

Infrared Thermographic Diagnostic for Imaging Hall Thrusters

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This paper describes a thermographic measurement system designed to map temperature in a Hall current thruster. The system comprises a FLIR A320 infrared camera equipped with a telephoto lens housed in a pressurized, temperature-controlled enclosure with a germanium window. When located in a vacuum chamber 4 m in front of a thruster, it has a spatial resolution of 1 mm. An array of boron nitride disks, each with a different known temperature placed in the field of view of the camera allows frame-by-frame temperature calibration. Absolute temperature error governed by variation in material emissivity is less than 5% or 25 °C at 500 °C. Relative temperature precision measured by statistical variation from the measured calibration curve is less than 5 °C. Examples of the performance of this system measuring the temperature of the Zero-erosion™ XR-5 (BPT-4000) Hall thruster in operation at the NASA Glenn Research Center are presented.

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Nomenclature

$B(T, \alpha)$	= the spectral radiance (W/m ² /μm/steradian)
c	= speed of light = 2.9979×10^8 (m/s)
$C(T)$	= the signal counts
h	= Planck's constant = 6.6261×10^{-34} (J-s)
k	= Boltzmann's constant = 1.3807×10^{-23} (J/K)
$R(T)$	= camera response for range n (counts/J)
T	= temperature (Kelvin unless otherwise noted)
Δt	= the integration time of the measurements (seconds)
ΔA	= emitting area
$\Delta \Omega$	= solid angle subtended by emitting area at pixel
$\epsilon(\alpha, T, \theta)$	= emissivity or surface emittance
$P(T)$	= emitted flux (Watt/m ²)
λ	= wavelength of radiation (m)
π	= 3.1415926535
σ	= Stefan-Boltzmann constant = 5.6704×10^{-8} (W m ⁻² K ⁻⁴)
τ_f	= filter transmission
τ_w	= window transmission
I_{mag}	= current through the thruster magnet coils

I. Introduction

WHILE high power Hall Current Thrusters (HCTs) are designed to have power densities similar to those of the well-established low power designs, quantitative understanding of the thermal stresses on high power HCTs is more important because of increased power dissipation. Power losses through heat transfer inside the discharge channel determine to a large degree the efficiency of the thruster. Heat losses to the channel walls are intricately connected to the secondary electron emission and erosion rate, and thus affect the operation of the thruster and its life expectancy. On the other hand, thermal losses to the anode may result in thruster damage if the heat is not dissipated properly. Furthermore, thermal gradients, especially during transient operation, can stress thruster components. For these and other reasons an accurate diagnostic method to measure temperature inside an HCT is needed.

Temperature measurements using thermocouples are often problematic because: 1) they cannot be reliably imbedded in the surfaces of interest, 2) the surfaces of interest may be at high voltage, and 3) the number of thermocouples may be insufficient to measure sharp temperature gradients. A properly engineered thermographic imaging system can overcome these shortcomings. Furthermore, a quantitative spatially and temporally resolved temperature image of the front of the thruster allows verification of thruster thermal models and the observation of the asymmetric thermal gradients that may not be predicted by a model. In this paper we describe the design and implementation of such an infrared imaging system. The system was found to be especially useful to create movies of the thermal history of a thruster as it transits different power levels or operational modes.

Infrared cameras have been previously used to image thrusters. Temperature images have been made of British T5 ion engine,¹ the PPS[®] 1350 and SPT-100 HCTs^{2,3} and Busek's 200W and 600W HCTs^{4,5} with varying degrees of accuracy. In all cases the thrusters were imaged from an off-axis viewing geometry. We also performed initial thermal imaging studies on the Zero-erosion[™] XR-5 (BPT-4000) from a 45 degrees off axis position at the Aerojet test facility in Redmond, WA.⁶ Results of this study led us to believe that thermal reflections from inside of the discharge channel could compromise the accuracy of the measurements. Consequently, we developed a system that could be placed precisely on the thruster axis centerline so that there would be high confidence that any azimuthal asymmetry observed would be real. Another feature that distinguishes this work from previous measurements is the development of a real-time, in-situ calibration system which permitted an individual calibration function to be measured for every frame of data acquired. This feature was essential as the transmission of the germanium viewport window would decrease after long exposure to the plume from the thruster.

