Design of a Heated Hollow Cathode for CubeSat Applications

Colin Warn*
Washington State University, Pullman, Wa, 99163

Placeholder for abstract.

I. Introduction

Electric propulsion devices have historically been an efficient method of spacecraft orbital propagation. Their use cases range in everything from orbital station-keeping to orbit transfers. The Hall Effect Thruster is one of the leading electric propulsion designs for such applications: Due to it's high specific impulse and relatively large instantaneous thrust compared to traditional gridded electric thrusters.

Hall Effect Thrusters however, have not seen much use in the a form factor called a CubeSat. A CubeSat is a low cost satellite the size of a tissue box that has enabled more cost-prohibited entities such as universities and startups to develop spacecraft technology. Their lack of use in CubeSats is primarily due to their historically complex power processing unit as well as high energy demand. One of the core components that leads to the high energy demand is the hollow cathode that is required to be integrated with the system.

In order to make the Hall Effect Thruster feasible for the CubeSat form factor, a low energy hollow cathode must be designed to partially address this problem. A Hall Effect Thruster operates by ionizing a gas through a circulating sea of electrons and accelerating it by means of an electric field. These electrons must be generated by a source. The hollow cathode is currently the most efficient source for these electrons, therefore this paper sets out to demonstrate a theoretical design for such a device in a CubeSat form factor. An priority on design simplicity has been chosen for this paper.

II. Methods

A. Selection of Cathode Configuration

A hollow cathode is a device which emits electrons by means of heating up a thermionically emitting material (i.e. insert). This device is more efficient and longer lasting than their thermionic filament counterpart due to the cathode's protection against ion bombardment and lower thermionic insert work function requirement.

There are two types of hollow cathodes: heated and heaterless. Both refer to the manner in which the insert's operating temperature is achieved. Heated raises the insert to it's operating temperature by means of a coiled wire. This design is shown in figure 1. A heaterless cathode raises the insert to it's operating temperature by means of electrically breaking down the inert gas fed into the system. This design looks a lot like the design shown in figure 1, minus the heated element.

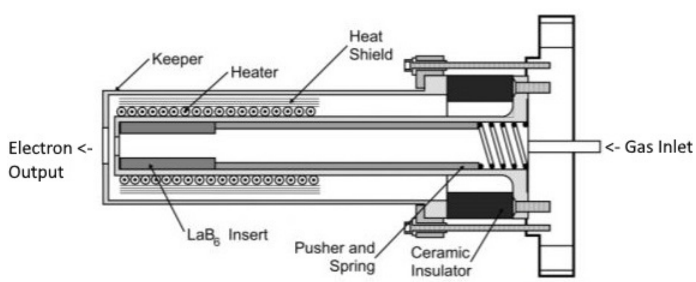


Fig. 1 Hollow cathode engineering layout. Diagram taken from Emily Chu. [1]

The heaterless cathode, though requiring less power, is operationally more difficult to engineer for first-time cathode developers. Therefore, the heated hollow cathode design will be chosen due to it's simpler electrical and propellant feed system requirements.

*Undergraduate Researcher, Voiland College of Engineering, colin.warn@wsu.edu

B. Insert Material Selection

The first factor to consider in designing a hollow cathode is the emitted electron current from the cathode. This parameter is determined by the overall discharge current of the Hall thruster (denoted J_D) the cathode is being attached to. As the discharge power is proportional to the thruster dimensions, the following rule of thumb is used to determine the emitted electron current: [2]

$$\text{Electron Current} = J_D \cong D * 0.1\frac{A}{\text{cm}^2} \tag{1}$$

Where D is the diameter of the thruster in centimeters. For this cathode, the Hall thruster it's being attached to is 6.5 cm. Therefore, a minimum electron current of 0.65 $\frac{A}{cm^2}$ is required. (Dr. Lev suggests 5-10 times higher current densities. Citation?)

