Design and Analysis of the Heater Region of a Low Current Hollow Cathode

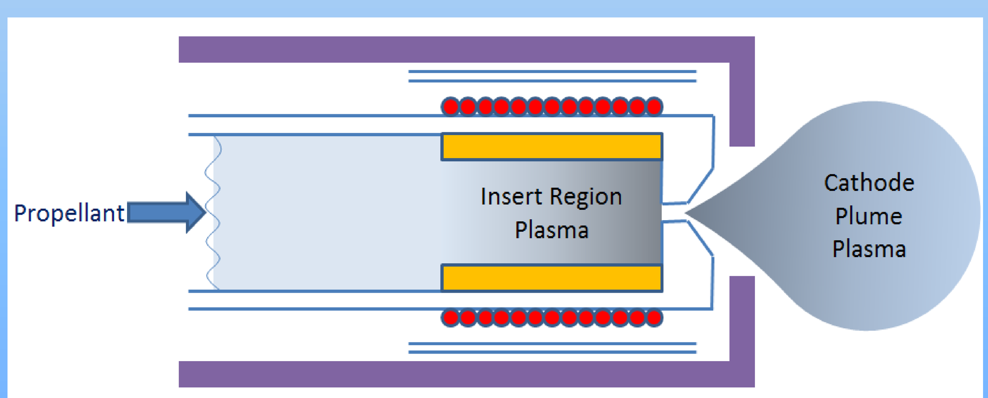
Ali Enes Ozturk, Oguz Korkmaz, Murat Celik
Bogazici University, Bebek, Istanbul, 34342, Turkey

Abstract

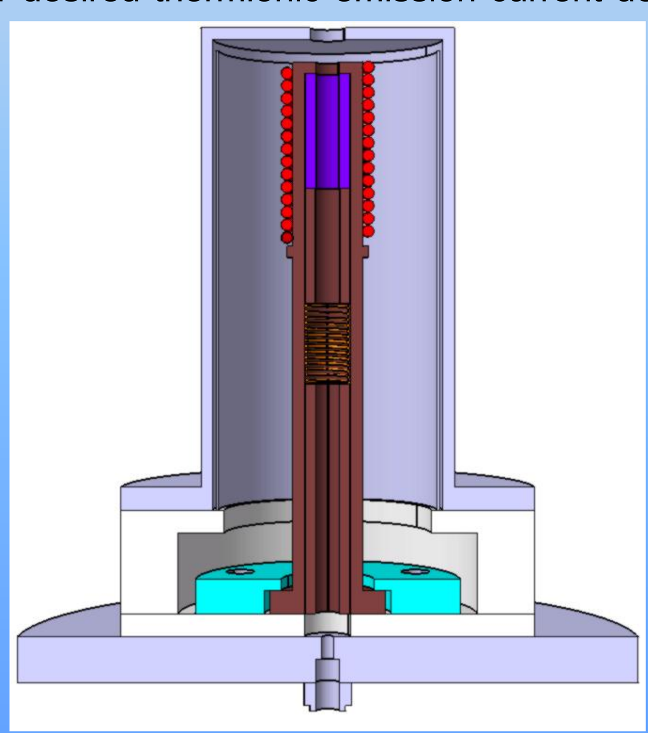
Several space electric propulsion devices, such as ion engines and Hall effect thrusters, use hollow cathodes as the electron sources for providing the necessary electrons for the ionization of the propellant and to neutralize the ion beam leaving the thruster. Most of the hollow cathodes used in space applications have used Barium-oxide impregnated Tungsten (BaO-W) inserts as the thermionic emission material due to its low work function. However, recent studies have shown the advantages of using Lanthanum-hexaboride (LaB_6) insert material as the thermionic emission source. However, due to its higher work function, the LaB_6 inserts have to be heated to a much higher temperature compared to the BaO-W inserts. In this paper, design and thermal analysis of the heater of a prototype hollow cathode with an LaB_6 insert as the thermionic emission material is presented. The built hollow cathode will be used as a neutralizer electron source for BURFIT-80, an 80 mm diameter laboratory RF ion thruster running on Xenon propellant.

