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Design Process of the Hollow Cathode Manufactured for Use in Electric Propulsion Systems as Electron Source

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ABSTRACT

Hollow cathode, which is an indispensable device for ion and Hall effect thrusters, has been under investigation for more that 50 years. Hollow cathodes, which are composed of three main components as insert, orifice and keeper, and which work according to a physical process known as thermionic emission, provide the necessary electron current for ionization of neutral propellant atoms and neutralization of the ion beam at the exit for ion and Hall effect thrusters. Hollow cathodes, apart from electric propulsion systems, are used in wide variety application areas such as lasers, plasma generators and material processing. In addition, hollow cathodes are promising candidates for use in microsatellites and nanosatellites as stand alone propulsion devices due to their small physical size. In its simplest form, thermionic emission is the release of electrons from an emissive material. It is necessary to heat the emissive material up to a temperature in order to start electron emission. The properties of the emissive material used in hollow cathodes play an important role on power consumption, lifetime and desing of this devices. Therefore, extreme attention should be paid in selection of insert material. In this study, summary of a comprehensive literature survey about kinds and properties of insert materials and the things considerations while using them are shared. The need that the insert material should be heated up to a temperature, keeps hollow cathode from operating quickly. Therefore, the heater used in a hollow cathode and its heating performance has an extreme importance. In this study, the results of the performance analysis of different heater designs, which is performed by using a commercial finite element analysis software COMSOL Multiphysics at initiation stage of hollow cathode are shared as well. Moreover, the design process of the hollow cathode that is designed at the Bogazici University Space Technologies Laboratory (BUSTLab) according to the experiences that are obtained from this literature survey and analysis are shared with the research community.

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INTRODUCTION

Hollow cathodes, which are used in ion and Hall effect thrusters, plasma generators and ion sources as electron sources, have been under investigation for more than 50 years. The hollow cathodes, which work according to the physical phenomenon known as thermionic emission, are composed of three main regions as insert, orifice and keeper (Figure 1). In its simplest explanation, thermionic emission is the release of electrons from a material when it is heated up to necessary temperature. It is compulsory to heat the emissive material up to a particular temperature in order to initiate thermionic emission. Therefore, the heater wires, which are wrapped around the insert region of the cathode tube, are added to the hollow cathode design. The heat is provided to the insert material by the current passing through this high resistance wires.

The hollow cathodes used in electric propulsion systems have a thin, long, cylindrical hollow tube in which the insert material is placed. Orifice is a refractory material that is welded at the tip of the cathode tube. Orifice maintains high internal pressures on the order of $10^3 - 10^4$ Pa. The orifice designs are divided into three groups: A type, B type and C type. In A type orifice design, length of the orifice is greater than its diameter. Therefore, heat conduction from orifice to insert is an important heating mechanisms. In B type orifice design, the orifice diameter is greater than orifice length hence, internal pressure value is low. In C type orifice design, there is no orifice. The internal pressure value is really low in this type of cathodes. The ions coming from plasma and recombining on the insert wall provide an important heating mechanism in the hollow cathodes with C type orifice [Goebel and Katz, 2008].

Another component of a typical hollow cathode is the cylindrical keeper tube that is placed around the cathode tube. The main task of keeper tube is to create an attracting potential difference for the electrons released from insert material. With this potential difference, the electrons gain enough momentum in order to ionize the neutral particle gas atoms. At initiation stage, the neutral gas atoms, which are injected from upstream end of cathode tube, ionize by colliding with the electrons released from insert material via thermionic emission. Thus a dense plasma environment is created in insert region. After the system reaches the steady state operation condition, the electrons and ions coming from insert region plasma, and transferring their energy to insert material by striking on it, provide a self heating mechanisms. After this point on, the external heater is turned off. Another task of the keeper is to prevent the erosion cathode assembly that ion bombardment coming from surrounding plasma (ionization chamber of an ion thruster or ion beam at the exit etc.) can cause.