A thermionic material must be selected for the insert in order to meet this current density requirement. Two materials are commonly used in modern cathodes: Lanthanum Hexaboride (LaB_6) and Barium Oxide-Impregnated Tungsten (BaO-W). Though BaO-W has a lower work function leading to lower power requirements, it's highly sensitive to poisioning by water vapour which makes it extremely difficult to work with for first time cathode developers. LaB_6, though having a higher work function of the two, is not as sensitive to waper vapour poisioning. Therefore, LaB_6 has been selected as the insert material due to it's relatively low work function and ease of use.

The Richardson-Dushman equation is used to determine the temperature at which a given insert material needs to be kept at to meet electron current density requirements. The formula is as follows: [3]

$$J = DT^2 \exp\left(\frac{-e\phi_o}{kT}\right) \tag{2}$$

Where D_o is the temperature-modified coefficient to the Richardson-Dushman equation, T is temperature in kelvin, ϕ_{wf} is the work function, e is the charge of the electron in eV and k is Boltzmann's constant in $\frac{eV}{K}$. Experimental values for each have been compiled and presented nicely by Emily Chu and Dan Goebel in their papers on hollow cathodes, and are are shown below: [1] [4]

	D_o	ϕ_{wf}
BaO − W411	120	$1.67 + 2.82 \times 10^{-4}$T
BaO − W411	1.5	1.56
LaB_6	29	2.67
LaB_6	110	2.87
LaB_6	120	2.91
LaB_6	120	$2.66 + 1.23 \times 10^{4}$T
Molybdenum	55	4.2
Tantalum	37	4.1
Tungsten	70	4.55

Table 1 Work function and Richardson coefficients for different cathode materials.

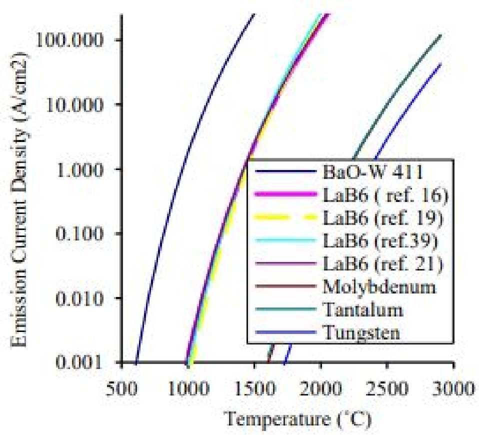


Table 2 Emission current density versus temperature.

A conservative temperature modified coefficient of 110 and a work function of 2.66 have been chosen for calculating the insert's temperature. An insert temperature of around 1300 °C will be selected to meet the system's current density requirement of 0.65 $\frac{A}{cm^2}$.

C. Cathode Thermal Modelling

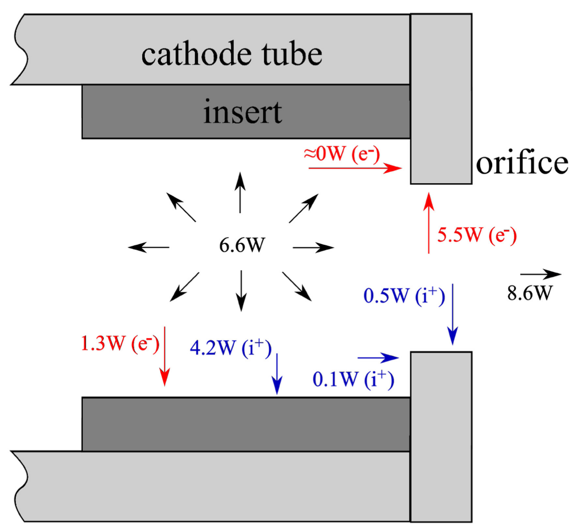
A zero-dimensional analysis of a LaB_6 hollow cathode has been done by Gurciullo et. al which allow for the estimation of power deposition on walls due to electron and ion bombardment in both the insert and orifice regions. [5] Our cathode will use their dimensions as shown in Figure 2, as their 1 A of discharge current is more than enough to meet our 0.65 $\frac{A}{cm^2}$ requirement.