II. Instrumentation Theory and Implementation

A. Theory of thermographic imagery

Thermal imaging cameras produce signal digitized into counts. The counts produced in a given pixel of a camera as a result of detecting a thermally radiating body through a window and filter can be written:⁷

$$C(T) = \Delta t \Delta A \Delta \Omega \int_{-\infty}^{\infty} R(\lambda) \tau_f(\lambda) \tau_w(\lambda) \epsilon(\lambda, T, \theta) B(T, \lambda, \theta) d\lambda, \quad [\text{counts}] \quad (1)$$

where $B(T, \lambda)$ is the spectral radiance given by:

$$B(T, \lambda, \theta) = \frac{2hc^2 \times 10^{-6}}{\lambda^5 \left(e^{-\frac{hc}{\lambda kT}} - 1 \right)} \cos(\theta) \quad [\text{W/m}^2/\text{micron/steradian}] \quad (2)$$

To good approximation all other factors in Eq. (1) are constant from pixel to pixel with the exception of the emissivity, $\epsilon(\lambda, T, \theta)$, which can vary with position and viewing angle, θ . Assuming a flat wavelength response over a narrow wavelength band centered on λ_1 , we have evaluating Eq. (1):

$$C(T) = K(\lambda_1) \epsilon(\lambda_1, T, \theta) B(T, \lambda_1) \cos \theta, \quad [\text{counts}] \quad (3)$$

where $K(\lambda_1)$ is the camera system response and the cosine term explicitly identifies that the surface is a Lambertian radiator (emission varies with projected area). If we integrate over the entire physical spectrum and all space we recover the Stefan-Boltzmann law for a greybody for the power flux:

$$P(T) = \epsilon(T) \sigma T^4, \quad [\text{W m}^{-2}] \quad (4)$$

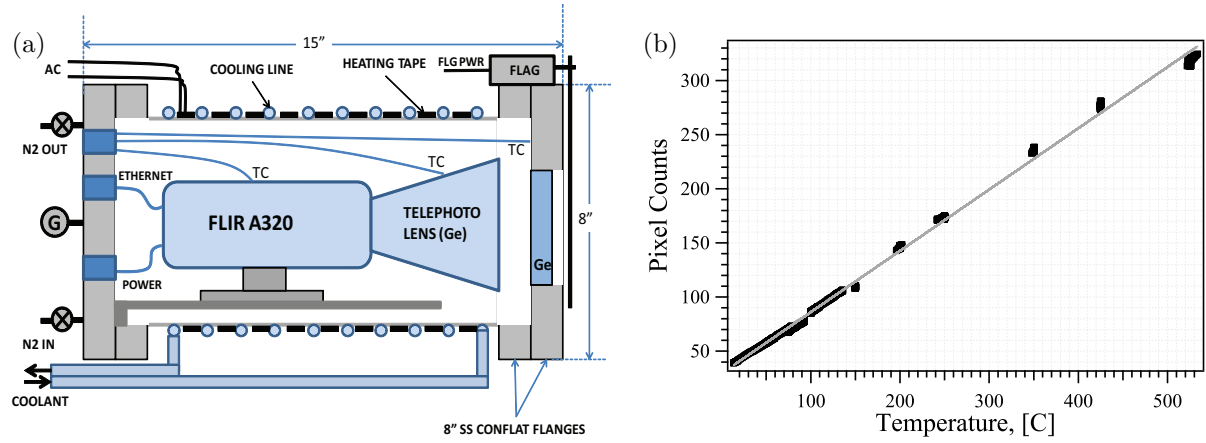


Figure 1. Panel (a) shows a schematic of the camera mounted in the pressure vessel. Panel (b) shows a typical calibration curve.

where for a true greybody the emissivity is a constant with a value between 0 and 1 and is independent of wavelength and temperature.

It is difficult to infer temperatures from radiated emission images of an operating Hall thruster because the thruster is a non-flat surface (encompassing cavities) of several materials each of unknown emissivity^a. At best, the materials are grey bodies (emission is a constant fraction of the blackbody emission) but even grey bodies of known emissivity will emit in an unknown fashion if embedded in a recess. The emissivity of boron nitride has been found to be a constant with value of 0.85 above 100 °C (and with a value of 0.95 near room temperature).⁵ Stainless steel, the other major component of an HCT, can have values between 0.075, for newly polished surface, to 0.85, for weathered surface. Typically, type 301 stainless steel has values in the range of 0.54 - 0.63.⁸