Problem

The hollow cathodes used in electric propulsion systems usually have a thin, long, hollow cylindrical conductor pipe in which an insert material with low work function is placed. Hollow cathodes operate based on a physical effect called *thermionic emission*. Thermionic emission is basically the release of electrons from an emitter material. The heating of the insert material causes increased electron emission from the surface to the hollow inner part of the cathode tube where a propellant flow is supplied. During steady state operation, the plasma generated inside the cathode tube provides a self-heating mechanism to keep the thermionic emission from the surface at a steady rate. However, in order for the cathode discharge to begin, an external heating mechanism has to be used. This heater increases the temperature of the insert to the levels required for the desired current emission density from the insert surface. For starting the thermionic emission, the insert should be heated above 1600 ^oC for LaB_6 inserts. Therefore an external heater is required for the initial heating. Once the emitter reaches the required temperature for desired thermionic emission current density level, the heater is turned off.



This paper discusses a detailed thermal analysis for this LaB_6 hollow cathode. COMSOL is a multi-physics solver program based on the balance equations for mass, momentum and energy, with an implicit scheme solving. This is a thermal analysis of an available LaB6 insert during initial heating.

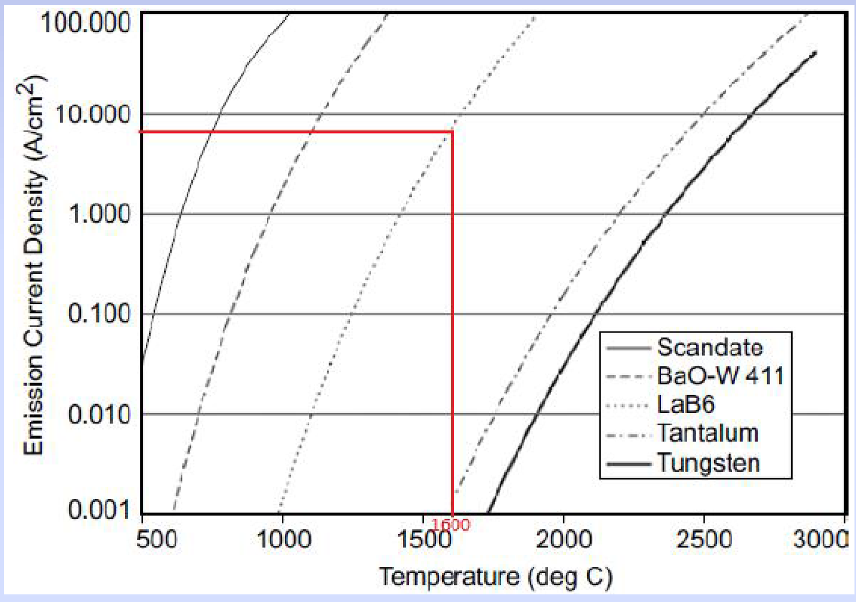


Cross section of designed hollow cathode

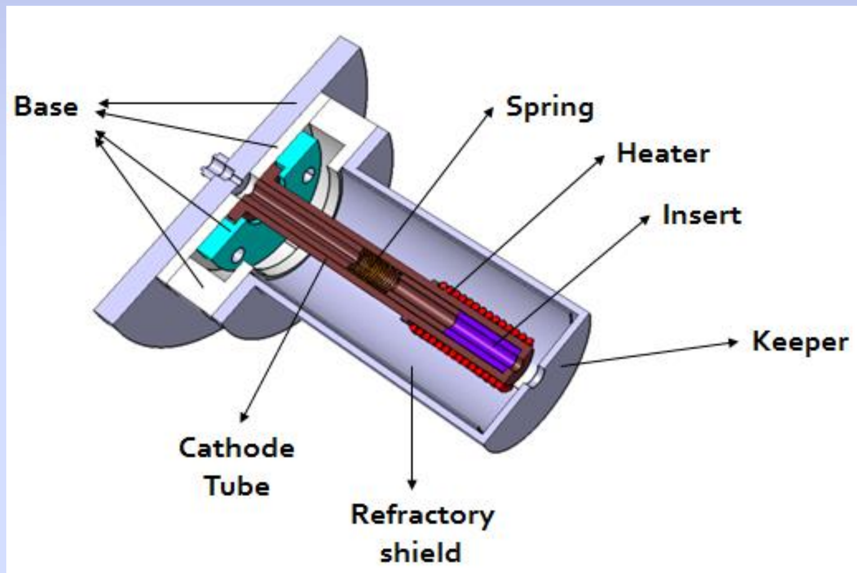
Theoretical Prediction