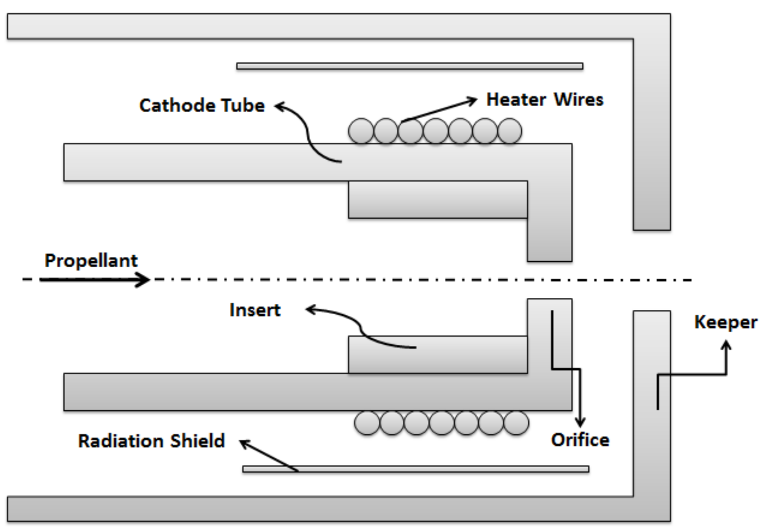

Figure 1: Schematic of hollow cathode

In this study, information regarding the design processes of the hollow cathode, that is being manufactured and will be tested in a near future at Bogazici University Space Technologies Laboratory (BUSTLab), are shared. Detailed information regarding the selection of emitter material, different heater designs and their analysis, the solid modelling of the whole system, prototype manufacturing, eventual production of hollow cathode and planned tests in the future are presented to the attention of researchers.

Thermionic Emitter Materials

It is of extreme importance for hollow cathode operation parameters and power consumption whether it is easy to emit electrons from thermionic emitter. Therefore, the insert material should be selected with a great care. Work function, evaporation rate and resistance against impurities are important parameters for emitter material selection. The most frequently used emitter materials in the literature are barium oxide impregnated tungsten $(BaO - W)$, lanthanum hexaboride (LaB_6) or cerium hexaboride (CeB_6) [Warner, 2008].

Barium oxide impregnated tungsten can be used as emitter material. The work function of this material known as oxide cathodes or dispenser cathodes is less than 2 eV and it can provide high electron current densities. Dispenser cathodes are divided into two groups: cavity reservoir dispenser cathodes and impregnated dispenser cathodes. There are many types such as L cathode, MK cathode, CPD cathode, B cathode. The most common cathode used in thrust systems is Philips S type cathode. This material is composed of a mix of barium, calcium oxide and alumina that is impregnated in a tungsten matrix. For instance, 4:1:1 $(4BaO : 1CaO : 1Al_2O_3)$ emitter material is generally used in ion thrusters. The work function of 4:1:1 material at 800 °C is around 2.06 eV [Cronin, 1981]. The most important disadvantage of $BaO - W$ emitters is that they are prone to impurity poisoning. This material can easily be affected by the impurities in the propellant and as a consequence, the work function increases dramatically and electron emission ceases. Therefore, high purity propellant usage is a must in order to guarantee long lifetime in hollow cathode working with BaO-W. Need of high purity propellant usage (around %99.99) demands a propellant purification system and this brings a financial burden around $0.5-1 M per spacecraft [Goebel and Katz, 2008].

LaB_6 emitter material can give high current densities as well. Moreover, evaporation rate of this material is small compare to the one of $BaO - W$ and it is not affected by the impurities in the propellant (Figure 2). The work function of LaB_6 emitter material is around 2.67 eV. LaB_6 can give 10 A/cm^2 current density at 1650 °C. It is observed that the work function of LaB_6 emissive material does not change even if its surface is exposed to a poisonous environment. LaB_6 was first discovered by Lafferty [Lafferty, 1951] and it is studied by many other researchers [Jacobson and Storms 1978], [Storms and Muller, 1979] in the following years. It has been used in hollow cathodes as emitter material since 1970.

Lanthanum boride compounds can be divided into three categories, LaB_4, LaB_6, LaB_9. LaB_6. LaB_6 has purple, LaB_4 has grey, LaB_9 has blue surface colour. Lanthanum hexaboride (Figure 3) reacts with many refractory material such as tungsten. Especially, it reacts with molybdenum. Boron atoms coming from LaB_6 diffuses into metal lattices and forms interstitial boron compounds. The boron diffusion toward refractory material embrittle the material and may cause to fracture at high temperatures. Therefore, LaB_6 must be supported with a material which obstructs the boron diffusion [Lafferty, 1951]. In order to prevent this boron diffusion, LaB_6 should be supported with carbon, tantalum carbide or rhenium.

