Thermal Analysis of Lanthanum Hexaboride Hollow Cathode with Radiative Carbon Heater

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Abstract: The thermal analysis of a Lanthanum Hexaboride hollow cathode is conducted in order to design a high current hollow cathode for the high power electric propulsion. A 50 A class hollow cathode tester with a radiative carbon heater is manufactured, which is expected to have better robustness against thermal deformation or erosion than the conventional heaters. The temperature of a dummy insert is measured using the radiation pyrometer, which amounts to over 1700 °C. Based on the experimental results, the thermal analysis model is tuned to reproduce the results. The experimental and numerical results indicate that the temperature of the insert reaches 1500 °C at 455W. This suggests that the radiative heater has enough potential for the high current hollow cathode, whereas the heating efficiency is lower than conventional direct heating heater. The discussion on the heat balance also offers suggestion for the performance improvement of the radiative heater.

Nomenclature

D_o	=	temperature-modified coefficient to the Richardson–Dushman equation
J	=	current
k	=	Boltzman's constant
L	=	insert length
T	=	temperature

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z	=	length along insert
φ_{wf}	=	work function

I. Introduction

In-space transportation of large masses and manned space mission is proposed in recent year.[1] High power ion engines and Hall thrusters of several kW or several tens kW class are developed for these missions.[2-4] These thrusters need an electron source to ionize propellant and to neutralize the ion beam. The electron source is a key technology of ion engines and the Hall thrusters, because the lifetime and performance of these thruster systems strongly depend on the performance of the electron source. The hollow cathode is the most promising candidate for the electron source. The designs of high current hollow cathodes have been investigated for years at discharge currents up to 100 A or higher.[5-8]

In hollow cathodes, electrons are emitted from the low work function material which is called the insert or emitter. Thermionic emission current can be estimated by the modified Richardson–Dushman equation.[9]

$$J = D_o T^2 e^{\frac{-e\phi_{wf}}{kT}} \tag{1}$$

where φ_{wf} is the work function. Oxiside impregnated tungsten such as BaO-W is widely used particularly for space application as the thermionic emission material, because the work function is very low of 2.06 eV at temperatures of about 1000 °C.[10] Instead, we employ Lanthanum-hexaboride (LaB_6) insert material as the thermionic emission material due to lower evaporation than the oxiside impregnated tungsten, although it has slightly higher work function of 2.67 eV than oxiside impregnated tungsten. [10] LaB_6 emitter was developed and investigated by Lafferty in 1950s,[11] and it experienced first flight as the emitter of stationary plasma thruster (SPT) in 1972 by Russia.[12] In recent years, the LaB_6 inserts have been studied intensively for the high current hollow cathode at Jet Propulsion Laboratory (JPL).[13,14] For ignition, the LaB_6 insert should be heated over 1500 °C which is higher temperature than that for oxiside impregnated tungsten 1100 °C .[15] The conventional heaters located around the cathode tube are composed of a wire of refractory metal insulated with dielectric material which is indispensable to avoid short-circuit between the heater and the cathode tube. One of the major causes of trouble of conventional hollow cathode, however, is damage of the heater. It was reported that the insulator and the refractory metal are often damaged due to erosion and chemical reaction,[16-18] which can cause the heater failure. In order to reduce failure mode, we are developing a cathode with a radiative carbon heater which utilize radiation to heat up the insert. A schematic figure of a hollow cathode with the radiative heater is shown in Fig.1. The hollow cathode consists of the insert, the cathode tube, the keeper, the heater and the structure supporting them. The gas flows from the upstream of the insert and electrons emitted from the insert ionize the gas. Thereafter, the electrons are drawn to the anode or the thruster. Since the radiative heater does not need the insulator between the heater and the cathode tube, it is expected to reduce failure mode of the hollow cathode, i.e., it can prevent the damage caused by the thermal expansion of the cathode tube. Whereas the thermal characteristics of the conventional heater for the high current hollow cathode have been investigated by the experiment and the thermal analysis,[18,20,21] the thermal characteristics of the radiation heater have not been revealed. To demonstrate its feasibility and investigate its thermal characteristics, the thermal analysis were conducted by means of FEM (finite element method) simulation software (Femtet®, Murata software Co., Ltd).[22] Also, a 50A class hollow cathode tester was manufactured, and a preliminary heating test was conducted. The model parameters of the thermal analysis were tuned by using the experimental results. In addition, not only the radiation heating type but also the direct heating type heater was simulated for comparison.

