Combined Plasma and Thermal Hollow Cathode Insert Model

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Abstract

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.

Introduction

High power, long life electric thrusters are needed to perform many of the challenging missions under study by the Prometheus Program. These missions may require an increase in both life and emission current compared with hollow cathodes used on NASA's DS1 spacecraft. While both the discharge and neutralizer hollow cathodes were operating at the end of the NSTAR thruster 30,000 hour Extended Life Test, the future missions may be even more challenging. A previous test at NASA/GRC of the Space Station Plasma Contactor hollow cathode ended after 28,000 hours when the cathode would no longer ignite. In previous papers we showed how the barium depletion in xenon fed hollow cathodes was related to barium depletion in the conventional impregnated cathodes used in the traveling tube industry. 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 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 2-D hollow cathode plasma model, IROrCa2D[1], self-consistently solves the ion, electron, and neutral mass continuity, momentum, and energy equations. The interactions with hollow cathode insert region surfaces is 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. 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 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 mechanisms. Results from the calculations are compared with in-situ insert temperature measurements on a hollow cathode running at NSTAR discharge parameters.

Background

A hollow cathode is a device that provides amperes of electrons to ionize electrons (discharge cathode) or neutralize the thrust producing ion beam (neutralizer cathode). Both 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 impregnated tungsten emitter. Electrons, gas, and ions leave the orifice and enter the neighboring discharge chamber or ion beam expansion region.

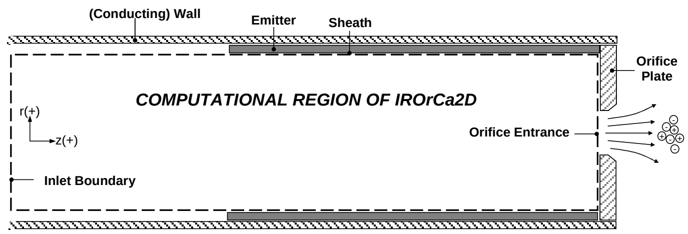

Figure 1. Hollow cathode emitter region schematic showing the region modeled by IROrCa2D.

The 2D, time-independent **I**nsert **R**egion of an **Or**ificed **Ca**thode (IROrCa2D) codewas developed to identify those mechanisms that affect the life of the emitter. 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 Figure 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.

Thermal Model

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

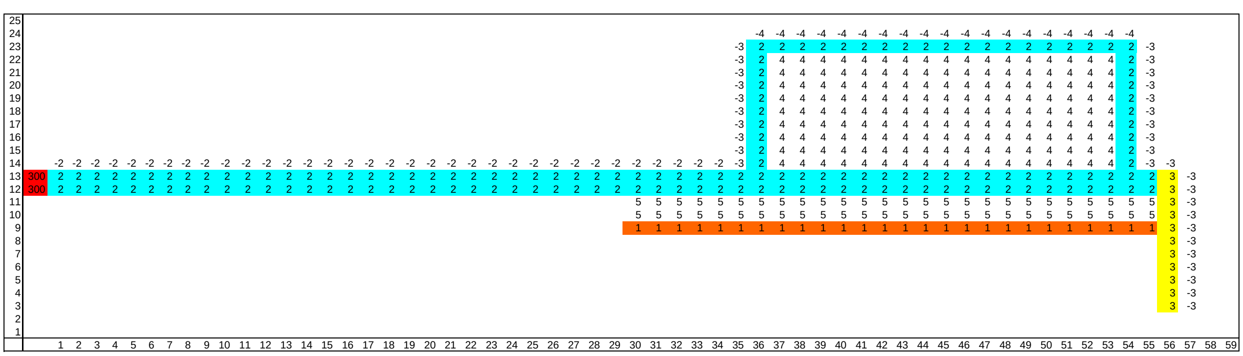

Figure 2. An input geometry for the hollow cathode thermal model. The orifice plate is located at the right of the model.

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 rapid (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 ΔR and a fixed 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. Emissivities of the insert and the upstream side of the orifice plate are tied to their material numbers. The value for Tungsten emissivity was taken as 0.21. This is higher than the reported value for polished tungsten (Ref 3) and was adjusted to best fit the measurements. The code does not include the variation of emissivity with temperature. 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.