Rhenium does not allow interstitial diffusion of boron atoms due to the fact that it has hexagonal closed packed lattice structure. In addition, it has a high melting point (3180 °C). Because of these reasons, rhenium is a suitable support material for LaB_6 [Goebel, Hirooka and Sketchley, 1985].

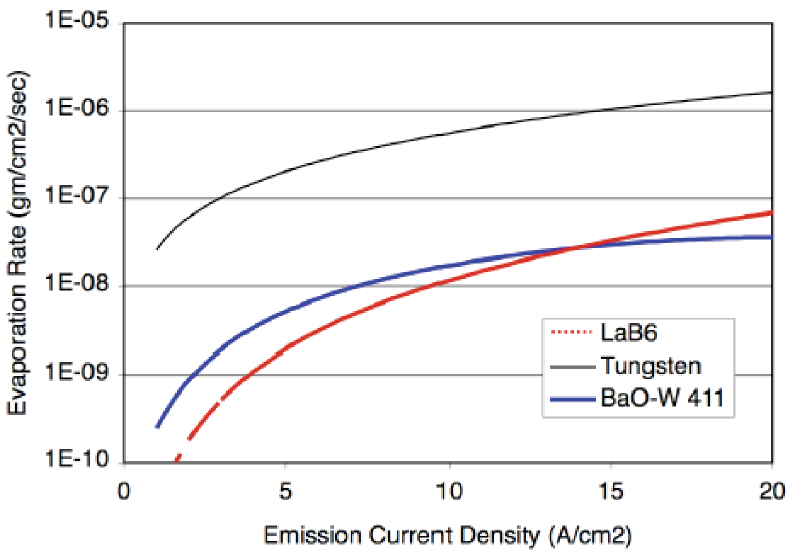

Figure 2: Evaporation of different emissive materials [Goebel and Chu, 2011]

Graphite can be used as support material for LaB_6 as well. Graphite totally eliminates the boron diffusion problem. Moreover, its high melting point, thermal expansion coefficient, which is similar to that of LaB_6, put this material forward as a suitable support material for LaB_6 [Goebel and Watkins, 2010], [Goebel, Watkins and Jameson, 2010], [Goebel, Hirooka and Sketchley, 1985].


Figure 3: Lantanum hexaboride tube

Different Heater Designs and Their Analysis

At initiation stage of hollow cathode, insert must be heated up to a temperature in order to obtain desired level of electron emission. Since rapid heating and cooling can cause fractures in cathode assembly, the heating should be gradual. Especially, it is known that LaB_6 emitter material fractures in case of rapid heating and cooling [Goebel, Crow and Forrester 2008]. This gradual heating process prevents hollow cathode to be operational quickly. Hence, cathode heater design is very important in order to heat the cathode up to necessary temperatures as quickly as possible.

The heater commonly used in hollow cathodes is made out of winding of a resistive material, which can withstand high temperatures such as tungsten and tantalum, around cathode tube. In this design, isolation of heater wires with a material, which is dielectric and can stand high temperatures, is a must to prevent short circuit. This type of heater is the most common heater design in hollow cathodes.

Apart from the wrapping of sheathed heater wires, another heater design is the placement of the heater wires in the grooves that is machined on a ceramic tube in radial direction. In addition, a sleeve placed around the heater design is used to keep the heater wires in their position. This heater is designed in order to provide better surface connection between heater and cathode tube [Courtney, 2008].

Another heater in the literature is designed at the Michigan University. In this design, rather than radial grooves, axial pattern is used. The heater wires are wrapped around this axial patterns and a sleeve is placed in order to keep the wires in their positions [Trent, McDonald, Lobbia and Gallimore 2011].