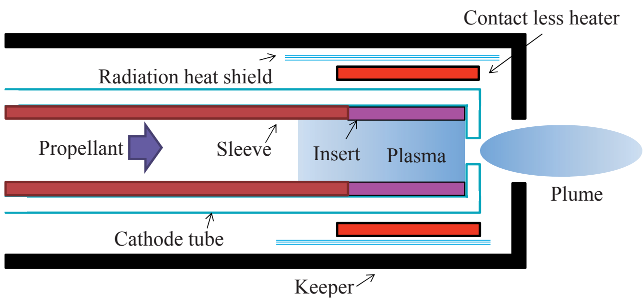

Figure 1. Schematic drawing of hollow cathode with radiative heater.

II. Design and Thermal Modeling of Hollow Cathode with Radiative Heater

In this study, we conduct thermal analysis of two types of heaters: the direct heating heater and the radiative heater. Figure 2 (a) and (b) show cross section of both heaters and the main heat transfer path. The heater is located around the cathode tube to heat up the insert in both heater types. In the radiation heating type, the heat from the heater is transferred to the cathode tube by radiation, and then it is conducted to insert. In the direct heating type, the heater is directly wrapped around the cathode tube, hence the heat is directly transferred to the cathode tube. There is the radiation shield outside of the heater in both heaters to reduce the radiation heat loss. A multilayer tantalum foil is often used as the radiation shield. Other factors of heat loss are conduction heat loss through the cathode tube, and the sleeve supporting the insert and so on. Although these losses cannot become zero but we reduce these losses by installing the low thermal conductivity material. The hollow cathode is installed to the flange as shown in Fig.2. The boundary condition of all outside surface is radiation to ambient temperature of 20 °C. The input power of the heater is set in the whole of the heater uniformly.

III. Parameter Tuning of Thermal Analysis

The 50A class hollow cathode tester with the radiative heater was manufactured as a reference of thermal analysis. The contact thermal resistance and effective emissivity of the radiation shield are unknown parameter. The unknown parameters of the thermal analysis are tuned by using the hollow cathode tester. The hollow cathode tester uses the dummy insert of isotropic graphite instead of the LaB_6 insert. The schematics view of the hollow cathode tester with dummy insert is shown in Fig.3. The temperature at the downstream surface of the dummy insert is measured by using the radiation pyrometer as shown Fig.3. The input power of this experiment was varied between 215-756 W. The temperature of the dummy insert amounted to over 1700 °C, but there were no notable problems, which suggest that the radiative heater has enough potential for the Lanthanum-hexaboride hollow cathode. The thermal analysis of the hollow cathode tester was conducted and was tuned by using the experimental data. The temperature of the dummy insert against the input power is shown in Fig.4. The thermal analysis results are good agreement with experiment results during 215 to 756 W. The effective emissivity of radiation shield and the thermal contact resistance are 0.1 and 0 respectively in this condition. We employ these parameters from the next section.