These variations in emissivity of the HCT would seem to make the extraction of temperatures from the radiation problematic. However, the errors in temperatures are not as great as Eqs. (1) – (4) might imply for two reasons. First, observing the front surface of the thruster head on ($\theta = 0$), stainless steel is imbedded in the recess of the discharge channel. This recess approximates a blackbody cavity, increasing the emissivity close to a value of 1. Second, the camera's digital output is computed to be linear in temperature, not in emission as indicated in the equations (see below) and thus varies as $\epsilon^{-1/4}$. Accordingly, a 15% error in emissivity (from 0.85 to 1.0) yields only a 4% error in temperature. Thus, if the camera's output is calibrated for boron nitride, the error in temperature for the stainless steel anode with an assumed emissivity of 1 is expected to be on the order of 5%. It should be noted here that there are other variations to the emissivity. For example, the emissivity of the boron nitride and stainless steel can change as the thruster ages. Furthermore, some of the boron nitride surfaces are angled with respect to the front surface of the thruster. Because emissivity is a strong function of surface roughness and the variation of surface roughness is 20X less at the measured IR wavelength than visible wavelengths (i.e. 10 microns/0.5 microns), variations of the emissivity are expected to be smaller than those seen by a visible detector and thus are expected to be smaller than previously described sources of error.

B. Development of the thermographic diagnostic

The thermographic diagnostic was based on a FLIR A320 infrared camera equipped with a 76 mm focal length, f/1.3 germanium telephoto lens with a $6^\circ \times 4.5^\circ$ field of view. The camera has a 320×240 ($25 \mu\text{m}$) array of microbolometer sensor elements that were sensitive to radiation from 7.5 to $13 \mu\text{m}$. This sensor-lens combination resulted in a spatial resolution of about 1 mm/pixel at a viewing distance of 4 meters.

The camera was sealed in a temperature-controlled, stainless-steel vessel pressurized with 110 kPa of nitrogen gas, as shown schematically in Fig. 1(a). The camera viewed the thruster through a germanium window that was covered with anti-reflecting coating (8 to $13 \mu\text{m}$) on the interior side only. The exterior

^aThe emissivity is the ratio of the radiation of a material at a given temperature and wavelength to that of a blackbody radiator. Thus, the emissivity of a black body = 1; a grey body has an emissivity < 1 which is independent of temperature and wavelength, i.e. a single constant number.

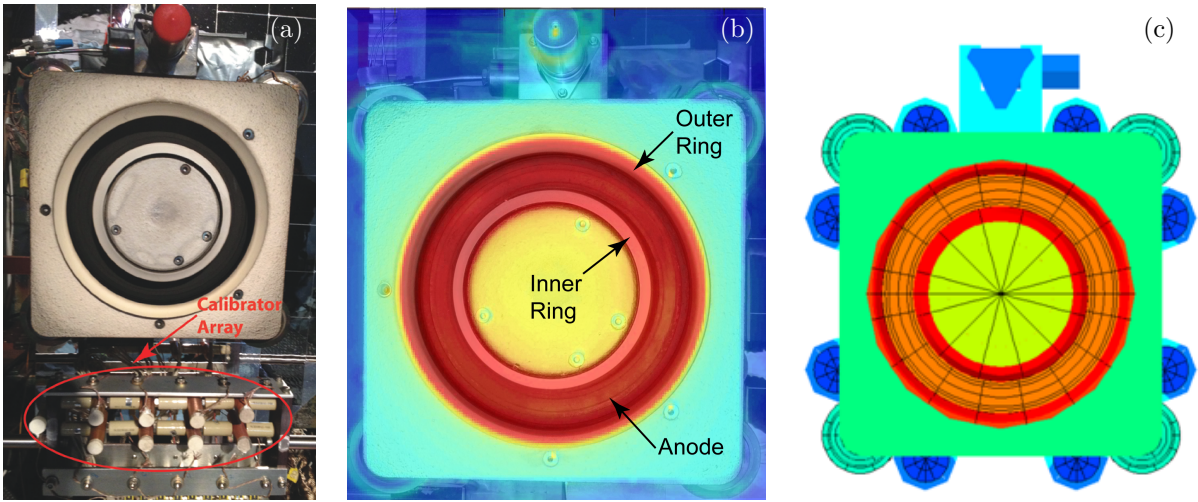


Figure 2. Panel (a) Photograph of the XR-5 thruster and the calibrator array (at the bottom). Panel (b) Picture of the XR-5 thruster is overlaid with an IR image to identify the locations of the outer and inner rings as well as the anode. Panel c) Representative temperature map produced by the Aerojet thermal model.

of the window was left uncoated because of its exposure to the thruster plasma plume. A flag could be activated to protect the window from the plume when the camera was not in use. Heaters and cooling coils were wrapped around the exterior of the canister for thermal control of the camera enclosure. During the test campaign reported here only the cooling lines were used. The camera, lens and window temperatures were monitored with thermocouples. All temperatures remained well below the 50 °C maximum operating temperature of the camera when the thruster operated at 4.5 kW.