The basic operation mechanism of a hollow cathode is as follows: The insert (LaB_6) is heated by an external heater coil to an elevated temperature where sufficient electron emission per unit area is achieved. The electrons which are emitted from the insert hit Xenon gas and cause the Xenon neutral gas to be ionized. Then, with the application of an electric potential to the keeper electrode, which is placed external to the cathode electrode, ionized Xenon atoms will move out. The cathode insert can maintain its emission temperatures with the heat flux from the plasma to the insert surface. This is called the self-sustaining mode of operation. The heater is required only to provide the initial heating of the insert.

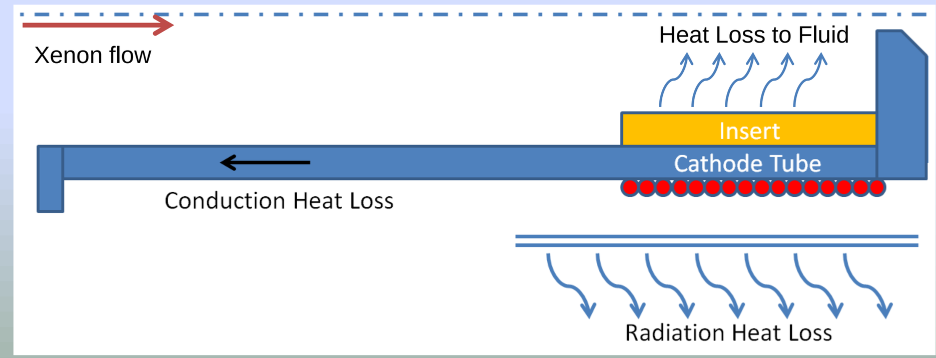
Normally hollow cathodes can provide self-heating to sustain the emission temperature. However for starting the thermionic emission, the insert should be heated above 1600 ^oC for LaB_6 insert. Therefore an external heater is required for the initial heating. The high temperatures required for heating are typically supplied by refractory metals, like Tungsten and Tantalum, that can withstand very high temperatures.



Emission current density versus temperature for various cathode material



Parts of hollow cathode



Heat losses of a hollow cathode

Thermal Modeling of the Cathode's Heater Region

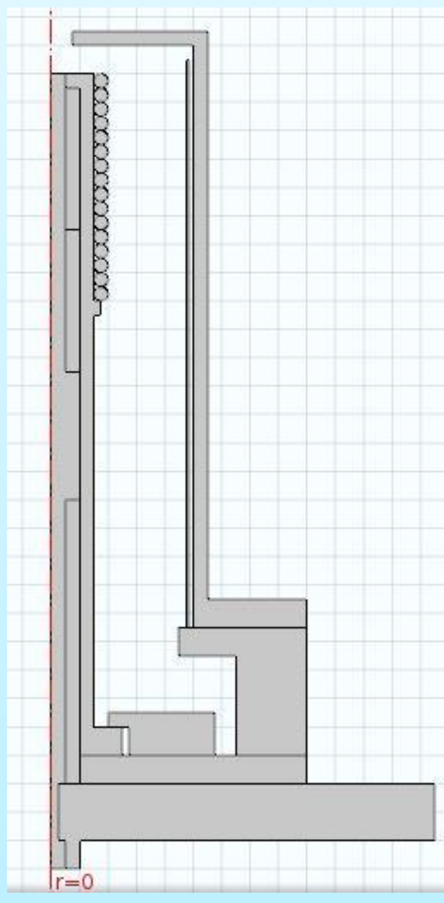
2D Axissymmetric Modeling

COMSOL, a FEM software, is used to analyze the heating time and the uniformity of the heating for these three different designs. The hollow cathode design is created in COMSOL with fluid flow. For the analysis, appropriate material properties are entered into COMSOL, and the tetrahedral mesh for the thermal analysis is generated.