The HCThermal calculates temperatures for the 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 interior to the orifice is presently assumed to be 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 results in a Poisson's equation that 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 (Ref 4) during each SOR iteration.

Calculation

A sample calculation was run using the insert plasma calculated in Ref 2 for the NSTAR nominal operating condition of 12A and 4.25 sccm. The calculated plasma density profile along the axis compared with a laboratory measurement is shown in Figure 3. Calculated plasma density and temperature contour maps are shown in Figure 4.

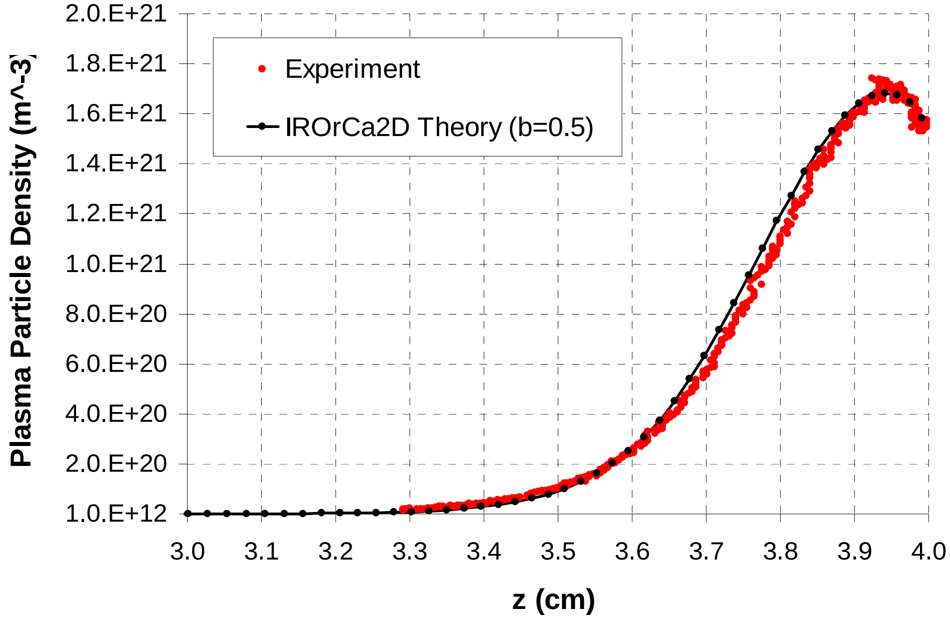

Figure 3. Comparison between measurement and theory (using the IROrCa2D code) for the plasma particle density along the axis of symmetry of the NSTAR cathode. Emission enhancement (with an enhancement factor b=0.5) and emission turn-off are both included in the IROrCa2D result.

