Design and Analysis of Different Insert Region Heaters of a Lanthanum Hexaboride Hollow Cathode During Initial Heating

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In Kauffman type ion engines and Hall thrusters, the electron-impact ionization is the main ionization mechanism; therefore these thrusters require electron sources that provide the necessary electrons for the ionization process. Hollow cathodes are the devices that are most commonly used for providing the needed electrons for ionization in such electric thrusters as well as for providing electrons to prevent spacecraft from charging due to the electric thruster ion beam. Hollow cathodes used in modern electric propulsion systems usually have a thin, long, hollow cylindrical conductor pipe in which an insert material with low work function is placed. 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. In this study, the thermal analysis around the heater region during initial heating is made by using commercial FEA software (COMSOL). Results of the detailed 2D axissymmetric analysis are presented in this paper. As a future work there will be experimental study to validate the analysis.

I. Introduction

Some of the 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. However, recent studies have shown the advantages of using Lanthanum-hexaboride (LaB6) insert material as the thermionic emission source [1, 2, 3]. However, due to its higher work function, the LaB6 inserts have to be heated to a much higher temperature compared to the BaO-W inserts. In this paper, design and thermal modeling of three different heater models of a prototype hollow cathode with an LaB6 insert as the thermionic emission material is presented. The built hollow cathode will be used as a neutralizer electron source of a 8 cm diameter laboratory RF ion thruster running on Xenon propellant.

The hollow cathodes used in modern electric propulsion systems usually have a thin, long, hollow cylindrical conductor pipe in which an insert material with low work function is placed. The basic operation mechanism of a hollow cathode is as follows: The insert (LaB6) 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 that is allowed to flow in the hollow region of the cathode tube and cause the Xenon neutral gas to be ionized. Then, with the application of a electric potential to the keeper electrode, which is placed external to the cathode electrode, electron emission to outside is achieved. 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

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only to provide first heating of the insert.

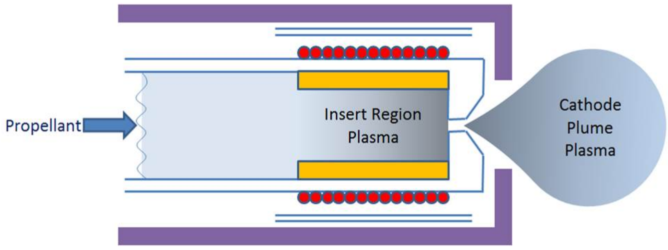

Figure 1: Schematic of hollow cathode

In the United States, NASA have used Barium Oxide impregnated Tungsten (BaO-W) dispenser hollow cathodes from the 1960s [4, 2]. In the United States, Goebel reported the first time use of LaB6 in a hollow cathode in 1978, and presented high current LaB6 cathodes developed for plasma sources in 1985 [2]. Goebel and his collaborators have been continuing their research about the LaB6 hollow cathodes [5, 6, 2]. Few other researchers have been following Goebels studies in recent years. By following Goebels research, Courtney [1] at MIT built and tested a small LaB6 hollow cathode which had a discharge current under 2 Amperes. Similarly, Warner [3] at Air Force Institute of Technology studied hollow cathodes with LaB6 and CeB6 insert materials.

BaO-W and LaB6 cathodes have been used as most common hollow cathode insert materials due to their low work functions. The work function of BaO-W is 2.06 eV at a temperature of around 1000 °C and the work function of LaB_6 is 2.67 eV around 1650 °C. [2]. From the point of the cathode lifetime, LaB6 cathodes have advantages as LaB6 has a lower evaporation rate [2, 6]. Moreover BaO-W cathodes are very sensitive impurity poisoning (water vapor, oxygen or other impurities in Xenon gas) at high temperatures and the poisoning can shorten the lifetime of the cathode or even prevent the cathode emission [1, 6]. For LaB_6 cathodes, special conditioning and storage procedures do not have to be followed and thus LaB_6 cathodes could be considered as more reliable than BaO-W cathodes [4].

Figure 2: Sheathed tantalum wire[3]

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 °C 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 metal wires, like Tungsten and Tantalum, that can withstand very high temperatures [1].