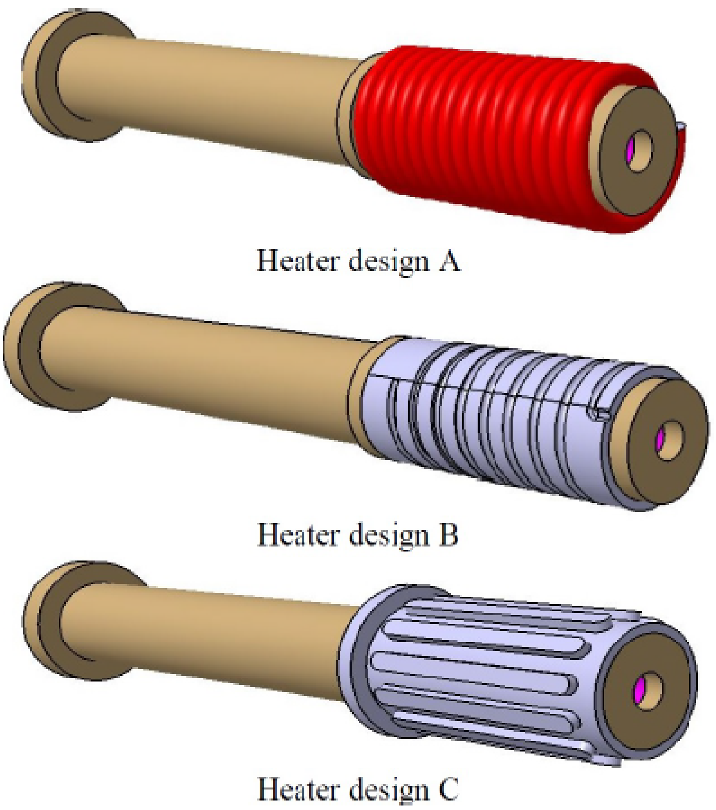

Figure 4: Solid models of different heater designs

During hollow cathode design, solid models of these three heater designs are created and their heating performance at initiation stage is assessed (Figure 4). COMSOL, a commercial finite element analysis software, is used in the analysis. The necessary material properties are given to COMSOL and a tetrahedral mesh is created (Figure 5). In this analysis, 107 W heat gain coming from heater, convective heat loss due to xenon gas flow, heat conduction to the base and radiation heat losses from whole cathode design is taken into account. Since this device works and will be tested in vacuum environment, other convective heat losses are not taken into account. Assigning a point on the insert surface just near the orifice, the time required for the defined point to be reached 1600 °C (1873 K) for different heater designs is investigated. As mentioned before, there is radiation sheath in heater assembly in order to reduce the heat losses due to radiation. In the analysis, radiation heat loss to this radiation shield and from this radiation shield is modelled as well.

The analysis showed that B and C designs show similar temperature distributions and these designs distributes heat on insert material more uniformly in comparison to the design A. Time steps of the cathode designs, at which they reach 1600 °C, are 405, 809 and 898 respectively. According to these results, even though design A cannot distribute the heat uniformly compared to the other designs, it was seen that it is the design which reaches the desired temperature fastest. These heater designs will be tested at Bogazici University Space Technologies Laboratory and the results will be compared with the ones obtained from COMSOL analysis [Ozturk, Korkmaz and Celik, 2014].

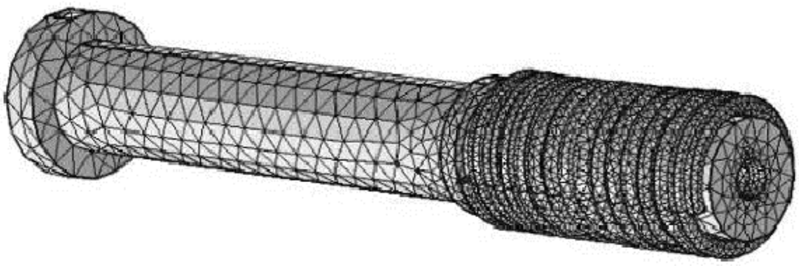

Figure 5: Tetrahedral mesh created in COMSOL for design A

Design of Bustlab Hollow Cathode

After experiences gained by this comprehensive literature survey on emission materials and the analysis of different heater designs, it is decided to manufacture a prototype hollow cathode. Electrical connections, thermocouple placements are determined and design mistakes are eliminated with this first prototype made out of brass and design and manufacturing process of the real cathode is started (Figure 6).

