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Research Paper

Design and analysis of a radiation cooling system for hollow cathode testing

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HIGHLIGHTS

- A method is proposed for radiation-cooling of hollow cathodes in vacuum.
- Four radiative cooling system configurations are suggested and analysed.
- The cooling effectiveness of each configuration is quantified numerically.
- Cooling effectiveness increases with the addition of Multi-Layer Insulation (MLI).
- Post cathode ignition cooling has negligible effect on cathode performance.

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ABSTRACT

Thermal analysis is used to determine efficient radiation cooling system geometry in order to reduce the pre-ignition temperature of a hollow cathode for electric propulsion applications. To do so four cooling configurations were modeled and their cooling capability, via radiation, explored. It is found that a horizontal cooling plate positioned above the cathode is insufficient to cool it down to the required temperature of −50 °C. On the other hand three other more suitable configurations, two side plates, open box and half cylinder shaped structures encapsulating the cathode are shown to satisfy the cooling requirement. For the most efficient case of half-cylindrical shaped configuration the required cooling power is computed and found to be below 100 W for all cases simulated; therefore indicating that relatively simple cooling devices may be used for cathode radiative cooling. It is also shown that the addition of Multi-Layer Insulation (MLI) on the walls of the vacuum chamber greatly improves cooling system performance as it reduces both hollow cathode temperatures and the power dissipated into the cooling source. Lastly, sensitivity analysis is performed to quantify the effect of deviations in structure emissivities on hollow cathode temperatures.

1. Introduction

Low power electric propulsion accelerators are a suitable solution for small satellite maneuvers such as orbit injection or Low Earth Orbit (LEO) keeping. Of the existing electric propulsion devices low power Hall thrusters are usually a desired solution thanks to their relatively high thrust-to-power ratio and technological maturity [1]. Since each Hall thruster unit consists of a cathode to enable thruster ignition and steady-state operation proper cathode development and qualification processes are needed. The goal of these processes is to assure sufficient cathode reliability and required performance throughout the designated mission lifetime. In particular, the cathode ability to operate under a variety of environmental conditions, such as different background temperatures, is examined [2]. As Hall thruster cathodes emit electrons via thermionic emission their ignition and operation phases are sensitive to low background temperatures. Consequently, a suitable cathode test facility is required where the expected thermal conditions of space are reproduced and cathode operation examined.

The thermal environment for electric propulsion components depends on various factors such as mission orbit, orientation relative to the sun or Earth, component location on the spacecraft and vicinity to protective surfaces. Conventionally the cathode is mounted on the thruster bracket and thermally insulated from it to prevent heat loss through conduction during steady-state operation. For this reason the cathode is expected to be susceptible to

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ignition and operation difficulties due to the extreme low temperatures experienced in its specific orbit. Lowest LEO thermal requirements are usually higher than −50 °C and depend on the component orientation. Geo-synchronous Earth Orbit (GEO) thermal requirements are usually more stringent and can be as low as −150 °C [3]. Since cathodes for low power Hall thrusters are designated to operate in LEO environment a target requirement of −50 °C is considered. This requirement accords with the qualification requirement of a higher power Hall thruster [4].

The aim of the work presented here was to design and computationally test a radiative cooling apparatus that reduces cathode temperature prior to its ignition. In addition, we examine the cooling effect of the designed apparatus on an operational cathode and quantify its ability to interfere with cathode operation. The presented cooling apparatus was designed to fit an existing cathode test facility where cathode ignition and steady state operation are assessed.

The structure of the paper is as follows. Initially, we present an existing cathode test facility to which the radiative cooling apparatus is designed to fit. Subsequently, we describe the computational tool used to simulate different radiative cooling facility geometries. We then briefly overview conventional and available cooling methods that can be applied to reduce the temperature of the considered cooling configurations. Lastly, using the simulation results the ability of each configuration to reduce cathode pre-ignition or operational temperatures is quantitatively estimated.