Parameter	Value
Orifice diameter $2r_o$ [mm]	0.3
Orifice length L_o [mm]	0.8
Insert diameter $2r_{in}$ [mm]	1.0
Insert length L_{in} [mm]	10.0
Insert temperature $T_{w,in}$ [K]	1310
Insert material (BaO) work function φ_{wf} [V]	$1.67 + 2.82 \cdot 10^{-4} T_{w,in}$
Discharge current I_D[A]	1.0
Xenon mass flow rate $\dot{m}_{Xe}$ [mg/s]	0.039

Fig. 2 Geometrical dimensions and operating conditions of a sample hollow cathode neutraliser. [5]

Parameter	[W]
Total input power P_{tot}	26.8
Discharge power P_D	26.2
Power transported by extracted electrons and ions	8.6
Power re-deposited into the cathode	18.2
Electron bombardment on orifice lateral surface	5.5
Ion bombardment on orifice lateral surface	0.5
Electron bombardment on orifice plate	≈ 0.0
Ion bombardment on orifice plate	0.1
Electron bombardment on insert lateral surface	1.3
Ion bombardment on insert lateral surface	4.2
Power associated with upstream ion flow, excitation and ionisation events	6.6

(a) Table.



(b) Photo.

Fig. 3 Power consumption and power deposition in the modelled cathode, whose geometry and discharge condition are listed in Figure 2. [5] These will be inputted into our Solidworks thermal model.

D. Operational Sequence

1. A minimum vacuum of 10^{-5} will be established.
2. Current will be run through the tantalum wire until the thermionic insert reaches a temperature of 1310 °K. A LaB_6 will emit the necessary electron current at this temperature.
3. Inert gas will be run through the hollow cathode to maintain a plasma that will self-heat the cathode until cathode is turned off. For initial lab tests argon will be used due to it's low cost.
4. For ground tests, argon will be run through the cathode until it has cooled down to ambient temperature to reduce poisoning effects.

E. Engineering Design

1. Current Through Tantalum Wire to Heat Insert

Tantalum wire will be used to heat the LaB_6 thermionic insert. A 27 awg wire size has been selected. The maximum current going allowable though this wire is 1.7 A following the Handbook of Electronic Tables and Formulas for American Wire Gauge. The electrical resistivity of tantalum is 131 $n\Omega * m$, given the wire will be wrapped 14 times at a diameter of 4mm, it's circumference is $2\pi * r$ per wrap. Therefore, the power being output by the wire is as follows:

$$1.7^2 A * \frac{(131n\Omega * m)}{14 * 2 * \pi * 0.002m} = 0.002W \tag{3}$$

2. Solidworks Thermal Model

This thermal model was to simulate the distribution of plasma heating after the insert was heated to 1300 K by the wire. The ion and electron bombardments on the insert and orifice sections as shown in Figure 3 will be the power inputs into our model.