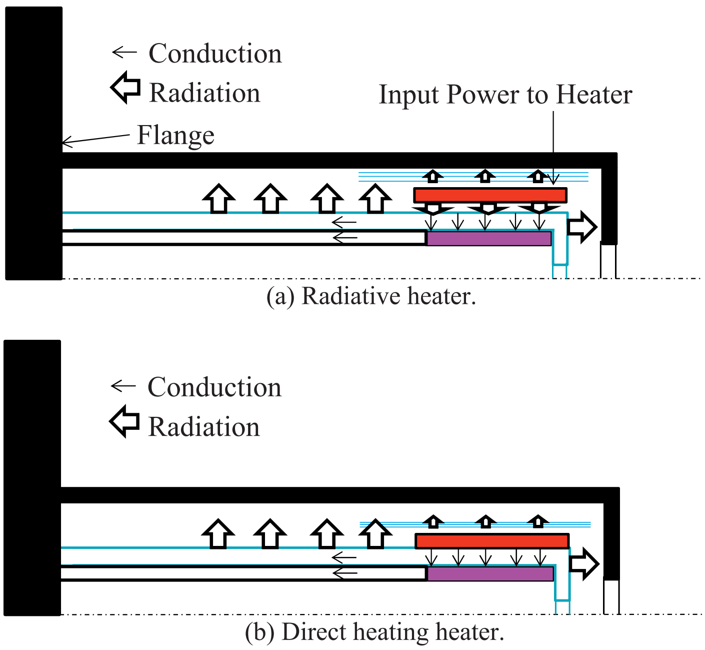

Figure 2. Cross section of hollow cathode and heat transfer path.

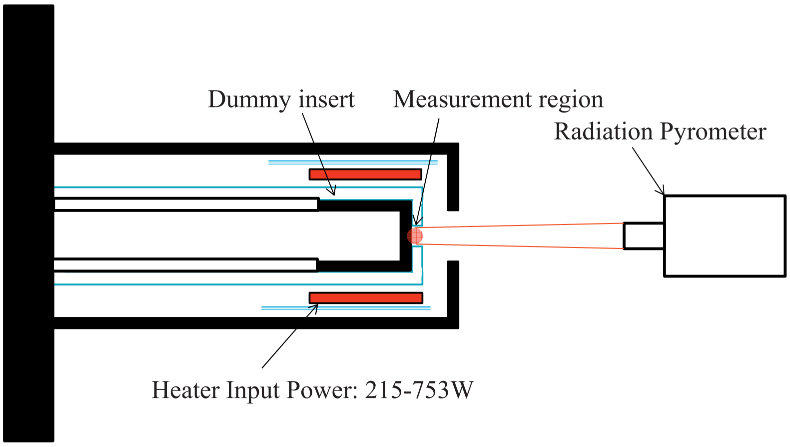

Figure 3. Schematic view of hollow cathode tester with dummy insert.

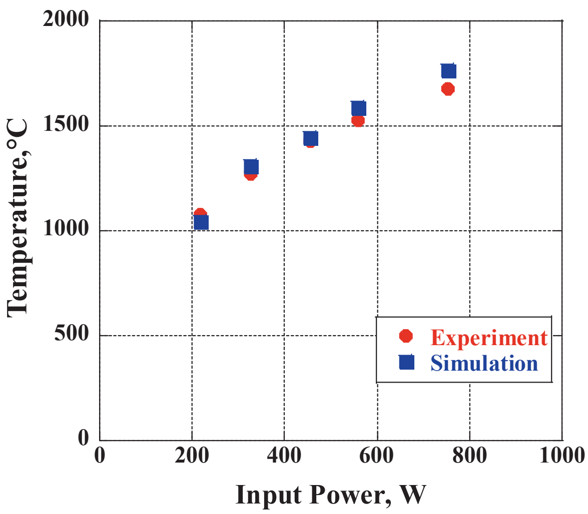

Figure 4. Temperature of dummy insert against input power.

