	456	212
250	0.8	0.86	200	593	512	233
300	0.7	0.73	210	600	538	243
300	0.8	0.94	240	594	563	250
300	1	1.23	300	611	639	271
350	0.8	0.94	280	614	647	278
400	0.8	1.01	320	596	668	244

The highest temperatures were recorded in the inner magnet coil. At even higher power levels than shown in table 2, the temperature of the inner pole would be above 800 degrees Celsius, which is greater than the Curie temperature for the material (around 770 degrees C). This would obviously be extremely detrimental to the magnetic field profile. The discharge current was observed to decrease 10-20% as the thruster warmed up (with the discharge supply voltage regulated and the mass flow rate held constant). This is thought to be a symptom of the magnetic field profile degradation. Even without reaching the Curie temperature, the coils tend to be hotter than the rated temperatures for any magnet wire insulation.

Low-Power TAL Thermal Model

To aid in improving the thermal design of the current thruster and also in creating future designs, a 3D finite element heat transfer model was developed in the Abaqus software package from Hibbitt, Karlsson & Sorensen, Inc. This model was developed using the temperature measurements made on the current thruster, and then used to model variations on the basic thruster design.

To thermally model the thruster, the components of the magnetic circuit (the five magnetic coil cores and the front and rear plates) were drawn and meshed using the modeling software. Leaving out the anode and

other components simplified the model, but could impact its accuracy. There are two general sources of heat in the thruster: ohmic loss in the magnetic coils and heat transferred from the plasma. For these heat inputs, incoming heat flux was applied to the surface of the magnetic cores and the edges of the pole pieces that form the acceleration region. Thermal transfer from the model was modeled through applying thermal radiation to the rear surface of the rear plate, the front surface of the front plate, and the front surface of the inner pole. The thermal emissivity of these surfaces was set to 0.6 (an average from several different sources for cold-rolled mild steel). Figure 5 shows the model with some initial guesses for parameter values. The incoming heat fluxes and the thermal conductivity of the interfaces between components were then manually varied until the temperature distribution in the model closely matched the measured temperatures.

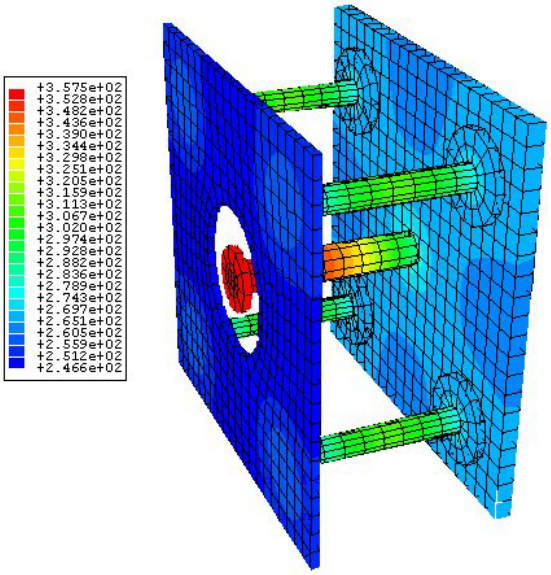

Figure 5: Thermal model, with only the magnet coils energized, before calibration to measured temperatures

The incoming heat flux to the magnetic cores in the model was calibrated to the measurements first. Measurements of the equilibrium temperatures in the thruster were taken with only the inner coil turned on, with only the outer coils turned on, and with all five coils turned on (all taken while the thruster was not in operation). A model was created for each of these situations, and adjusted until the temperature distribution matched up with the measured temperatures. The corrected temperature distribution model with all five coils energized is shown in Figure 6.