Generally heaters are made by wrapping a wire around the cathode tube and then covering it by a reflective foil as shown in Figure 2. Although it is a simpler method, this method may not be effective for heating the insert in small cathode tubes due to its weakness in uniform and efficient heating of the insert [1]. As an alternative, a threaded ceramic tube which is wrapped by the wire is used as the heater for providing better surface contact between the heater assembly and the cathode tube compared with insulated wire [1]. Also a different heater design study was made at the University of Michigan as shown in Figure 3 [4]. Axial pattern is used instead of helical wire path to make the machining of the ceramic sleeve easier [4].

Figure 3: Different heater design of the University of Michigan [4]

In this study, three different heater designs have been considered. These designs, shown in Figure 4, are inspired by the several other works mentioned in the literature. The considered heater designs will be called as design A, design B and design C. In design A, the heater wire is assumed to be a 1 mm thick insulated Tantalum wire making 15 turns around the tube. The heater is assumed to be approximately 15 mm long (5 mm longer than the insert). In design B, a Boron Nitrite ceramic tube with helical shaped grooves placed on the cathode tube in the insert region. A bare Tungsten wire is assumed to be wound inside these grooves. This shape will provide a more uniform heating of the insert as well as allowing a more compact wounding of the wire. In design C, similar to design B, a Boron Nitride ceramic tube is placed around the cathode tube, but this time vertical grooves, instead of the helical shaped, are machined on the ceramic. Again, a bare Tungsten wire provides the resistive heating. A cylindrical Tantalum sheet, placed around the cathode tube and the heater coils, is used as a refractory material to prevent the radiative heat loss and aid maintaining the self-heating of the hollow cathode. The cylindrical Tantalum sheet radiates heat back into the system so that the generated heat is encapsulated and higher temperature values are achieved.

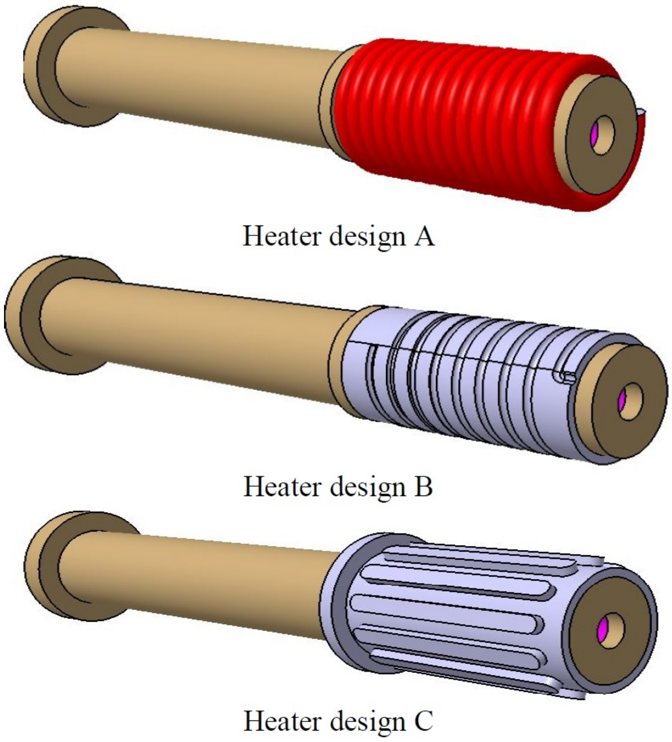

Figure 4: Heater designs for the hollow cathode

This paper discusses thermal analysis of three different heater designs for this LaB_6 hollow cathode during. Several parameters are varied to obtain the better heater configuration. COMSOL, a finite element analysis program, is used for the thermal analysis of the three heater designs. COMSOL is a multiphysics solver program based on the balance equations for mass, momentum and energy, with an implicit scheme solving. Thermal analysis just consists of the initial heating. Results of the analysis will be corrected by experimental work in the future.

II. 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 Xe 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 first heating of the insert.