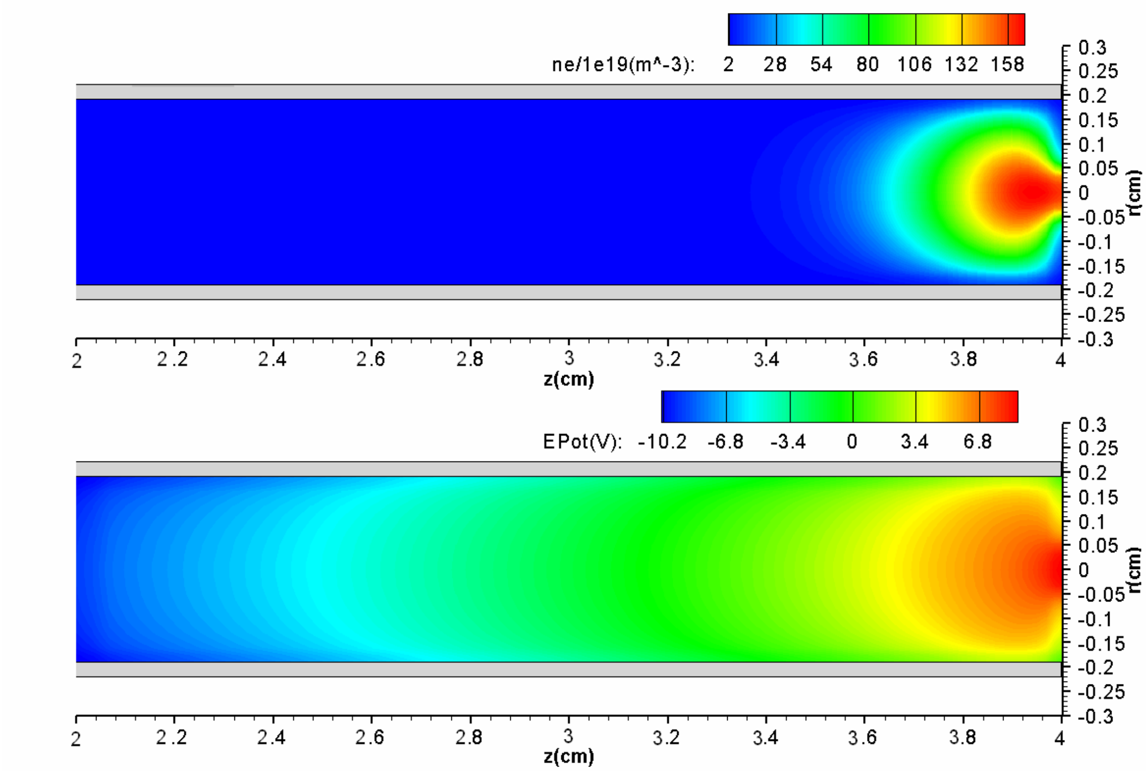

Figure 4. IROrCa2D computed profiles of the plasma particle density (top) and plasma potential (bottom)

The 12A net cathode current resulted from almost 32A electron emission from the insert countered by 20A 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 1).

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

Table 1. Components of the net hollow cathode current

The calculated thermal fluxes to the insert is shown in Figures5. 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.

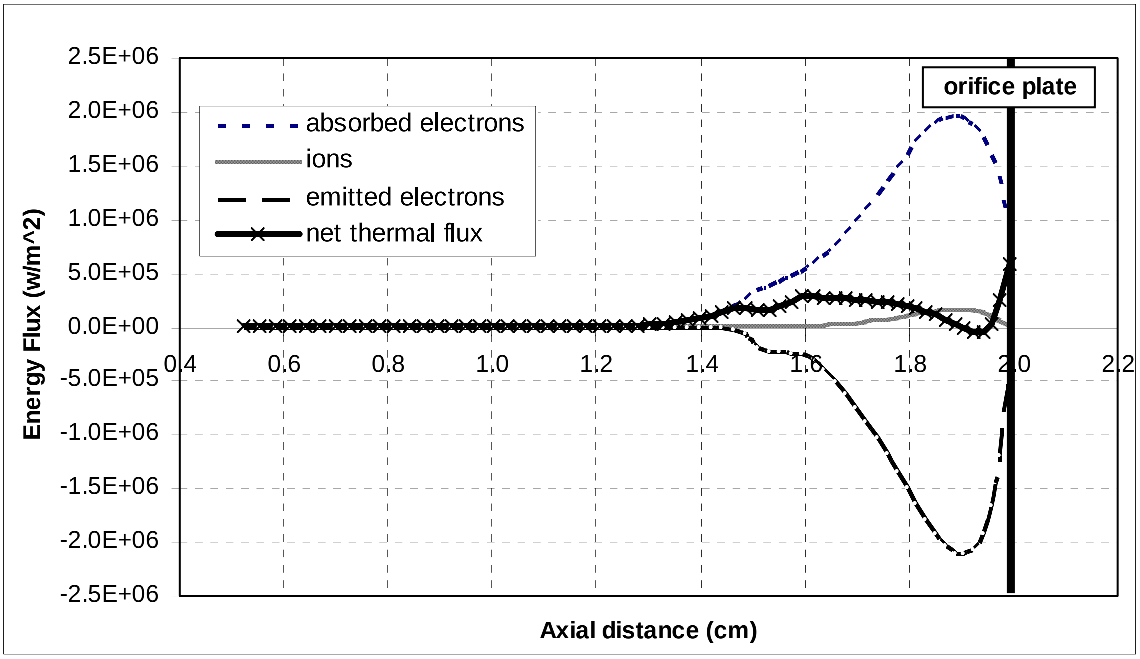

Figure5 Components of the plasma thermal flux to the insert emitter surface.