The camera system was placed in the vacuum chamber and was calibrated in-situ using an array of 8 heated and one unheated boron nitride disks. A heated copper tube that housed a cartridge heater was inserted into the hollow back of each disk. A fine-wire type K thermocouple was embedded less than 1 mm behind the front surface of the boron nitride disk through a side hole. This assembly is shown mounted below the XR-5 thruster in the VF-5 chamber at the Glenn Research Center (GRC) in Fig. 2(a). Thus, a flat boron nitride surface with a constant known emissivity and temperature was always registering counts on camera pixels. The nine boron nitride disks were heated to temperatures between 25 and 550 °C. This allowed a new counts-versus-temperature calibration curve to be measured on every image. Temperature of the disks varied throughout the test due to the heat load from the operating thruster, resulting in the spread of points shown in the sample calibration curve in Fig. 1(b). The data acquisition rate was between 1 – 10 frames/second chosen manually, depending on the expected rate of temperature change.

A computer analysis program calculated the calibration curve by measuring the counts of the identified pixels at the center of each boron nitride disk and associating these counts with the recorded thermocouple temperature of the disk. The program then applied the calibration curve to the entire image to produce an absolute temperature map. This procedure was repeated for each image to produce temperature history movies.

As can be seen in Fig. 1(b), the calibration curve is linear. Previous studies reported a small deviation from this linearity (maximum of 15 °C) between 25 and 100 °C. This deviation at the lower temperatures is assumed to be due to the variation observed in the BN emissivity at these temperatures.⁵ The variation is small and not apparent in Fig. 1(b). Note that all the points in this figure lie within a few degrees from a straight line fit to the data; typically less than 5 °C. This scatter is interpreted as the precision of the measurement. The absolute accuracy is governed by the uncertainty of the emissivity as discussed above and is approximately 5%.

Transmission of the germanium window degraded throughout the test, caused by the plume erosion. For example, the slope of the calibration line was 0.59 counts/°C during the first day of testing at GRC but decreased to 0.44 after approximately 120 hours of plume impingement. This is a significant change; however, because the calibration is extracted from each frame this change has no effect on the accuracy of the measurement.