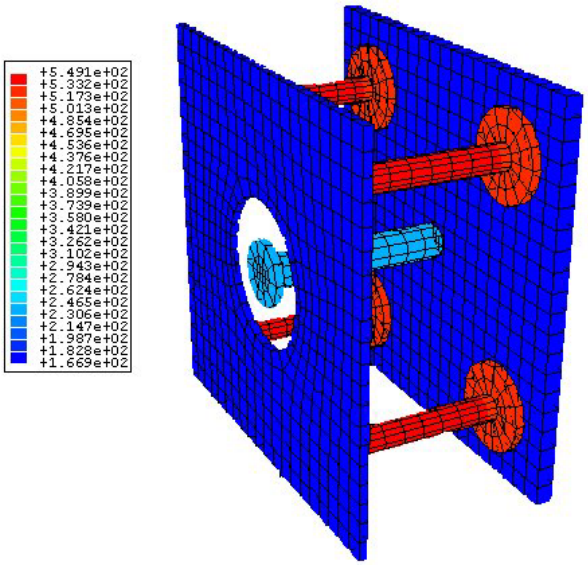

Figure 6: Thermal model, only magnets energized, after calibrating to measured temperatures

Originally it was thought that the calibrated model would look something like Figure 5, with large thermal gradients across individual parts. However, it turns out that the heat transfer characteristics of the model (and therefore the thruster itself) are dominated by the thermal contact resistivity between the individual parts (shown by the large temperature gradients across interfaces in Figure 6). When the thruster was originally constructed, no attempt was made to optimize these contact surfaces. The calibrated model shows an opportunity for improvement in more carefully constructing these interfaces.

After the model was calibrated for the magnets only, the incoming heat flux to model the heat transfer from the plasma was added. This method for modeling the heat from the plasma is crude, since it ignores the size of the plume and therefore the thermal radiation from the plume to the entire front surface of the thruster. It does however give some indication of what to expect from the temperature measurements in the rest of the structure. Figure 7 shows the thruster model with the plasma heat flux included.

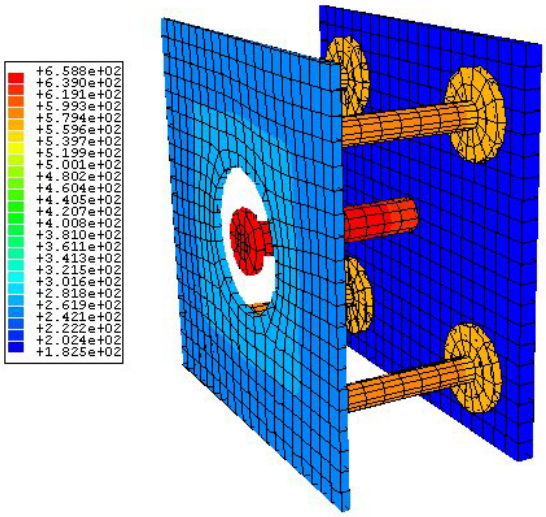

Figure 7: Thermal model, with heat flux inputs from both magnets and the plasma

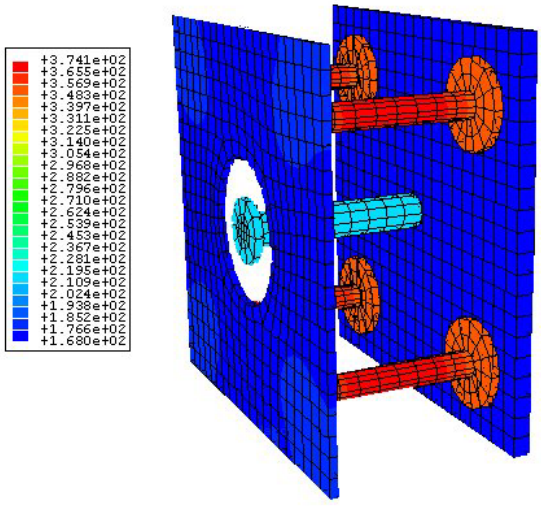

Figure 8: Thermal model with improved conductivity at contact surfaces

Applying the Thermal Model

The thermal analysis methods developed can now be used in experiments involving modifications to the current thruster design. When applying the model, it is important to remember that it is a very simple approximation to the current design. For example, the model only contains the parts of the magnetic circuit (not the anode or its associated components), and also does not take into account the radiation between different parts of the structure.

