Combined Plasma and Thermal Hollow Cathode Insert Model

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In this paper, we present the first results from a Hollow Cathode Thermal (HCThermal) model that uses the spatially distributed plasma fluxes calculated by the Insert Region of an Orificed Cathode (IROrCa2D) code as the heat source to predict the hollow cathode and insert temperatures. Calculated insert temperature profiles are compared with measured values for a cathode similar to the NSTAR discharge cathode. The insert temperatures can be used in the previously reported models to predict cathode life from barium depletion. When fully validated, the combined models will give thruster designers a tool to predict cathode life prior to cathode fabrication and test, and predict the variation of life over a range of operating conditions. Presently, uncertainties in material properties prevent the code from being an absolute, predictive tool. However, preliminary modeling results and related experiments have yielded three important conclusions. First, the emitter in the NSTAR hollow cathode is not operating in the emission-limited regime. The thermionic electron current is 20 amperes higher than the discharge current and requires significant reverse electron flux from the plasma to satisfy current continuity. Second, the high plasma density near the centerline of the cathode results in power deposition on the orifice plate which is more than twice the emitter power deposition. Third, despite a higher heat load to the orifice plate, its operating temperature is approximately 100°C lower than the emitter. This is due to poor thermal contact between the emitter and the cathode tube and higher than anticipated radiative losses from the external surface of the heater.

I. Introduction

HIGH power, long life electric thrusters were considered necessary as NASA planned many of the challenging missions under the Prometheus Program. These missions might have required an increase in both life and emission current compared with hollow cathodes used on NASA's Deep Space 1 spacecraft. While both the discharge and neutralizer hollow cathodes were operating at the end of the NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) thruster 30,000 hour Extended Life Test,[1] the future missions may be even more challenging. A previous test at NASA/GRC of the International Space Station Plasma Contactor hollow cathode[2] ended after 28,000 hours when the cathode would no longer ignite. In previous papers we showed how the barium depletion rates in xenon fed hollow cathodes are related to barium depletion in the conventional impregnated cathodes used by the traveling tube industry,[3] allowing use of a large database of measurements from that community. The previous work assumed that the cathode temperatures were known through measurements. In this paper, we present the first results from a Hollow Cathode Thermal (HCThermal) model that uses the spatially distributed plasma fluxes calculated by the JPL Insert Region of an Orificed Cathode (IROrCa2D) code as the heat source to predict the hollow cathode and insert temperatures. Calculated insert temperature profiles are compared with measured values for a cathode similar to the NSTAR discharge cathode. The insert temperatures can be used in

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the previously reported models to predict cathode life from barium depletion. When fully validated, the combined models will give thruster designers a tool to predict cathode life prior to cathode fabrication and test, and predict the variation of life over a range of operating conditions.

The 2D hollow cathode plasma model, IROrCa2D,[4,5] self-consistently solves the ion, electron, and neutral mass continuity, momentum, and energy equations. The interactions with the hollow cathode insert region surfaces are through a sheath that attracts electrons from the emitter, and accelerates plasma ions to the walls. The sheath also acts as a barrier that prevents most plasma electrons from returning to the emitter. Electrons are emitted using the Richardson equation including Schottky enhancement due to sheath fields. If a measurement exists, the emitter temperature in IROrCa2D is specified (and held fixed) during the plasma calculation, otherwise it is determined by iteration. For the NSTAR calculation presented in this paper the emitter temperature in IROrCa2D was specified. Emitted electrons cool the cathode by the work function, incident ions heat the wall by their kinetic energy (sheath and presheath potential) plus ionization energy minus the work function, and returning electrons heat the walls by their kinetic energy and the work function. These plasma fluxes are used as source terms in the thermal model.