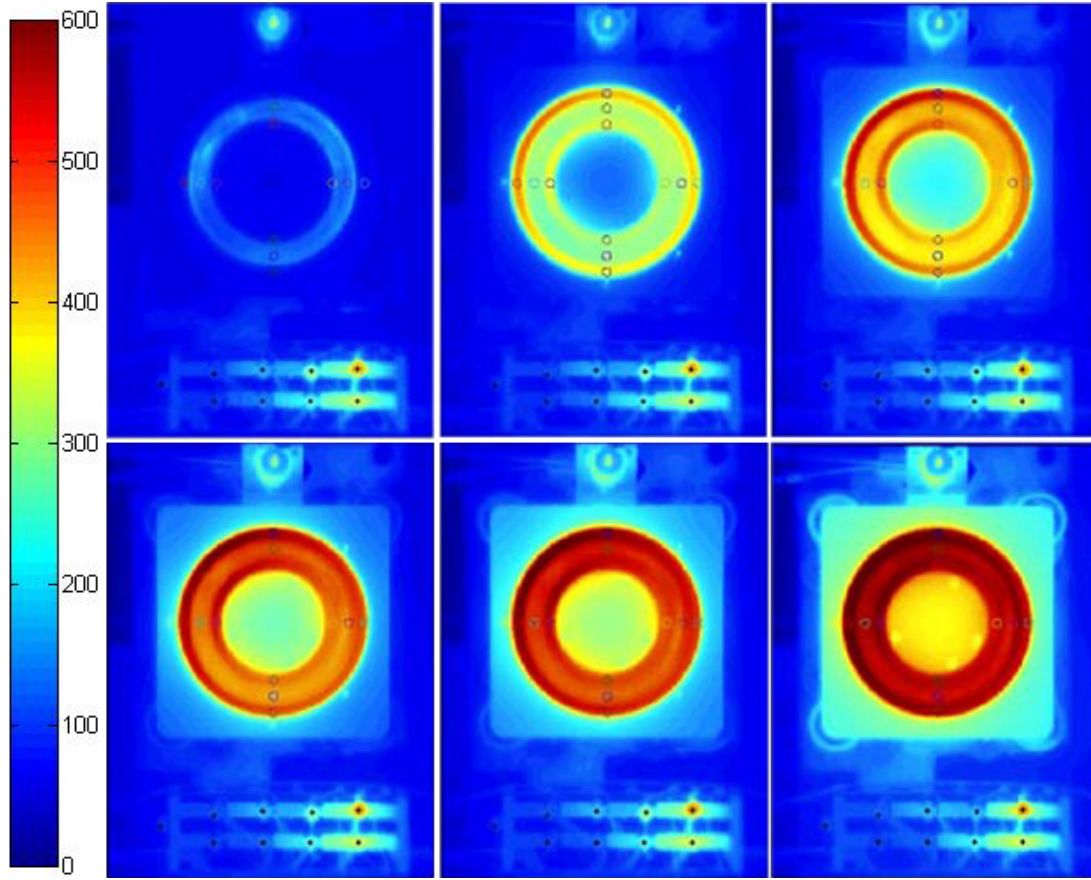


Figure 3. Sequence of IR images taken during thruster startup at 4.5 kW and 400 V. The snapshots taken (from left to right and from top to bottom) at approximately 1, 6, 16, 26, 36, and 106 minutes after the startup. The last snapshot shows a steady-state condition at 400 V.

A complication with this procedure was encountered at GRC. The large diameter (4.6 m) of the VF-5 vacuum chamber required the camera assembly to be suspended from the top. The axial position of the camera was 4 meters from the thruster near one end of the chamber, approximately in the center of the chamber and on the plume centerline. As the thruster operated, the temperature of the camera support structure increased, causing it to move. This resulted in a significant drift in the position of the calibrator array and thruster in the image. The magnitude and direction of the drift depended on the thruster operating parameters and was generally unpredictable. This drift could cause a significant error in the inferred temperature of the thruster. Structure reinforcement alleviated the problem, but thermal drift remained a critical issue for image analysis. The problem was solved by a custom made image tracking subroutine inserted into the main software. The subroutine was able to follow the image as it drifted in the camera field of view and compensate for this motion with a resolution of 1 pixel. This was accomplished by following a selected hot spot, such as one of the heater elements, as it moved in the image. The resulting uncertainty in the temperature measurement can be inferred from Fig. 4, where the sudden changes in the outer ring temperature (thick blue curve) are the results of the image tracking adjustments. We estimate the error introduced by the image tracking subroutine to be 2%.

III. Validation of the IR diagnostic

The IR diagnostic was tested with the XR-5 Hall current thruster. Details of the thruster design and performance characteristics can be found in Ref. 9 and here we only provide a brief description of the parameters relevant to the reported study. The thruster was operated at 4.5 kW of input power, with two standard operating voltages, 300 V and 400 V. For this study the Engineering Model #2 (EM2) version of