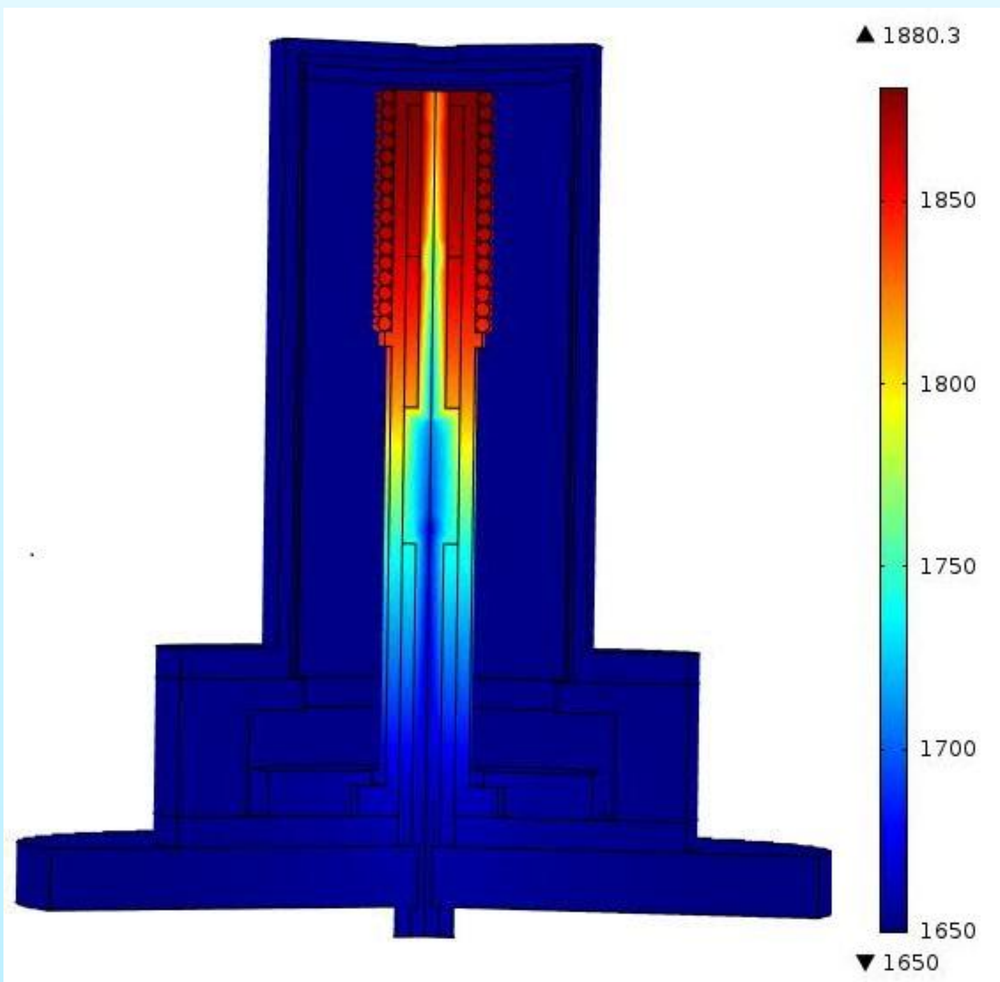
The designs elaborated in this work is supported by heat transfer simulations. In the thermal analysis, it is assumed that the heater coils consume a total power of 107 W. It is thought that a current of 7 Amperes at ~15.3 Volts will be provided to the heater coils by an external power supply. This value is adapted from the experimental observation of the highest power delivered to the heater, before the initiation of the discharge, for the heating of Busek BHC-1500 hollow cathode. Main heat loss of the cathode is the conduction heat transfer to its base that is assumed to be open boundary and loses heat with constant heat transfer coefficient. Since the cathode testing (and real life operation) will be conducted in vacuum environment; the convective heat loss from the outside of the cathode is neglected. Moreover there is a purging of the propellant gas (Xenon) inside the cathode tube during the initial heating of the insert region. Although there is radiation heat loss, it is calculated that the radiation heat transfer to the environment will be small compared to other heat losses during initial heating. Thus, only conduction heat loss to the base and convective heat loss to the inside flow are considered.