The thermal model is a simple 2-D model specifically designed to accurately represent the interface fluxes between various cathode components. Thermal transfer processes include bulk conduction, interface conduction, and radiation. The code is imbedded in an Excel spreadsheet, and the cathode geometry is entered graphically. Steady state temperatures are calculated in under a minute. Radiation from the orifice plate and other parts of the cathode is the primary heat loss mechanism. Results from the calculations are compared with in-situ insert temperature measurements on a hollow cathode running at NSTAR discharge parameters.

II. Background

A hollow cathode is a device that provides amperes of electrons to ionize neutrals (discharge cathode) or neutralize the thrust-producing ion beam (neutralizer cathode). Both types of cathodes share the same design, consisting of a hollow tube capped at the end with a plate with a small orifice. The tube wall immediately upstream of the orifice plate is lined with barium-impregnated sintered tungsten that serves as a low work function thermionic electron emitter. Xenon gas flows through the cathode and is partially ionized by electrons from the emitter. The ions both neutralize the spacecharge of the emitted electrons and serve to heat the emitter. Electrons, ions and neutral particles leave the orifice and enter the neighboring discharge chamber or ion beam expansion region.

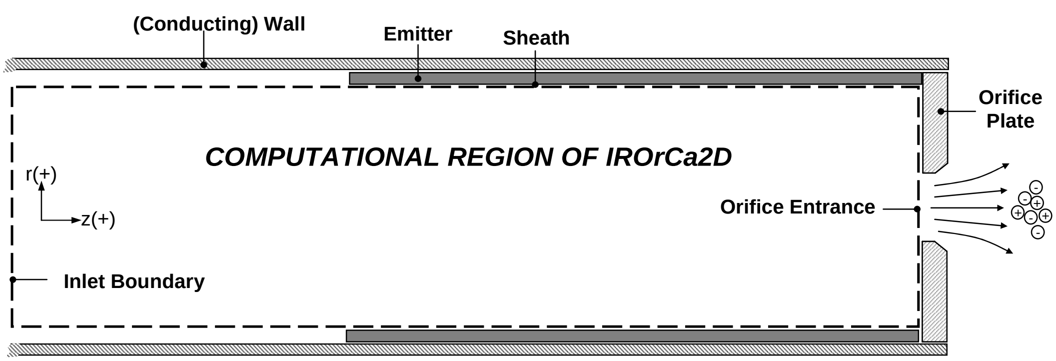

Fig 1. Hollow cathode emitter region schematic showing the region modeled by IROrCa2D.

The 2D, time-independent IROrCa2D code was developed at JPL to identify those mechanisms that affect the life of the emitter.[4,5] The objective was to develop a theoretical model that predicts the steady-state, two-dimensional distributions of all pertinent plasma properties, including electron and ion fluxes and the sheath potential along the emitter. The geometrical simplicity of the emitter region (see Fig 1) allows us to focus on accurately developing and validating the complex physics associated with the neutral and ionized gases in the presence of electron emission from the insert surface. The absence of time-dependent terms in the plasma conservation equations, and the neglect of neutral gas dynamics also simplifies the numerical approach, and reduces the computational times required to attain the steady-state solution.

III. Thermal Model

HCThermal (Hollow Cathode Thermal) is a 2D code in R-Z geometry, that uses the ion and electron fluxes from IROrCa2D as input to predict the temperature distribution in the cathode. A sample problem geometry modeled by the thermal code is shown in Fig 2. Positive numbers identify different materials and negative numbers are used to identify radiative boundary conditions.