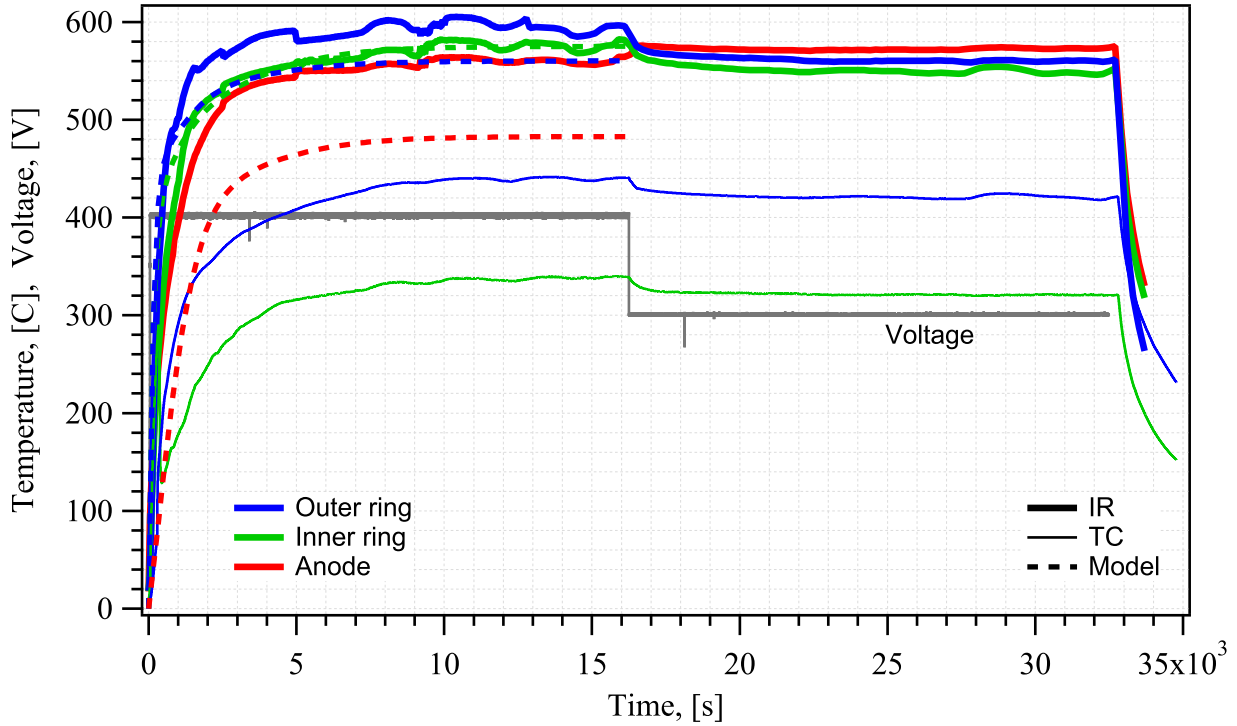


Figure 4. Ring and anode temperature evolution during a nine-hour long “thermal run” at 4.5 kW. The first half of the run was performed at 400 V and the second half at 300 V. The graph shows the discharge voltage for reference in gray. The IR data (thick lines) correspond to the 12 o’clock position in Fig. 3. Ring thermocouples (thin lines) show lower temperatures than the IR data. The model (dashed lines) agrees well with the IR ring temperatures, but not with the anode temperature.

the XR-5 was controlled by the qualification Power Processing Unit (PPU) in the constant power mode by adjusting the flow rate. The EM thruster and PPU were flight equivalent units, chosen for our test to provide flight-like operation of the HCT system in all respects. A typical startup procedure for the XR-5 brought the discharge power up in small increments to 4.5 kW within roughly a minute. During the 9 hour long thermal run described below the thruster operated at 400 V for the first 4.5 hours and then the discharge voltage was decreased to 300 V, while the current was increased to 15 A, to maintain 4.5 kW power consumption, for another 4.5 hours.

The top left image of Fig. 3 shows the temperature distribution in the thruster after it operated for 1 minute at 4.5 kW and 400 V. The bright spot at the top of the image is the cathode, while the turquoise ring below it is the anode. The inner and outer rings are 50 °C cooler than the anode and are indistinguishable from the low temperature background, shown in blue. The bottom of the image shows a series of bright spots of increasing intensity from left to right. These spots indicate the locations of the heated boron nitride disks of the calibrator array. To help with the interpretation of the subsequent images we have overlaid an IR image with a photograph of the thruster, as shown in Fig. 2(b), where we indicated locations of the inner and outer rings as well as the anode.

The subsequent images in Fig. 3 show temperature distribution during the same run at 6, 16, 26, 36, and 106 minutes after achieving full power (going left to right in the top row and then starting at the left in the bottom row again, moving to the right). While the entire thruster continued to warm up through the series of the images, the inner and outer boron nitride ring temperatures caught up with the anode temperature after about 1 minute of operation at full power and by minute 6 (top middle image) significantly exceeded it. While the rings and the anode temperatures reached the 550-600 °C range at the steady state, both rings remained hotter than the anode throughout the 400 V operation at 4.5 kW, as shown in Fig. 4.

The thruster was instrumented with two thermocouples to verify the IR measurements; one inserted into the inner and one into the outer boron nitride ring. As can be seen from Fig. 4, the temperature readings from both thermocouples were very low indicating a potential attachment issue, which was verified during