The electron emission of the insert at high temperatures is known as thermionic emission. Thermionic emission is the electrons emission from a heated filament or substance. If a filament like tungsten is heated to a high temperature, some electrons acquire sufficient energy and then they are able to break away from the surface of the material and go into space [7]. Thermionic emission by a material is described by Richardson-Dushman equation;

$$J = AT^2 e^{-e\phi/kT} \tag{1}$$

where J is the thermionic emission current density, A is a universal constant 120 A/cm^2K^2, T is the temperature in Kelvin, e is the electron charge, k is Boltzmanns constant and ϕ is the work function for the material [6].

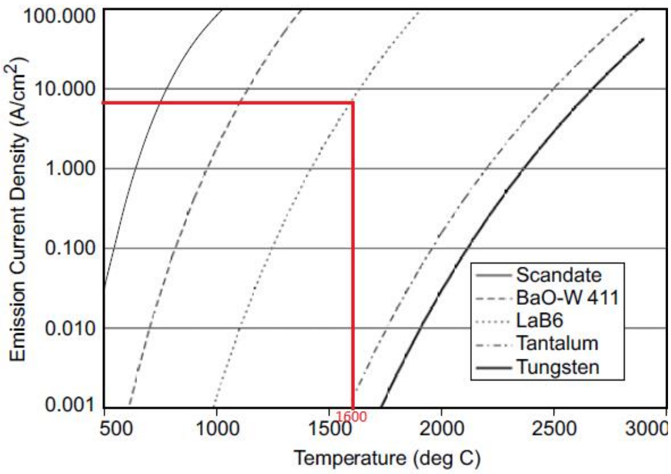

Figure 5: Emission current density versus temperature for various cathode material [6]

Figure 5 presents the temperature dependence of the electron emission current density for various materials low work function materials. As seen from the figure, the emission current density for LaB_6 would be significantly less that for BaO-W for the same temperature. In order to reach an electron emission current density of 8 A/cm^2, the LaB_6 insert should be heated to temperature of greater than 1600°C.

III. Design and Thermal Modelling of the Cathode Heater

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.

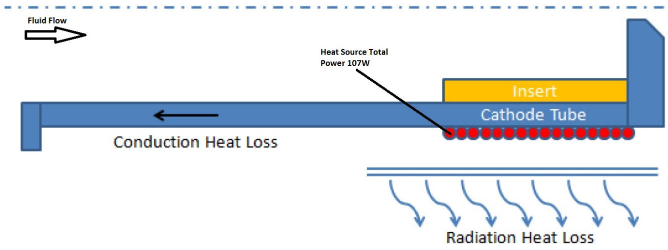

Figure 6: Schematic of the thermal analysis of hollow cathode

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 there is heat loss 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 a tantalum shield to prevent heat loss by radiation, there is still some radiative heat loss from the heater region.

For the proposed designs B and C, a tantalum wire of 0.25 mm diameter will be used as the heater wire. Even though tantalum has resistivity of 131 nΩ·m at room temperature, its resistivity increases to roughly 800 nΩ·m at 1600 °C [8]. With the current design, the total length of heater wire would be roughly 330 mm. Thus corresponding to a total resistance of 2.4 Ω. Hence for a current of 7 Amperes it would be possible to provide 100 W of heating power.