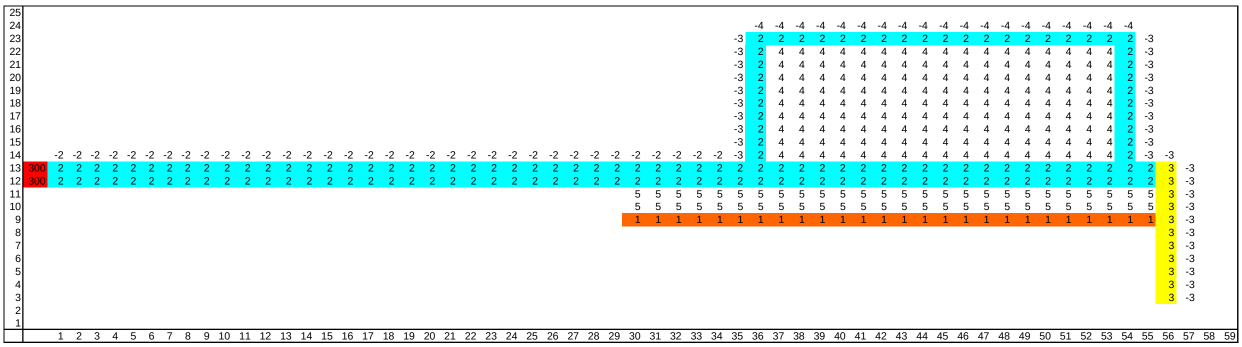

Fig 2. An input geometry for the hollow cathode thermal model. The orifice plate is located at the right of the model. The bottom of the figure represents the centerline of the axisymmetric geometry.

The hollow cathode thermal code models heat conduction and radiation in a simple geometrical representation of a hollow cathode. The purpose of the code is to provide a fast (calculations take less than a minute) assessment of how insert plasma thermal fluxes influence the cathode insert and orifice plate temperatures. The code includes thermal conduction, radiative heat losses, and, within the insert region, radiative heat transfer. The code is written in Visual Basic for Applications (VBA) and is run within an Excel spreadsheet.

The code employs a regular R-Z mesh with a fixed cell sizes ΔR and ΔZ. The hollow cathode geometry is defined graphically by entering the material number, a positive integer, into the spreadsheet. The code assumes that 1 is the emitter material, 2 is the tube, and 3 is the orifice plate. The material number is associated with a value for the thermal conductivity. The upstream boundary temperature is entered into the leftmost column. Exterior surfaces that lose heat by radiation are indicated by a negative integer in the neighboring cell. Emittances of the insert and the upstream side of the orifice plate are tied to their material numbers. The cathode heater is treated as metal cylinder filled with a weakly conducting material. Presently, the model does not include provisions for a keeper, but a simplified keeper model is planned.

HCThermal calculates temperatures for cathodes in self-heating operation using plasma thermal fluxes calculated by the IROrCa2D code. These include thermionic electron emission cooling, plasma electron backflow heating, and ion kinetic and recombination heating. Emited electrons cool the emitter by the work function, approximately 2 eV per electron. Back flowing plasma electrons heat the emitter by the work function and twice the plasma electron temperature. The ion kinetic energy includes acceleration across the local sheath as well as the ion thermal energy. The thermal fluxes are input in tabular form along the axial length of the emitter and radius along the upstream surface of the orifice plate. The heat flux inside the orifice channel is presently assumed to be of the same magnitude as the heat flux to the upstream orifice plate surface at the entrance to the orifice.

The steady state thermal transport equation is solved by the method of successive over-relaxation (SOR). About 1000 iterations are required to reach a solution, taking less than minute on a notebook PC. Radiative heat transfer in the insert region is modeled as radiation in an enclosure of diffuse-gray surfaces. The radiative heat transfer is calculated by inverting the enclosure equations during each SOR iteration.[6]

IV. Results

A sample HCThermal calculation is presented in this section that used the insert plasma fluxes calculated by IROrCa2D for the NSTAR nominal operating condition of 12A and 4.25 sccm.[5] The IROrCa2D plasma density profile along the axis of symmetry is compared with a laboratory measurement in Fig 3. Calculated plasma density and plasma potential contour maps are shown in Fig 4.