2. Method

2.1. Facility test platform

The simulated radiative cooling apparatus presented was designed to meet the existing structural constraints of the current heaterless hollow cathode experimental facility presented in Fig. 1. The current experimental facility is located in a vacuum chamber, 1.27 m in diameter and 1.3 m in length. The chamber includes an experimental mounting structure designated to facilitate cathode operation and diagnostics. The mounting structure consists of a 350×600 mm aluminum support/mounting plate that is fixed by four supporting aluminum rods. The cathode and anode, which are both part of the qualification process, are positioned on the center of the support plate and are roughly 50 mm apart. The support plate is thermally insulated, for conduction, from the vacuum chamber. The cathode has an axisymmetric shape, with dimensions shown in Fig. 2, and is thermally insulated, for conduction, from the support plate. Prior to and during cathode operation the vacuum chamber maximum pressure is 1×10^{-7} Torr and 2×10^{-5} Torr respectively.

2.2. Computational method

Thermal analysis was performed using ‘Simulations’, a commercial finite element add-on to ‘SolidWorks’ CAD modeling software. The software uses discrete methods to solve the energy equation in a continuous manner. In order to use this method, the 3D model is meshed using tetrahedral elements resulting in a closed net in which the discrete solving technique is applied at the nodes. Different mesh size was used for different surfaces depending on their relative sizes and expected contribution to the thermal simulation. For example, at the smallest component, the cathode, the cell size was about 2.5 mm in length whereas as the largest component, the vacuum chamber walls, the cell size was about 300 mm.

It is important to note that the hottest part in conventional active hollow cathodes, the orifice, is usually sub-millimeter in size and internal to the cathode [1]. However, since the analysis presented in this study is concerned with radiation heat transfer, while heat conduction to the cathode is eliminated via proper design, only cathode external surfaces play role in the simulation. Additionally, it was shown in literature [1] that the cathode external surfaces, mainly cathode keeper, have roughly a uniform temperature distribution. Consequently any power input from an operating cathode is treated as the same input power coming from the external surfaces of the cathode.

For each of the scenarios described hereafter a mesh refinement process was conducted in order to reach solution convergence and obtain appropriate mesh parameters and to minimize the use of computational resources. In total after the refinement process the thermal model reached more than 10^7 DOF for all cases investigated.

To simplify the thermal model all components with surface area smaller than 1% of the cooling structure surface area, and thermally insulated from the cathode, were assumed to have negligible effect on radiation or conduction thermal transfer and were omitted (Fig. 2). These are the mounting plate supporting rods, the cathode holder, the anode, thermocouples, pipes, fittings, nuts and bolts.

Boundary conditions were applied to all parts, components and surfaces in the simulation. These are surface-to-surface radiation emissivity, thermal conductivity, contact resistance, fixed temperatures and input heating/cooling power. All applied values were found in literature, as specified in the following sections, or in ‘SolidWorks’ materials library. All boundary conditions are presented in Fig. 2.

2.3. Radiative cooling system configurations

We define the optimal cooling geometry such that it involves no changes to existing experimental setup, can be mounted on the

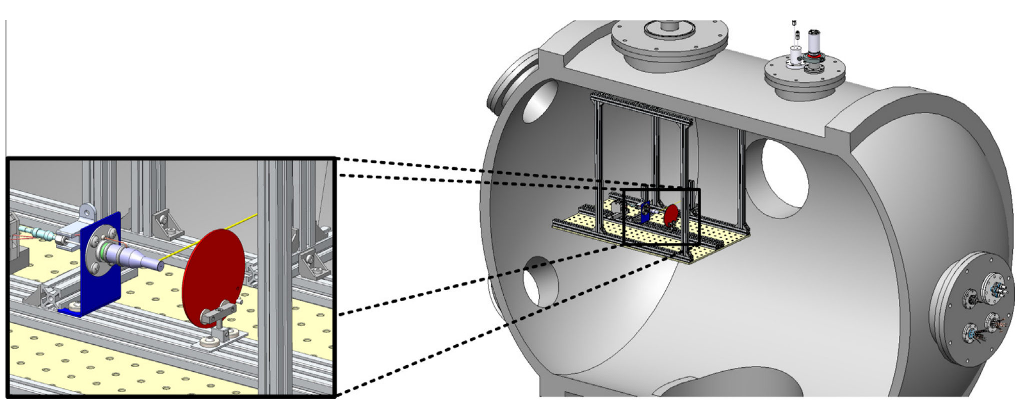

Fig. 1. Illustration of the cathode experimentation vacuum test facility. The cathode is presented in the middle of the zoomed-in view.