IV. Thermal Analysis Results

A. Insert temperature of radiation heating

This section describes the thermal analysis results of the hollow cathode with LaB_6 insert. The results of the thermal analysis in this study were obtained with the time-marching simulation. The temporal temperature change at the insert center is shown in Fig.5. The thermal analysis results reach thermal equilibrium after 1200 sec from the start of heating. Figure 6 shows the temperature distribution of inner insert surface. The length is normalized by the insert length. The temperature becomes the maximum temperature at z/L=0.4. The temperature variation along the insert surface is smaller than 100 °C under the all conditions. The insert temperature amounts to 1500 °C at 455W, therefore it is predicted that this hollow cathode is ignited at around 455 W, whereas this power is higher than the direct heating heater. In one example, the 100A class hollow cathode was ignited at about 240 W in JPL.[13]

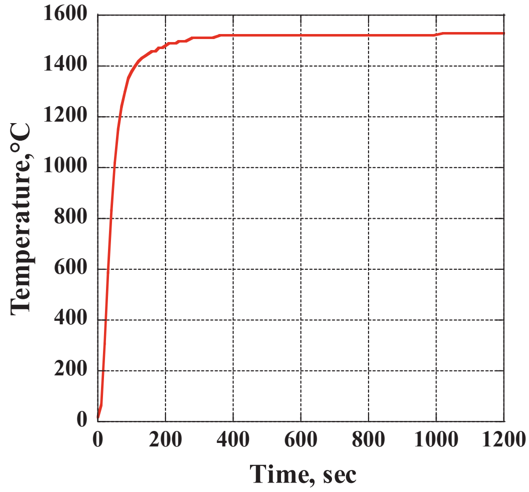

Figure 5. Temperature at insert center vs time. (Input power:455W, Radiation heating),

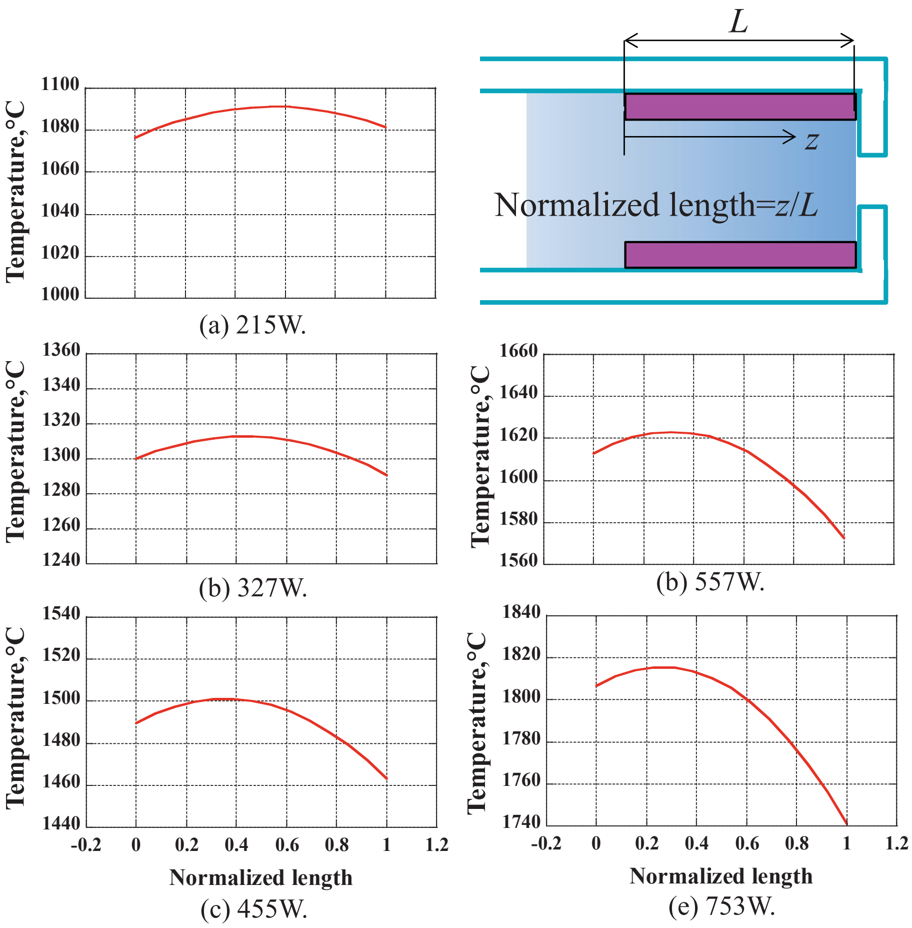

Figure 6. Temperature distribution of inner insert surface.