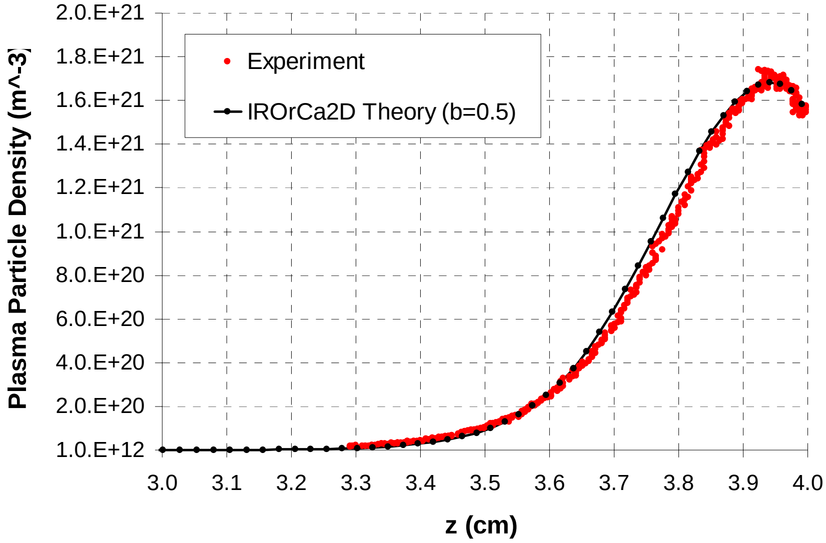

Fig 3. Comparison between measurement and theory (using the IROrCa2D code) for the plasma particle density along the axis of symmetry of the NSTAR cathode. Emission enhancement (with an enhancement factor b=0.5) and emission turn-off are both included in the IROrCa2D result.