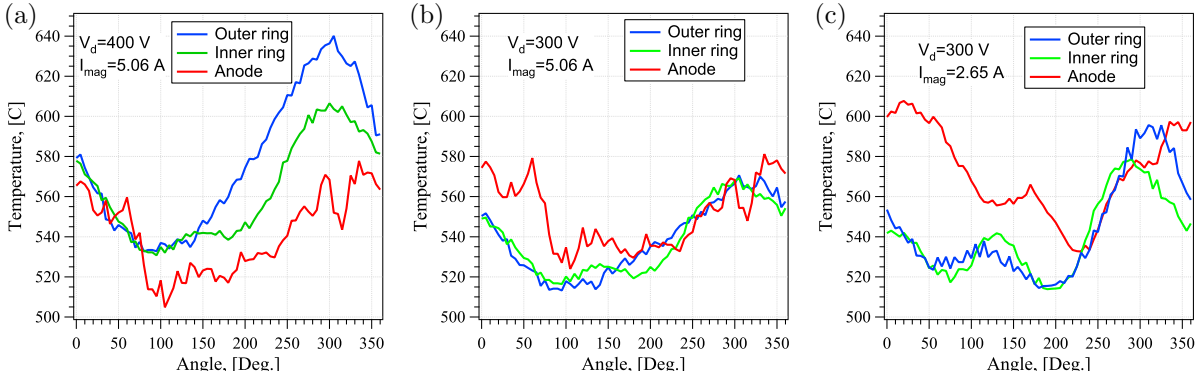


Figure 5. Panels (a) and (b) show azimuthal temperature distribution at 15,000 s (400 V) and 25,000 s (300 V) after ignition during the “thermal run” shown in Fig. 4. Magnetic field was nominal with $I_{mag}=5.06$ A. Panel (c) shows the thruster at 300 V, but with magnetic field held at 2.65 A. The degrees on the x-axes correspond to the clocking such that 0 degrees is at 12 o’clock, increasing clockwise.

the post-test inspection. While this rendered the comparison impractical, the qualitative trends between the thermocouple and the IR measurements match well. The IR data was validated against the model predictions instead.

Figure 4 shows thermal data (and the discharge voltage for reference) for the 9-hour run during which steady state conditions were achieved first at 400 V and then at 300 V, both at 4.5 kW. The inner ring, outer ring, and the anode temperatures measured by the IR camera shown in the plot correspond to the 12 o’clock position. Location of the measurements is shown by three small circles at the top of the thruster channel, vertically stacked, in each of the images in Fig. 3. The circles are most prominent in the center top image. We should note that the 12 o’clock position was chosen arbitrarily for plotting in Fig. 4. The images in Fig. 3 clearly show a thermal gradient in the azimuthal direction, with the hottest region centered at about 10 o’clock (or 300 degrees).

During the first four and a half hours we operated the thruster at 4.5 kW, 400 V set point. After achieving the thermal steady state, we reduced the discharge voltage to 300 V, while maintaining 4.5 kW, and allowed the thruster to reach a new thermal steady state. As can be seen in Fig. 4, at 400 V the IR data shows temperature variations with a period of roughly 30 minutes. Similar variations, albeit with lower amplitude, can be observed in the thermocouple data, and thus we conclude that the variations are not the artifact of the IR measurement. The long period of the variations suggests thermal expansion and relaxation of the thruster structure, however, more detailed investigation is outside the scope of this paper. In addition to variations at 400 V the IR data shows a few sudden jumps in temperature on the order of 10 °C. These jumps are caused by the image tracking software algorithm, which tried to offset the drift of the image across the camera sensor, as described earlier in the paper.

At 300 V the heat load to both rings decreased, as indicated by the 30 °C decrease in the ring temperatures as measured by the IR camera. The thermocouples also registered a temperature decrease. Corresponding to the decrease in the ring temperatures, the anode temperature increases by 15 °C. The increase in the anode temperature may be caused by the higher current at 300 V, since the power was maintained constant, as described by Eq. (7.3-49) in Ref. 10. The decrease in the ring temperature is more difficult to explain. The heat load to the walls of an HCT depends on the local plasma density as well as the electron temperature. The change in either quantity as the discharge voltage is adjusted would most likely indicate a shift in the ionization and acceleration regions. Given constant power operation, it is well known that a change in voltage implies a change in current which also means a change in flow rate. So both electron temperature and plasma density are affected by the change in operating point and hence cause heat load to change. A more detailed analysis requires plasma probe measurements, and is outside the scope of this paper.

Figure 5 shows the azimuthal temperature distributions for the inner and outer rings as well as for the anode with the thruster operating at various set points. The x-axis is in degrees with 0 degree corresponding to the 12 o’clock position at the top of the thruster channel and increasing clockwise. The left panel shows temperature distribution with the thruster operating in a thermal steady state at 4.5 kW and 400 V. This distribution was taken 15,000 seconds after thruster ignition. The middle panel in Fig. 5 corresponds to the

thruster operating in a thermal steady state at 4.5 kW and 300 V. This distribution was measured 25,000 seconds after ignition. As was already mentioned, the anode temperature at 300V was slightly higher than at 400 V, while the ring temperatures were slightly lower. The amount of change strongly depended on the azimuthal position. For example at 100 degrees the difference in the ring temperatures was around 20 °C when compared between the 300 and 400 V set points. On the other hand, that difference was closer to 80 °C at 300 degrees for the outer ring and 40 °C for the inner ring.