Improving contact resistance between magnetic circuit parts in current thruster

The first experiment that will be tried will be the improvement in the contact conductivity between the magnetic circuit components. This has the potential for drastically reducing the temperatures in the magnet cores. Improving the thermal contacts would involve increasing contact areas, being careful about making the contact surfaces smooth and square, and adding filler material to fill in any small gaps. Experimentation will have to show how much the joint resistance can be lowered. Figure 8 demonstrates the gain that would be made with the conductivity at the junctions doubled (without the plasma heat input).

Thruster with Relocated Magnetic Coils

Another experiment would be the relocation of the magnetic coils to behind the area of the current rear plate of the thruster. This would be an attempt to lower the temperatures that the magnet coils and the magnetic structure are exposed to. Figure 9 shows this concept. This model was made with a typical value of incoming plasma heat flux, and improved thermal conductivity at the part junctions. The middle plate of the thruster would be made of stainless steel. The windings would be located on the cores behind the middle plate, with the cores in front of the middle plate serving to carry the magnetic flux to the front of the thruster. This magnetic circuit would operate virtually the same as the current thruster, but with greater opportunity for thermal optimization. With an improved thermal design, it might even be possible to use standard magnet wire in the magnet windings.

Other Future Experiments

An area of interest involving Hall thrusters is pulsed mode operation. This would involve operating a thruster intermittently, with the discharge turned on for a period from a few seconds to a minute, and then shut off for a similar period of time. This might have the potential for operating a small thruster at higher peak power levels than would be possible under steady state conditions, due to a reduction in the intense temperatures at the center of the thruster. Using the

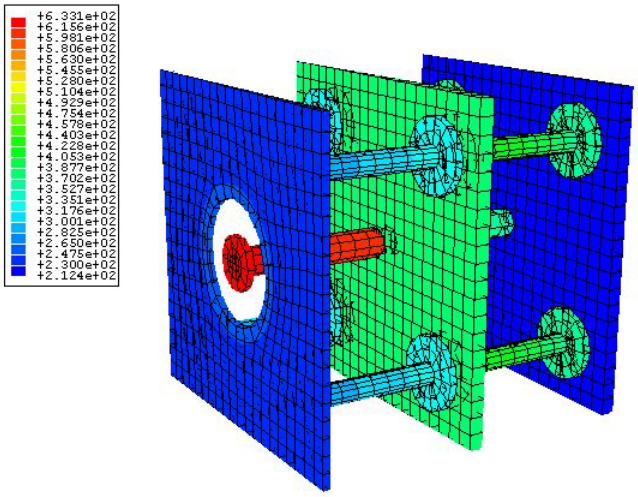

Figure 9: Thermal model of thruster with relocated magnetic coils

transient capabilities of the modeling software would allow experimentation with this concept without carrying out actual thruster testing.

Another experiment to be tried in the near future will be the development of a TAL with two concentric acceleration zones. This type of thruster would allow for a wider range of input power levels, and a higher power thruster in a lower power thruster package size. The thermal model developed for the low-power thruster design would be modified to fit this design, with the thermal load from a higher-power plasma discharge extrapolated from the smaller thruster. This model would lose much of its accuracy in the changes, but it would still give a good idea of where thermal problems might occur and how to solve them.

Conclusions

The thermal measurements and modeling carried out on the low-power thruster will be useful for future improvements of the design. Improving the thermal conductance between the magnet cores and the front and rear plates should help keep the magnetic circuit below the Curie temperature. The analysis techniques developed will also be very applicable to modifications to the design and to new designs.

References

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[2] TSNIIMASH, “Development of the anode layer thruster in the power range of 600 to 800 W: Technical Description and Test Results,” 1996.