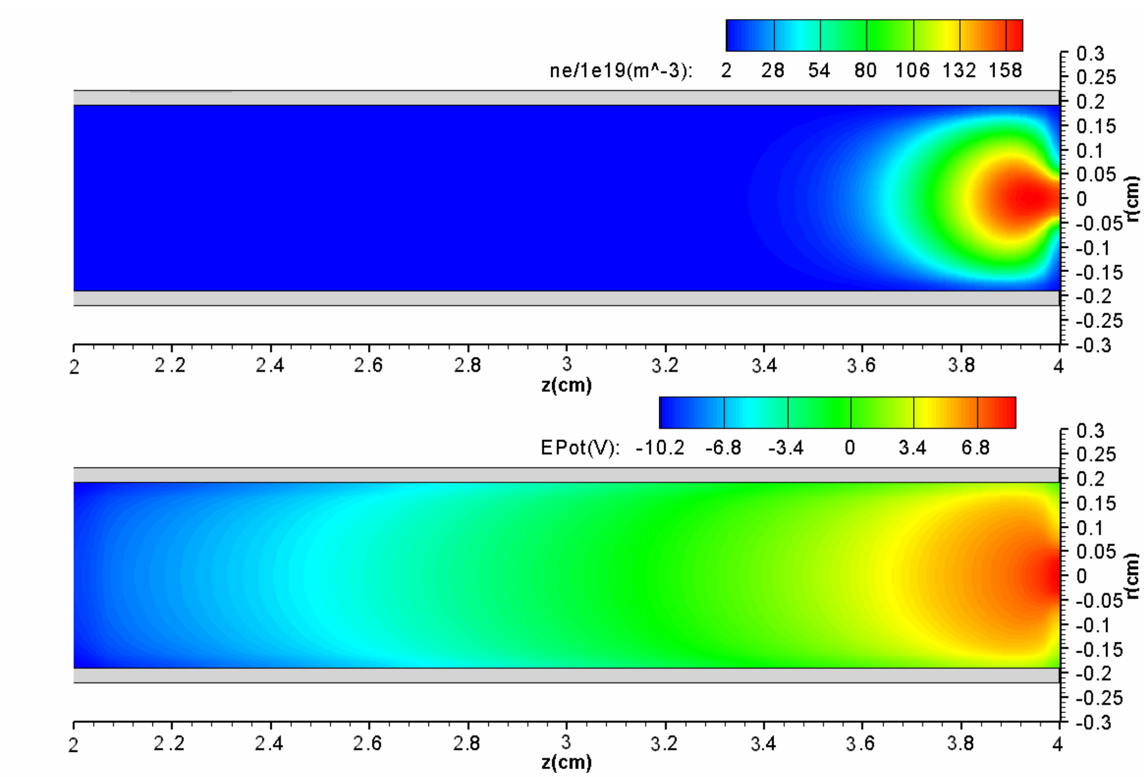

Fig 4. IROrCa2D computed profiles of the plasma particle density (top) and plasma potential (bottom).

The 12A net cathode current resulted from almost 32A electron emission by the insert countered by 20A of plasma (thermal) electron back to the insert and the orifice plate. The back flowing electron current is modeled as the one-sided plasma electron thermal flux reduced by the local sheath potential. Only about a half ampere of the net cathode current is due to ionization of the xenon gas (see Table I).

Table I. Components of the net hollow cathode current.

Emitted Electrons	31.7 A
Absorbed Electrons	20.2 A
Absorbed Ions	0.5 A
Net Current	12 A

The calculated thermal fluxes to the insert are shown in Fig 5. The net thermal power to the insert is about 13W and is the result of near cancellation of cooling by electron emission and heating from absorption of plasma thermal electrons. Ions contribute about 4W to insert heating.