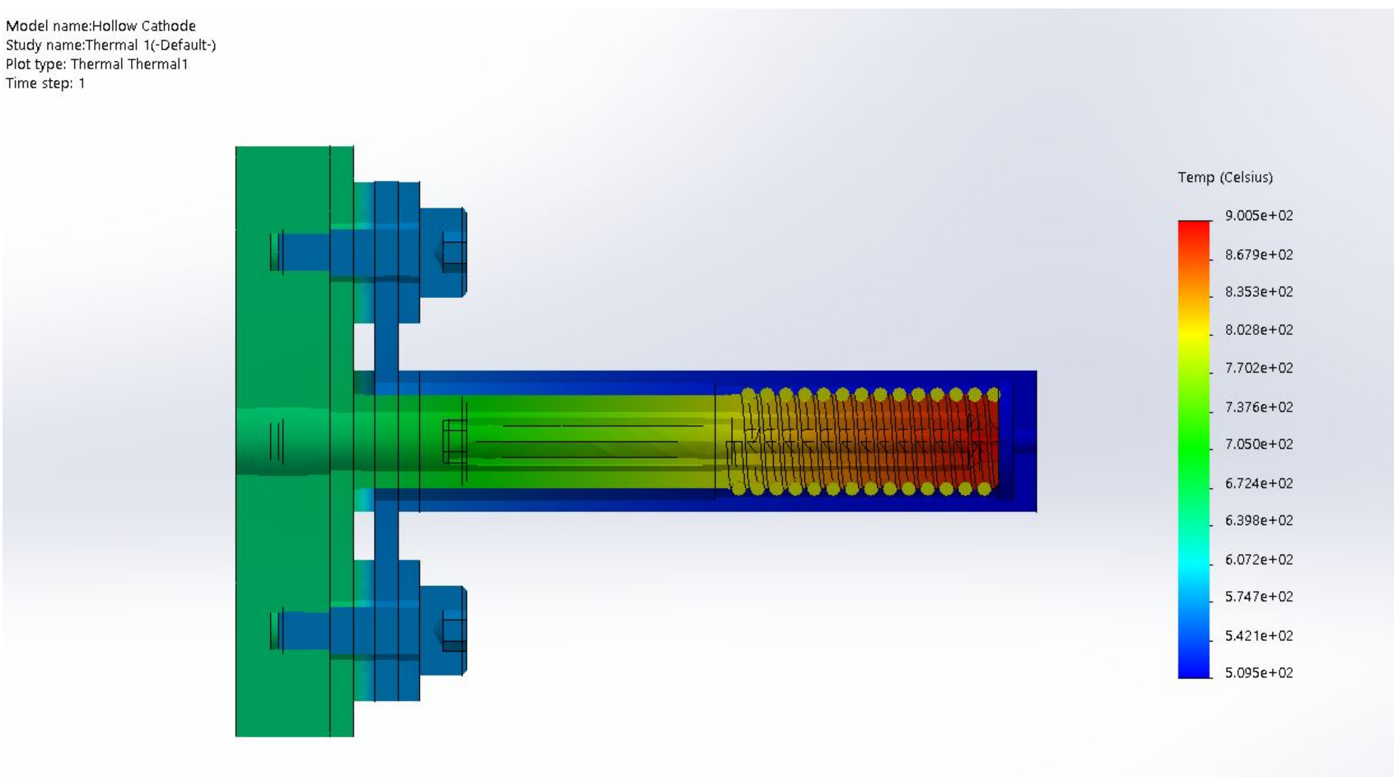


Fig. 4 Results of running a hollow cathode designed using Gurcillo's paper. [5]

References

[1] Chu, E., "External Mass Injection to Reduce Energetic Ion Production in the Discharge Plume of High Current Hollow Cathodes," *EScholarship*, 2013. URL `escholarship.org/uc/item/2kt8s39z`.

[2] Boeuf, J.-P., "Tutorial: Physics and modeling of Hall thrusters," *Journal of Applied Physics*, Vol. 121, No. 1, 2017, p. 011101. https://doi.org/10.1063/1.4972269, URL https://doi.org/10.1063/1.4972269.

[3] Forrester, A. T., *Large ion beams : fundamentals of generation and propagation*, New York : Wiley, 1988. URL http://www.gbv.de/dms/bowker/toc/9780471625575.pdf, "A Wiley-Interscience publication.".

[4] Goebel, D. M., *Fundamentals of Electric Propulsion: Ion and Hall Thrusters 1st Edition*, Wiley, 2008.

[5] Gurciullo, A., Fabris, A. L., and Potterton, T., "Numerical study of a hollow cathode neutraliser by means of a zero-dimensional plasma model," *Acta Astronautica*, Vol. 174, 2020, pp. 219 – 235. https://doi.org/https://doi.org/10.1016/j.actaastro.2020.05.006, URL http://www.sciencedirect.com/science/article/pii/S0094576520302885.

3. Bills of Materials