B. Comparison between direct heating and radiation heating

This section shows comparison between the direct heating and the radiation heating. The multilayer tantalum foil was also used as a radiation shield in the direct heating. The heater is directly coiled around the cathode tube as shown Fig.2 (b). The effective emissivity and contact thermal resistance is 0.1 and 0 respectively. The input power was varied in the range of 100-327 W in the direct heating. The maximum temperature of the insert inner surface is shown in Fig.7. The temperature amounts to 1500 °C at 455W in the radiation heating and to 200W in the direct heating. The results indicate that twice the input power is necessary for the radiation heating to achieve the same temperature as the direct heating, therefore the improvement of the thermal insulation is needed, although the radiation heating type is expected to have higher robustness than the conventional heaters.

C. Heat flux balance

In the next, we discuss the heat flux on the insert and heater surfaces in order to obtain the improvement policy of the thermal insulation. The heat flux of the insert is separately discussed on four surfaces: outside surface, inside surface, upstream surface and downstream surface as shown Fig.8 (a). The heat flux from the heater is input to the outside surface of the insert through the cathode tube. The heat flux out of the insert is shown in Fig.9. The total heat flux in Fig.9 corresponds to the input heat flux to the insert, which is 39.6 W, 55.3 W, 71.8 W, 84.2 W, 107 W respectively. These input powers are about 15% of the total input power. Although the heat fluxes flowing from the upstream surface is almost constant, the heat flux flowing from the downstream surface increases, because the heat loss of the radiation from the tube end becomes large in high temperature conditions. This suggests that the radiation insulation improvement between the tube end and the keeper is important to improve performance of the heater. The outflow of heat flux from the heater is shown in Fig.10. We divide the heat balance of the heater into four surfaces like the insert as shown Fig.8 (b). The heat flux on the inside surface corresponds to the heat flux heating the cathode tube. The heat flux integrated on the inside surface is 73.5W, 103W, 135W, 165W, 217W respectively. This result shows that only 30% of input power is used for heating to cathode tube. The heat flux flowing from the outside surface is the largest heat loss, which is 50-60% of the input power. Additionally, the heat flux from the upstream surface, which is conducted to the heater support, also accounts for 10-15%. The improvement of the radiation shield and the heater support method is needed.

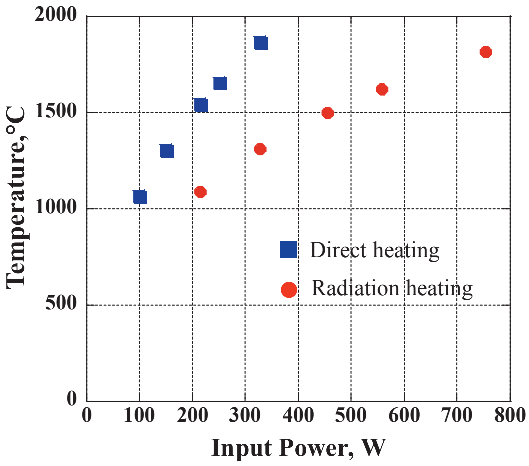

Figure 7. Comparison between insert temperature of direct heating and radiation heating.