Figure 6: Prototype hollow cathode made of brass

Generally a hollow cathode is composed of insert, cathode tube, heater, keeper tube, spring, base parts and other parts (screw, wire etc.). Hollow cathode design starts from the inner part and goes towards the external parts. It is really important for material to be compatible with each other since hollow cathode works at high temperatures. Especially, having similar thermal expansion coefficient, high melting point and not reacting with each other are important points that one should keep in mind while selecting the materials used in the hollow cathode design. Insert is located at the center of cathode design. LaB_6 is selected as emitter for BUSTLab hollow cathode, since it has low evaporation rate and it is not affected by impurities. After the decision is made for the insert material, the dimensions of the insert are determined according to the desired current density. Desired current density for BUSTLab hollow cathode is decided to be 8 A/cm^2. In this regard, inner diameter, outer diameter and length of the LaB_6 material, which will be used as insert material in BUSTLab cathode, is determined to be 2 mm, 4 mm and 10 mm respectively.

After design of the insert material, the cathode tube is designed. Most of the heat that is produced during thermionic emission is lost to the cathode base through cathode tube via conduction. If this heat transfer is not large enough, the orifice may overheat which makes the cathode incapable to work. In the case of very large amount of conduction, temperature of the insert cannot be kept at a necessary value to have desired current density or operation of the cathode ceases. It is necessary to make an optimum cathode tube design in order to ensure constant insert temperature. The diameter, length and thickness of the cathode tube is designed by considering heat transfer. After design of the cathode tube, the material of the support, which will work with insert material, is determined. POCO graphite is selected as the support material since it does not react with LaB_6 and has similar thermal properties with LaB_6.

The most frequently used materials for manufacturing the cathode tube are molybdenum and POCO graphite in the literature. As stated before, hollow cathode works at elevated temperatures. It has an extreme importance, for the materials used in hollow cathode design, to have similar thermal expansion coefficients for system to operate in accordance. POCO graphite is selected for cathode tube manufacturing to have accordance with insert and support part.

It is necessary to compress the insert with a spring in order to keep it in its right position in the cathode tube. The spring is generally made out of tungsten or tantalum so that withstand high temperatures. It is decided to use tantalum wires, which was purchased to use in heater, for spring as well.

As mentioned before, there are three different heater designs in the literature. It is agreed that boron nitride will be used for manufacturing of B and C heater, since boron nitride has a melting point above 3000 K in vacuum environment and it is easy to machine.

Cathode tube is fixed on the base parts. The expected properties of base parts are to be dielectric and having low coefficient of thermal conductivity. It is agreed that ceramic will be used in the manufacturing of the base parts. Since the keeper tube will be kept at a biased voltage, in addition to the material selected for base parts, the screws used in assembly should be dielectric as well.

First of all, a design study is conducted utilizing the studies [Goebel, Watkins and Jameson, 2010], [Warner, 2008] and [Courtney, 2008]. Later, based on these studies, the parts of the hollow cathode are designed and materials are selected. The first design is manufactured from brass, except for insert and spring, at the university machine shop. This prototype was an important experience and helped to correct the design flaws. Afterwards, the design flaws have been eliminated gradually (Figure 8). The cathode tube, which was considered to be made of molybdenum at initial stage, is agreed to be manufactured from POCO graphite. This changed the cathode tube design as well. The base parts are enlarged to do screw and wire connections easily. Finally, the cathode base design is renewed to assemble the cathode parts in an easier way (Figure 9)