2D Axissymmetric Model

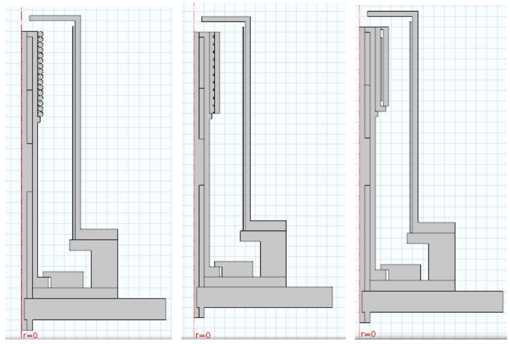

Figure 7: 2D axissymmetric geometries generated by COMSOL

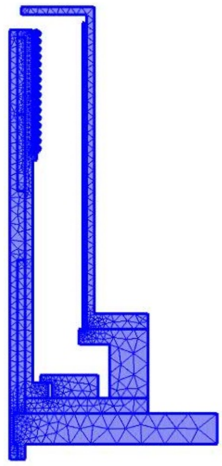

Figure 8: Generated mesh for design A

First of all, hollow cathode design was generated by COMSOL geometry feature in 2D axissymmetric plane. Because every part of hollow cathode is cylindrical, 2D axissymmetric model is used. Materials were assigned to all domains of the geometry. Then the physic model is established by adding heat source, heat losses and boundary conditions. As mentioned before, heat source's power was adopted from a commercial hollow cathode. During initial heating, the flow rate of the fluid is suggested as 1 sccm by Dan Courtney's thesis [1]. For our designs, 1 sccm corresponds to 5.8 mm/s. Mesh was generated automatically by COMSOL. Finally the study was computed by heating all cathodes to 1600°C (1873°K) to get results.

As a result of the analysis, from Figure 9 it is observed that heater designs B and C show similar temperature distribution and these designs distribute heat more uniformly compared to heater design A. Also there is no heat flow through the keeper. Heat directly flows from cathode tube to base plate which corresponds to the computational boundary for the analysis. Surface radiation between the heater and the tantalum shield lead to the heating of tantalum shield.

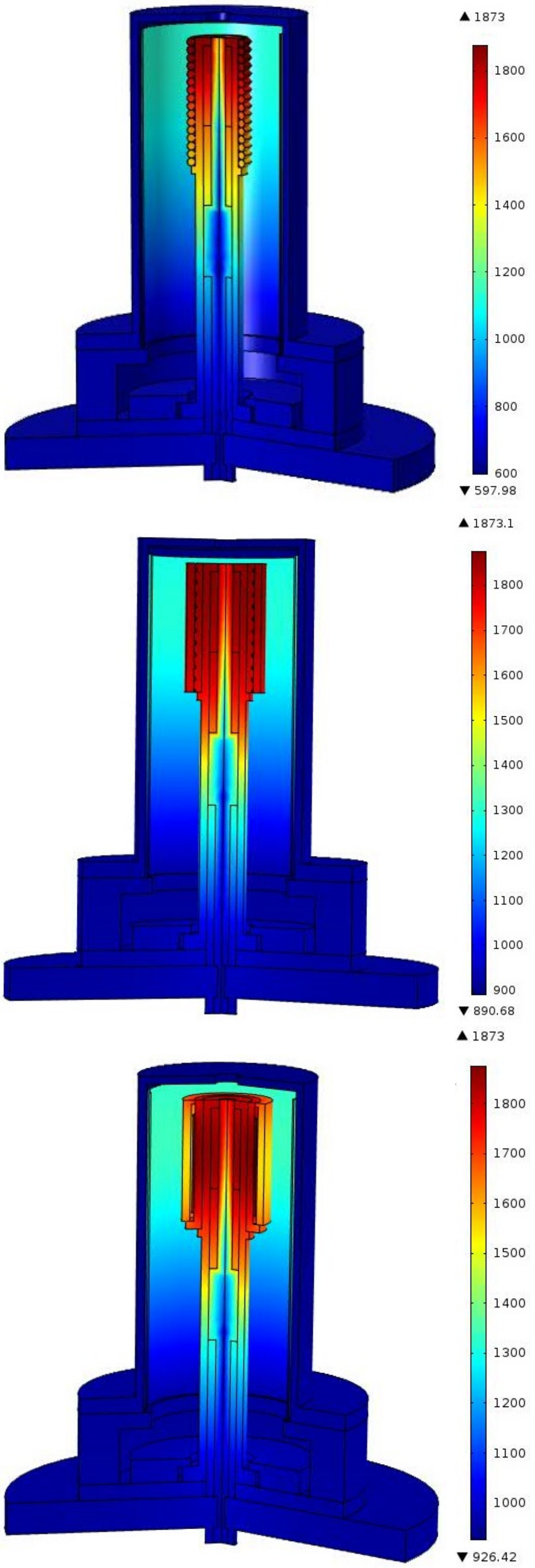

Figure 9: Thermal analysis of hollow cathode generated by COMSOL of graphs of designs A, B and C respectively

Cathode designs A, B and C reached 1600°C (1873°K) by time steps 405, 809 and 898 respectively. This shows that although heater design A cannot distribute heat uniformly, it reaches the expected temperature in almost half the time in comparison to other two designs.