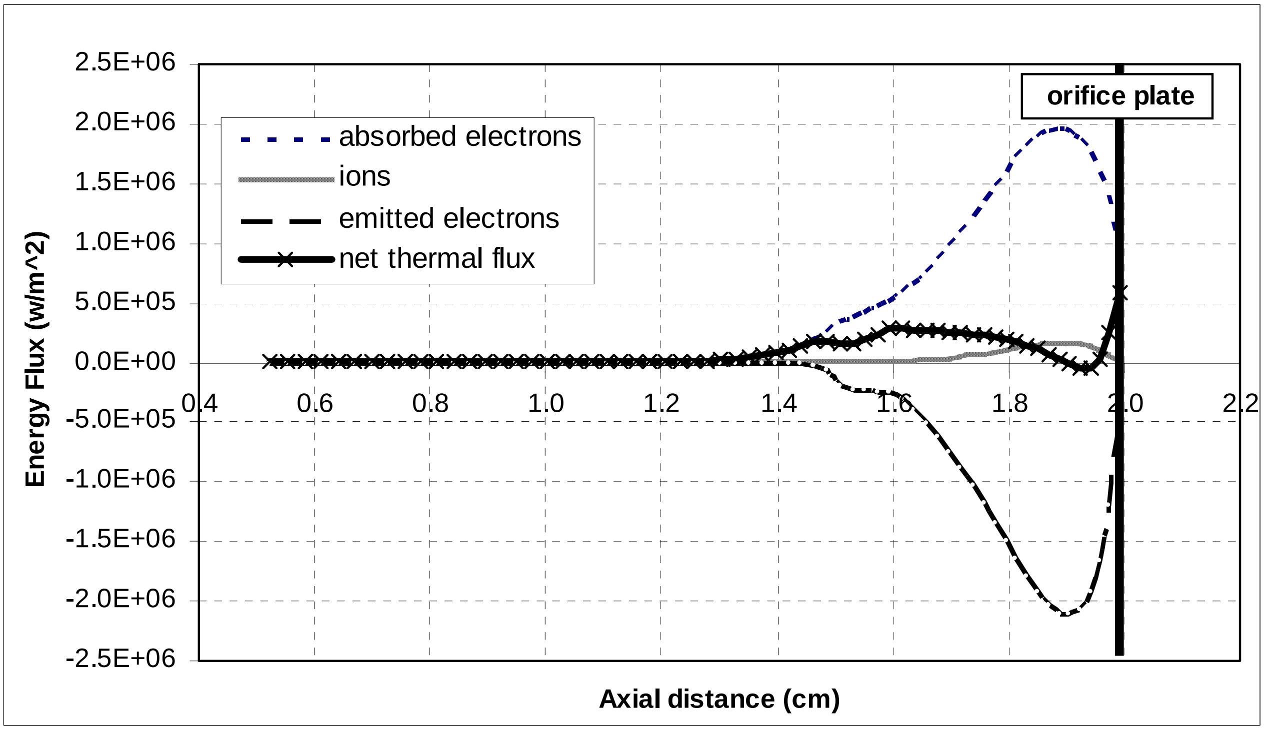

Fig 5. Components of the plasma energy flux to the insert emitter surface.

The bulk of the heating is along the orifice plate, where, due to the high work function, the emission cooling is small. The components of the thermal flux to the orifice plate are shown in Fig 6. Note that near the orifice, ion heating becomes significant which is due to both the high plasma density and the high sheath potential in this region. The calculations use the value on the upstream surface orifice plate thermal flux at the orifice radius to approximate the value of the flux inside the orifice. The combined orifice plate upstream surface and orifice interior heating is more than twice that of the insert alone. The emitter and orifice plate heating are shown in Table II.

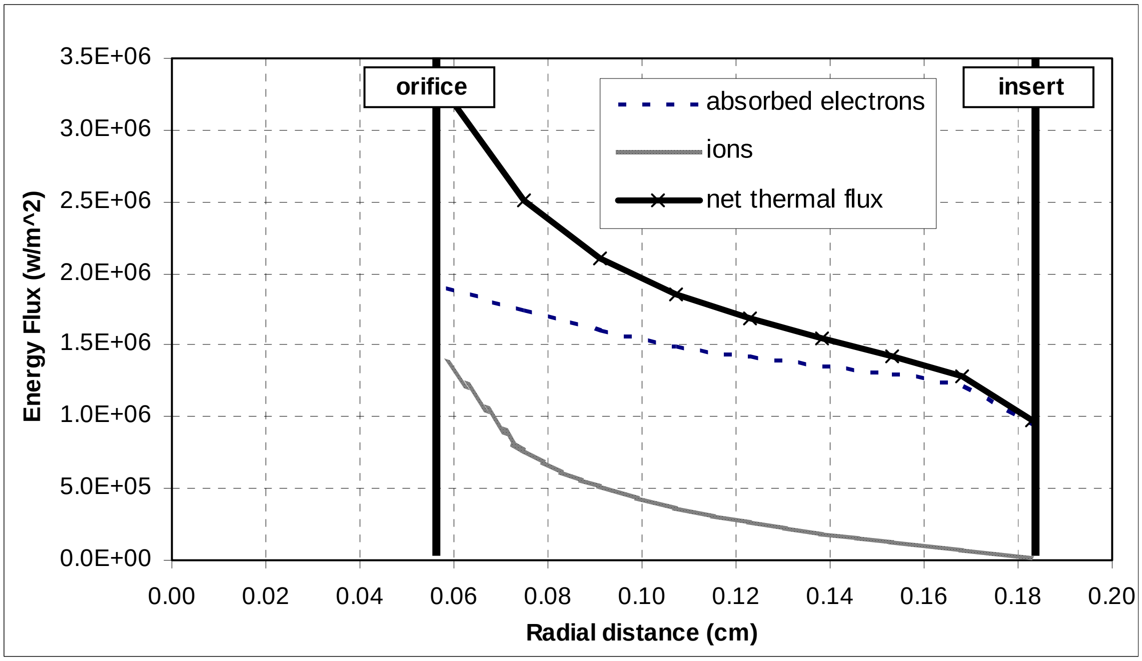

Fig 6. Components of the plasma thermal flux to the upstream surface of the orifice plate.

Table II. Insert surface and orifice plate heating.