First of all, hollow cathode design was generated by COMSOL geometry feature in 2D axissymmetric plane. The reason of using 2D axissymmetric model is that every part of hollow cathode is cylindrical. Materials were assigned to all domains of the geometry. Then the physic model is established by adding heat source, heat losses and boundary conditions. Mesh was generated automatically by COMSOL. Finally the study was computed to get results. In additon to 3D temperature plot, 1D temperature plot of the intersection of the insert and orifice was computed to see convergence of temperature over time step.

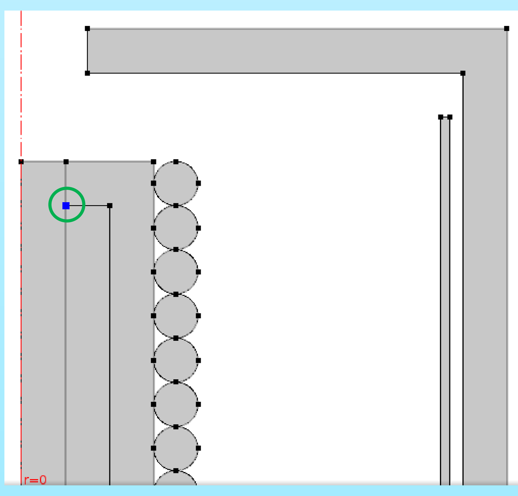
As a result, the maximum reached temperature is 1880 ^oK around the orifice. Heat flow through cathode tube and Xenon gas can be seen on 3D plot. Also from 1D graph it is seen that temperature is converged.



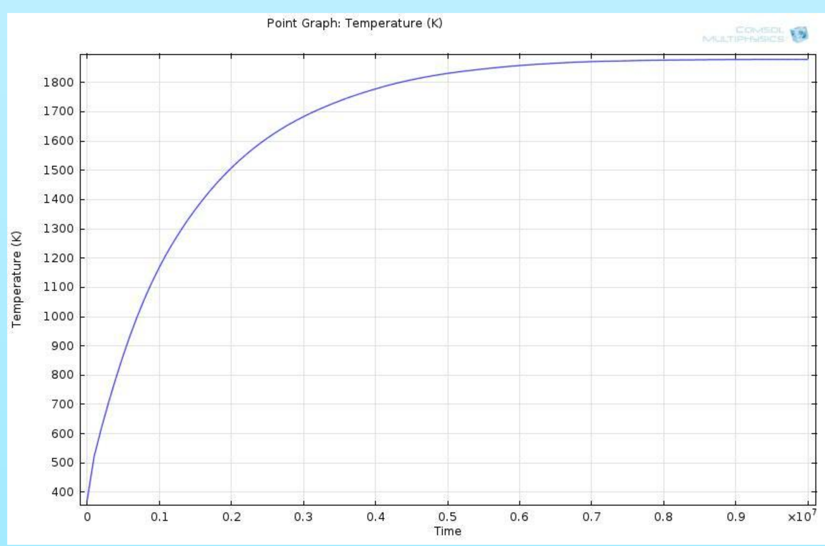
2D axissymmetric model



The 3D surface plot of the temperature distribution.



Intersection point of insert and orifice



1D Temperature graph of the intersection point

Conclusion and Future Work

Ion engines and Hall effect thrusters that are used for certain propulsive applications of spacecraft and satellites need devices called hollow cathodes for the delivery of the electrons needed for their operation. Most of the hollow cathodes used in space applications have used Barium-oxide impregnated Tungsten (BaO-W) inserts as the thermionic emission material due to its low work function. However, recent studies have shown the advantages of using Lanthanum-hexaboride (LaB_6) insert material as the thermionic emission source. Due to its higher work function, the LaB_6 inserts have to be heated to a much higher temperature compared to the BaO-W inserts. In this study thermal analysis work are presented for a hollow cathode with LaB_6 insert during initial heating. The analyzed hollow cathode will be produced and tested. The result of the analysis will be used to decide on thermouple points during the test. Test results and analysis will be compared. Also analysis can be enhanced like using joule heating model.

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