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 Figure 6. Note that near the orifice, ion heating becomes significant. This 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 2.

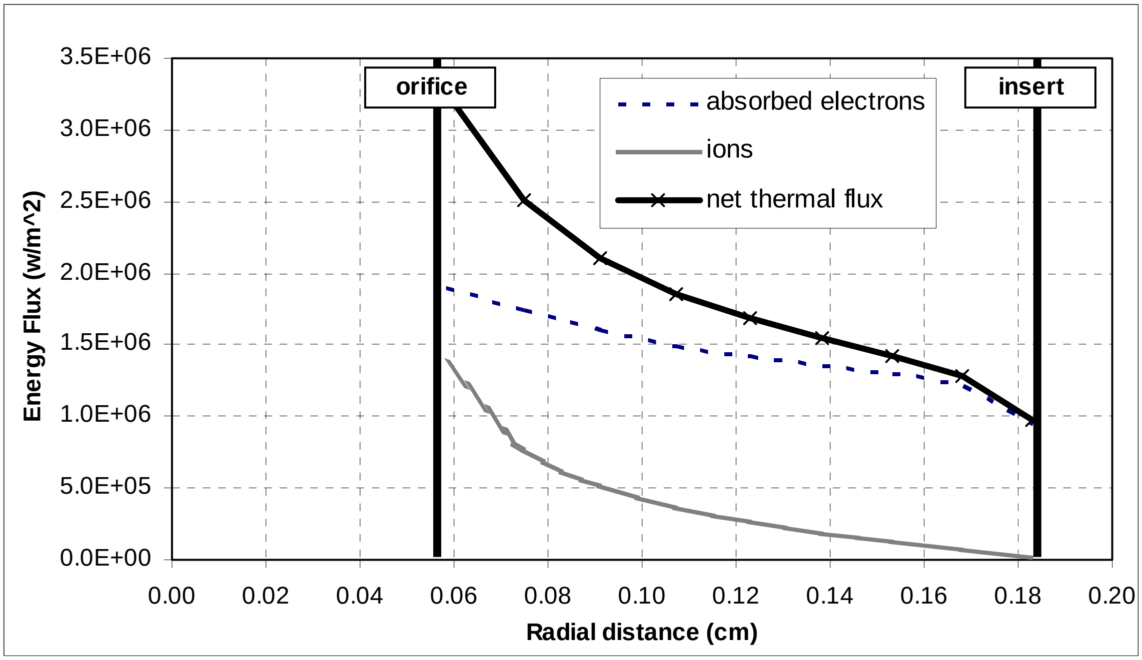

Figure 6. Components of the plasma thermal flux to the upstream surface of the orifice plate.

Insert Surface Heating	12W
Orifice Plate Heating	29W

Table 2. Insert surface and orifice plate heating.

The HCThermal results depend strongly on the orifice plate emissivity. As discussed above, the value used, 0.21, slightly higher than literature values for polished tungsten.. The peak orifice plate temperature in the calculation is 1420 K. Comparison between measured thermocouple values and the code calculated values are shown in Table 3. The most significant result of the calculation is that the overall trend is 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 3. 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.

	Measured	HCThermal
Current	12.0	12.0
TC1	1092	1096
TC2	715	720
TC3	TBD	634
TC4	284	284

Table 3. Comparison of measured thermocouple temperatures with the code results with the adjusted tungsten emissivity of 0.2.

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 [Ref 5,6] and is displayed in Figure 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. The peak insert temperature is about 100°C higher than the temperature near the orifice plate.