Insert Surface Heating	12W
Orifice Plate Heating	29W

The HCThermal results depend strongly on the orifice plate emittance. The value for tungsten emittance was taken as 0.21. This is higher than the reported value for polished tungsten[7], 0.175, and was adjusted to best fit the measurements. While slightly higher than the polished tungsten value, it is lower than measured values for rough, porous tungsten.[8] The code does not include the variation of emittance with temperature. The orifice plate of the cathode used in the experiments was textured by ion bombardment (a natural evolution from the original machined surface that is observed in all cathodes after several hundred hours of operation), and had a surface roughness intermediate between polished and porous tungsten. The value of emittance chosen to reproduce the measured orifice plate temperature is therefore not unreasonable. The peak orifice plate temperature in the calculation is 1420 K. A comparison between measured thermocouple values and the code calculated values are shown in Table III. The most significant result of the calculation is that the overall trend in temperature is in rough agreement with the measurements. Internal and external temperatures were measured on a cathode with the same geometry as the NSTAR cathode operated at the same conditions modeled with the IROrCa2D code. External temperatures measured with W-Re thermocouples on the cathode tube near the orifice plate and just upstream of the heater coil are listed in Table III. The temperature measured at the upstream mounting flange in tests with a similar cathode is also shown in this table and was used as the upstream boundary condition for the HCThermal code.

Table III. Comparison of measured thermocouple temperatures (˚C) with the code results with the adjusted tungsten emittance of 0.21.

	Measured	HCThermal
Current	12.0	12.0
TC1	1092	1096
TC2	715	720
TC4	284	284

The axial temperature distribution on the emitting surface inside the cathode was measured using a fast scanning fiber optic probe and a 2 color pyrometer system[9,10] and is displayed in Fig 7. Results from an earlier test with a different insert and slightly lower flow rate are also plotted and show similar behavior. The temperature peaks at about 1200 °C at the downstream end of the insert and drops by 200°C along the emitter.

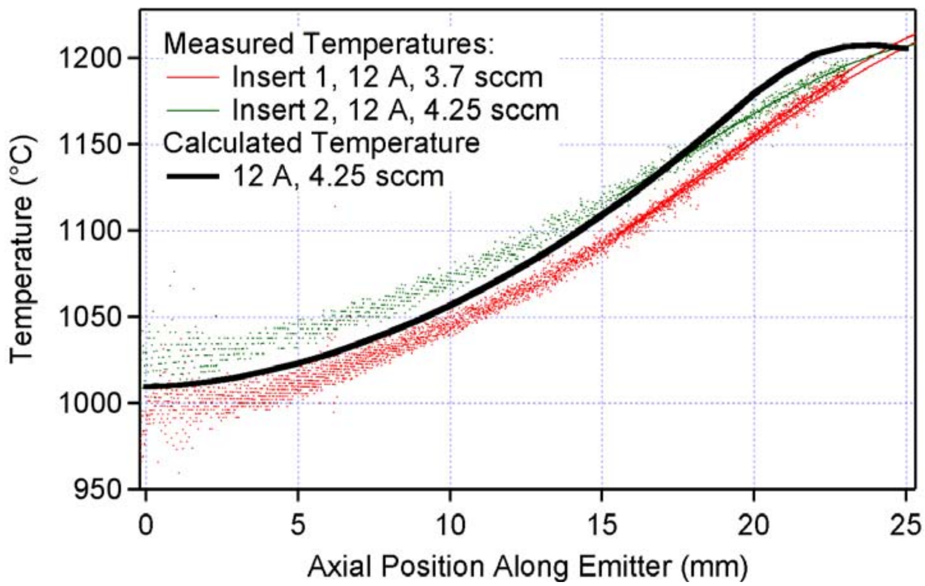

Fig 7. Measured emitter temperatures. The HCThermal calculation was performed for Insert 2.