In both Fig. 5(a) and (b) the magnet current was 5.06 A, which produced nominal magnetic field at 4.5 kW. In Fig. 5(c) we show the azimuthal temperature distribution with the thruster operating at 4.5 kW and 300 V, but with the magnet current of 2.65 A, which produced suboptimal magnetic field strength. Considering that magnetic field was reduced almost by a factor of two, it is somewhat surprising that the temperatures were not strongly affected. The anode temperature increased by about 20 °C in the region from 0 to 200 degrees, and the ring temperatures increased by about 40 °C in the region centered at 300 degrees.

A. Thermal Model

Aerojet created a XR-5 thermal model to determine operational margins of key components in both test and space flight environments. Figure 1(c) shows the head-on view of the model results at 4.5 kW and 400 V. The model operated with Thermal Desktop[®],¹¹ used as a graphical user interface for SINDA/FLUINT.¹² The 3-D model used approximately 7,100 nodes, incorporating a mix of finite elements and finite difference solids and surfaces to provide sufficient thermal resolution. The model assumed uniform azimuthal plasma heat distribution on the wetted surfaces of the thruster and temperature and current dependent ohmic-heating within the magnet coils. Steady-state and transient temperatures could be obtained utilizing temperature dependent material properties and heat transfer via conduction and radiation within the HCT.

In the early stages, the model was correlated with thermocouple data obtained from multiple developmental and qualification test series. The model successfully predicted most of the observed temperatures within 20 °C. In the few instances where the model results diverged from the experimental data the issues could be attributed to inconsistencies in the data itself and difficulty in obtaining thermocouple data in the anode region. The anode thermocouple data was especially unreliable since the thermocouples were at the high anode potential, which caused frequent thermocouple burn outs and other issues. Even taking those issues into account, the model shows that temperature of all thruster components is well below allowable limits.

Figure 4 shows the inner and outer ring as well as anode temperatures obtained from the model as a function of time from the cold start to a steady-state condition at 4.5 kW and 400 V. The inner ring temperature, shown by a thin dashed green curve, is in excellent agreement with the IR measurement, shown by the thick green curve. The outer ring temperature obtained from the thermal model, and shown by the thin dashed blue curve, is within 20 °C of the IR measurement. The anode temperature obtained from the model, and shown by the thin dashed red curve, is significantly below the IR measurement. The most likely source of the disagreement, as was mentioned earlier, is the inadequate thermocouple data in the anode region used to calibrate the model. On the other hand, some inaccuracy is also due to the anode emissivity assumptions made in the IR measurement, as explained in the earlier section of this paper. However, the error introduced by this assumption is small compared to the disagreement between the model and the IR measurement.

IV. Conclusions

This paper presented design and validation of a new thermographic diagnostic that enabled accurate temperature measurements of the material surfaces inside a Hall current thruster chamber. The diagnostic is based on a FLIR A320 infrared camera equipped with a 76 mm focal length, f/1.3 germanium telephoto lens. The camera was inserted in a temperature controlled, pressurized enclosure, which in turn was placed inside a vacuum chamber at the center axis, 4 m in front of the thruster. The in-situ real-time calibration was achieved by placing a calibrator array within the field of view of the camera. The calibrator array consisted of 9 boron nitride disks, which were maintained at different temperatures in the range expected inside the thruster.

The diagnostic system was able to resolve features on the order of 1 mm and azimuthal and radial

temperature gradients inside the discharge channel. The original plan to validate the IR system against thermocouples inserted in the thruster rings failed due to the issues with the thermocouples. Instead, the IR imagery was compared with the thermal model developed for the thruster. Excellent agreement between the two results was observed for the thruster rings. Anode temperatures did not match within the accuracy of the model and the IR uncertainty. This disagreement, however, is not surprising given the inadequacy of the thermocouple measurements at the anode upon which the thermal model was based.

Although it is beyond the scope of this paper, we concluded that the developed thermographic diagnostic added a critical capability which allowed our team to study the performance of the XR-5 thruster under various operating conditions using thermal data to correlate behaviors to aspects of the thruster design.

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