The insert has the highest temperature near the orifice region. Therefore the temperature of the insert was measured at the point shown in Figure 10. Measured temperature values are plotted for every heater design in Figure 11.

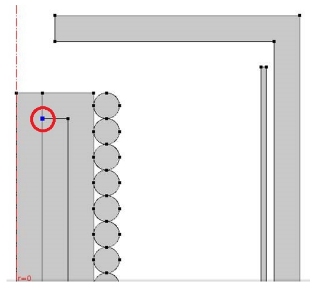

Figure 10: The point of generated graphs

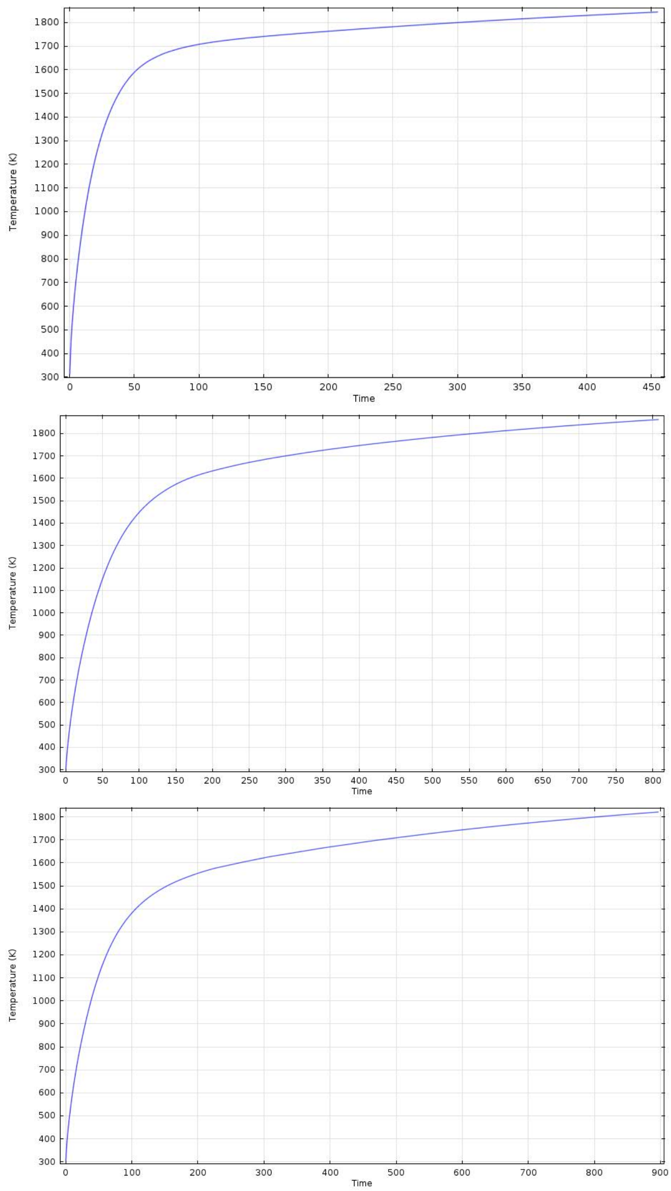

Figure 11: Temperature vs time step graphs of designs A, B and C respectively

IV. 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 is presented for a hollow cathode with LaB_6 insert during initial heating. The analyzed hollow cathode will be manufactured and tested. The results of the analysis will be used to decide on thermocouple locations during the tests. Test results and analysis will be compared. Also analysis can be enhanced using Joule heating model.

Figure 12: Manufactured cathode tube and heater B

Except base pieces, hollow cathode's parts were manufactured. Also vacuum chamber test setup has been established for experimental work.

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