The calculated temperature along the insert surface is also shown in Fig 7. Note that the temperature profile flattens within a few millimeters of the orifice plate where most of the heat input occurs. The peak insert temperature is about 100°C higher than the temperature near the orifice plate, even though the orifice plate power input is 2.4 times higher than that into the emitter. This is an indication of poor thermal contact between the emitter and the tube that surrounds it, necessitating large temperature differences to reject the input heat flux. Poor contact is to be expected in this geometry because the emitter outer diameter is slightly smaller than the inner diameter of the cathode tube, resulting in a gap of about 100 microns between the two surfaces. Even in regions where the insert is resting on the tube wall, the rough surface of the porous tungsten results in a small contact area. The primary heat conduction mechanism between these two components initially is radiation. After long periods of operation, this gap fills with barium oxide released from the impregnant,[11,1] which has a very poor thermal conductivity. In the HCThermal code this coupling is modeled effectively as an interface conductivity. Radiative coupling at the expected temperatures yields an interface conductivity of approximately 150 W/m^{2}K, and conduction through barium oxide increases the conductivity to about 400 W/m^{2}K. Agreement between the measured and calculated peak insert temperatures shown in Figure 7 was achieved with an interface conductivity of 300 W/m^{2}K, which is consistent with radiative coupling and some conduction through contact points or barium oxide deposits.

Above we examined the relative heating of the cathode insert and orifice plate. It is also constructive to examine where the heat is lost. While the orifice plate is the hottest surface, it has a small area. The calculation shows that only about 5 W are radiated from the orifice plate. About half of the power is radiated from the heater coils, due to their very large area. About 10 W are conducted through the tube to the upstream mount.

V. Discussion

The thermal model shows the sensitivity of hollow cathodes to the emittance of the orifice plate and the thermal contact between the emitter and the tube. Table IV below compares the code results with the adjusted orifice plate emissivity and with the literature value for polished tungsten. The fractional change in the peak absolute temperature is about one fourth of the change in emissivity. This is consistent with the conclusion that most of the cathode heat is lost through radiation. However, 50 ˚C, while only about a 5% change in emitter temperature, has major consequences on insert impregnate life and electron emission.

Table IV. Comparison between thermocouple temperatures (˚C) calculated using adjusted and polished tungsten values for the orifice plate emissivity.

	Adjusted	Polished
Emissivity	0.21	0.175
TC1	1096	1146
TC2	720	758
TC4	284	284

Using calculated plasma thermal fluxes and by adjusting these two parameters, the code was able to reproduce the axial variations of both insert and tube temperatures. The combined IROrCa2D-HCThermal model provides some insight into the operation of the NSTAR discharge hollow cathode. The insert region plasma calculation, which was validated with laboratory measurement, shows that the insert was not operating in an emission-limited regime. The emitted current was almost three times the circuit current. Most of the emitted current was balanced by the plasma electron current returning to the cathode surfaces. The sheath potential adjusts to control the return electron current in order to maintain the circuit current. The exponential dependence of the return current on the sheath potential gives the hollow cathode its nearly vertical current-voltage characteristic. This result has important implications on hollow cathode life because all cathode insert failure modes are strongly dependent on the operating temperature. Conceivably, with an improved thermal design the required discharge current could be emitted at lower operating temperatures, yielding improved life, but probably at the expense of a slightly higher cathode sheath voltage.

In the NSTAR-like cathodes the relatively small orifice leads to high internal pressure, which results in a very short emission zone and high plasma densities at the downstream end, particularly near the centerline. The combination of these high densities and a sheath voltage sufficiently low to allow significant reverse electron flow yields very high orifice plate heat loads. The thermal analyses suggest that these heat loads are rejected largely by radiation from the heater assembly. This also has interesting implications for cathode thermal design trades. Improved radiation shielding to decrease losses during heater operation will result in higher cathode temperatures during operation with a discharge.

Finally, poor thermal contact between the emitter and the cathode tube results in large temperature differences between these components. Improved thermal contact at this interface would result in lower emitter temperatures for a given circuit current.

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