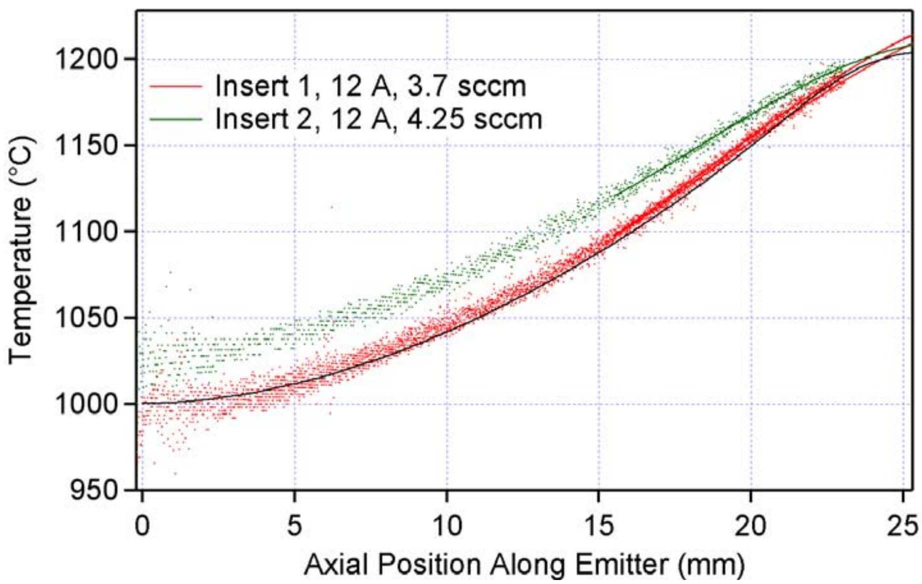

Figure 7. Measured emitter temperatures. The calculation is for Insert 2.

The calculated temperature along the insert surface is shown in Figure 8. Note that the temperature profile flattens within a few millimeters of the orifice plate. The thermal contact between the insert and the tube sets both the magnitude of the emitter. The results are for 300 W/˚C/m^2.

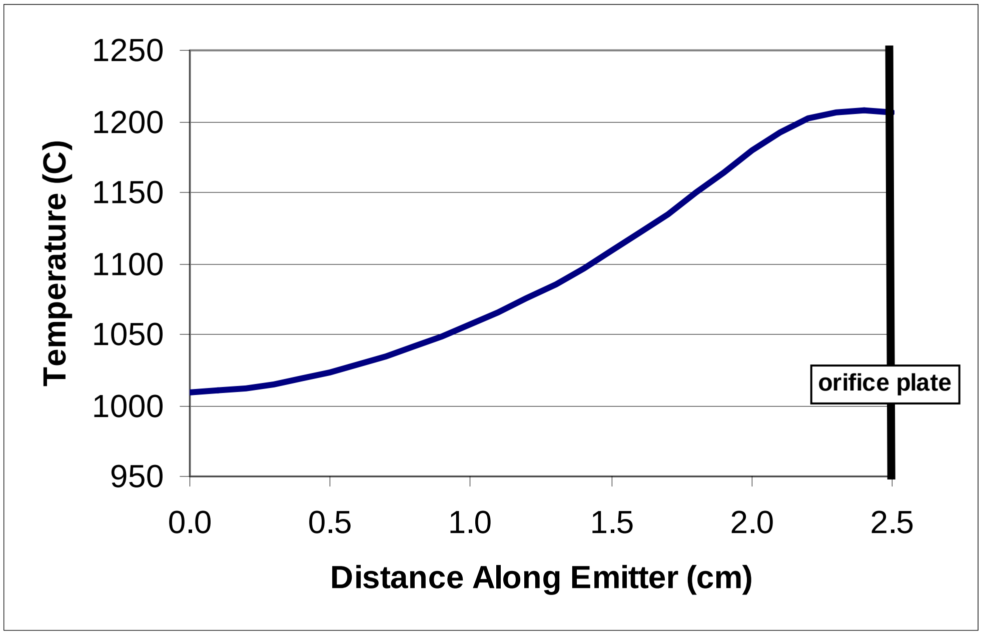

Figure 8. Calculated temperatures along the insert emitter surface.

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.

Discussion

The thermal model shows the sensitivity of hollow cathodes to the emissivity of the orifice plate and the thermal contact between the emitter and the tube. Using calculated plasma thermal fluxes, by adjusting these two parameters, the code was able to reproduce the axial variations of both insert and tube temperatures.

The combined plasma code and thermal code 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 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 plasma electron current returning to cathode surfaces. The sheath potential adjusts to control the return electron current in order to maintain the circuit current. The exponential dependence on the sheath potential gives the hollow cathode its nearly vertical current-voltage characteristic.   This result has important implications for 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. [it would be interesting to run a few cases at different temperatures to see how the heat loads and voltage change…]

In these 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.

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