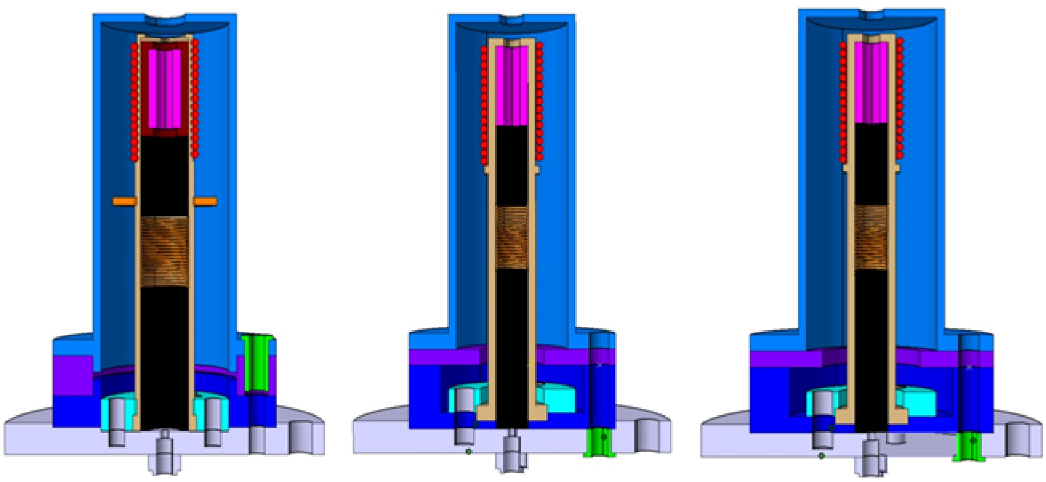

Figure 8: Evolution of the cathode design

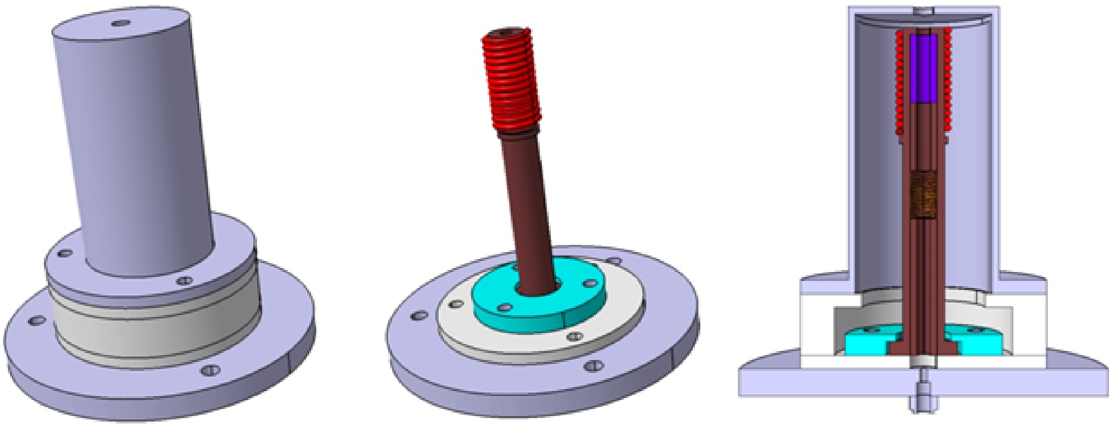

Figure 9: : Final desing of prototype hollow cathode in March 2014

CONCLUSION

In this study, a general review of the emitter materials in the hollow cathodes used in many applications as electron source are shared. The points that one must pay attention while using emissive materials, the advantages and disadvantages of one on the other are discussed. In addition, the informations regarding design and analysis process of the hollow cathode that will be tested at Bogazici University Space Technologies Laboratory are summarized.

LaB_6 is preferred as the emissive material of the hollow cathode that is designed and will be tested at BUSTLab. The reason of the selection of LaB_6 is that it is not affected by the impurities in the propellant and it has low evaporation rate. Selection of the materials with low evaporation rate is quite important because evaporation rate directly affects insert lifetime and therefore cathode lifetime. The material of the support that holds LaB_6 in its position should be selected with extreme care due to the fact that LaB_6 react with many refractory materials, therefore endangers the operation of the system. POCO graphite is selected as the support material, since it does not react with LaB_6 and it has similar thermal properties with LaB_6. POCO graphite, due to the similar reasons, is preferred not only for support but also for cathode tube and keeper tube.

One of the important components in hollow cathode design is the heater design. The performances of three different heater designs in the literature at initiation stage is assessed with COMSOL Multiphysics software. Analysis results showed that conventional heater design of hollow cathodes (heater design A) is the fastest heater. The performance of these heater designs will be tested experimentally as well and the results will be compared with the analysis results. Taking advantage of the literature reviews and analysis, the first preliminary design of the hollow cathode was done. The brass prototype of this first design was manufactured. This prototype is used to improve the hollow cathode design gradually.

ACKNOWLEDGEMENT

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