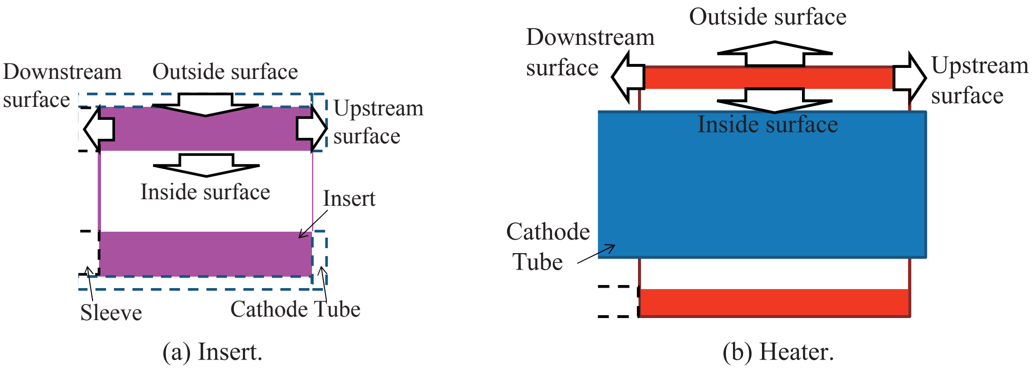

Figure 8. Definition of Surface of Heat Flux discussion.

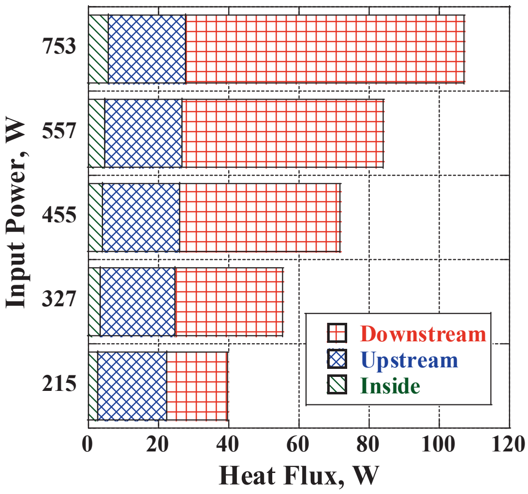

Figure 9. Components of heat flux flowing outward of insert. Heat flux is integrated by area of each surface. The total heat flux of this figure corresponds to the heat flux flowing into the insert.

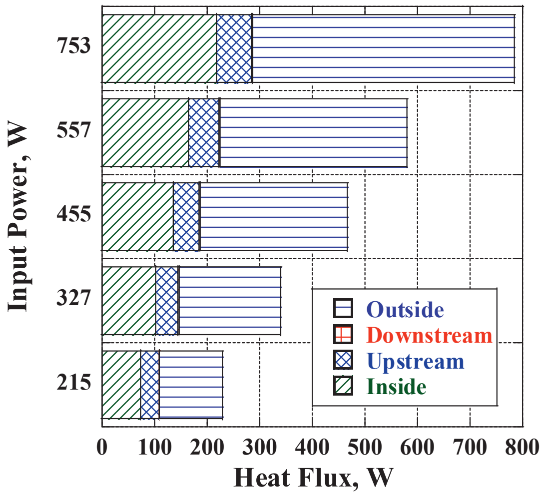

Figure 10. Components of heat flux flowing outward of heater. Heat flux is integrated by area of each surface. Input power corresponds to total of heat flux flowing outward of insert.

V. Conclusion

The thermal analysis of the hollow cathode for the high power electric propulsion was conducted. The 50A class hollow cathode with the radiative heater was manufactured and the preliminary heating experiment was performed. The temperature of the dummy insert amounted to over 1700 °C, but there were no notable problems. The unknown model parameters of the thermal analysis were tuned by using the experimental data ranging between 215-756W. Subsequently, the thermal analyses of the direct heating and the radiation heating were compared. The temperature of the insert reaches 1500 °C at 455W in radiation heating and 200W in direct heating. The radiative heater has enough potential for the high current hollow cathode, although improvement of the thermal insulation is needed in future work. The dominant heat loss which should be improved is radiation from the outside of the heater, radiation from the orifice end and thermal conduction to the heater support.

In the future plans, we will ignite the hollow cathode tester and measure the performance. We analyze the thermal analysis in operation mode and compare the thermal analysis to the experimental data. In addition, this thermal analysis will be combined with the plasma simulation of the hollow cathode.

Acknowledgments

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