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THE IMPACT OF REPLACING MACOR WITH SHAPAL IN RF CATHODES FOR HALL THRUSTERS

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Abstract: Hall thrusters have been a cornerstone of electric propulsion for space applications, and the development of Permanent Magnet Hall Thrusters (PHALL) at the Plasma Physics Laboratory of the University of Brasília (LFP/UnB) has significantly advanced Brazil's space program. A key challenge in Hall thruster design is ensuring that the operational temperatures remain below the Curie temperature of the permanent magnets, which are essential for their functionality. To address this, an RF cathode was developed and thermally simulated with two different dielectric materials: Macor and Shapal. Simulations conducted using ANSYS software demonstrated that Shapal, due to its superior thermal conductivity, reduced the temperature gradient significantly compared to Macor. Results indicate that replacing Macor with Shapal decreases the maximum temperature by approximately 64 °C and external surface temperature by about 18 °C, ensuring optimal operational conditions for the permanent magnets. This study highlights the importance of material selection in minimizing thermal risks in advanced electric propulsion systems.

INTRODUCTION

Hall thrusters are among the most successful electric propulsion systems developed for space applications to date. Since 2004, the Plasma Physics Laboratory at the University of Brasília (LFP/UnB) has been actively developing a Permanent Magnet Hall Thruster (PHALL) as part of the Brazilian Space Program.

The LFP/UnB has been dedicated to the advancement of permanent magnet technology since 2002, receiving substantial support from several funding agencies. These include the UNIESPAÇO program of the Brazilian Space Agency (AEB), the Federal District Research Support Foundation (FAP-DF), the National Council for Scientific and Technological Development (CNPq), the Coordination for the Improvement of Higher Education Personnel (CAPES), the Study and Project Funding Agency (FINEP), and the Foundation for Scientific and Technological Enterprises (FINATEC).

One of the most notable achievements of this initiative was the development of the PHALL II-C, the penultimate iteration of the Hall thruster designed by the LFP/UnB (see Figure 1).

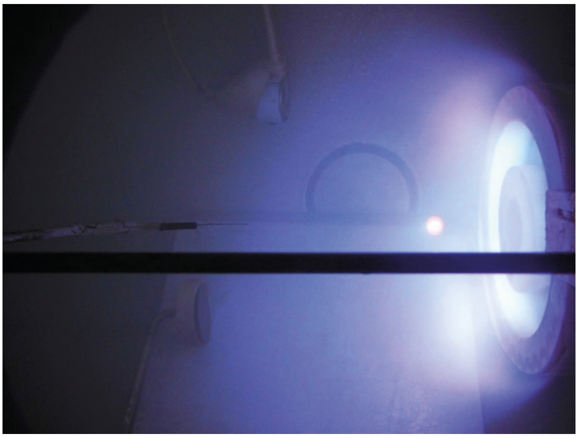

Figure 1: PHALL II-C was developed at the LFP/UnB.

Recently, the LFP/UnB has been developing a Hall thruster designed for application in nano- and micro-satellites [1], as illustrated in Figure 2. This thruster incorporates permanent magnets made of Samarium-Cobalt, which possess a magnetic field strength estimated between 80 and 100 Gauss and a Curie temperature ranging from 700 to 800 °C. To ensure the operational integrity of this system, it is crucial to design the new Hall thruster model in a way that prevents the internal temperatures from reaching the Curie temperature of the permanent magnets, thereby avoiding their demagnetization.

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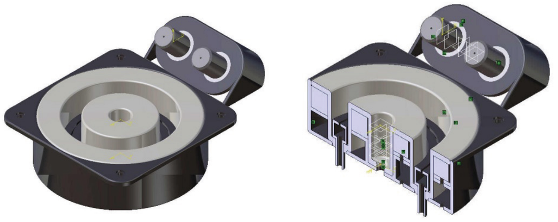
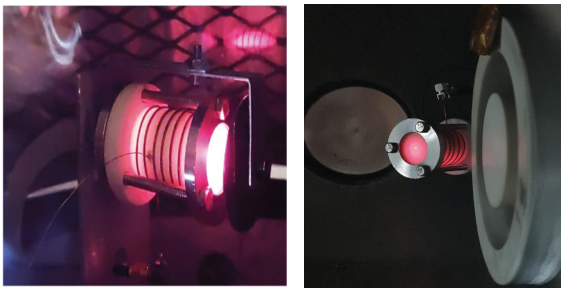


(a) Isometric view of 3D modeling of the new Hall thruster.

(b) Cross-sectional view of 3D modeling of the new Hall thruster.

Figure 2: Computed-aided design of the Hall Thruster.



(a) RF cathode isolated.

(b) The PHALL II-C with RF Cathode.

Figure 3: RF cathode of the LFP/UnB in operation.

The component of the Hall thruster that generates the most heat is the electron source. Historically, hollow cathodes have been the primary choice for electron emission in Hall thrusters. However, these devices require heating to high temperatures, are expensive to manufacture, and demand a complex power supply. In recent years, there has been growing interest in alternative electron sources for plasma thrusters. Among the most promising solutions is the radiofrequency (RF) cathode, known for its simple design, ease of fabrication, and cost-effectiveness.

The RF cathode primarily consists of dielectric material, stainless steel, and copper. Recently, the LFP/UnB developed its own RF cathode based on concepts derived from previous studies [2, 3, 4]. This cathode is being tested in two scenarios: as a standalone unit using a metallic element to attract electrons, and integrated with the PHALL II-C thruster model (see Figure 3).

To mitigate the risk of demagnetization of the permanent magnets in Hall thrusters, it is crucial to evaluate the thermal performance of the RF cathode. A thermal simulation has been proposed to investigate the impact of replacing the ceramic material in the RF cathode. The first model was constructed using Macor as the dielectric material. However, it is proposed that the new RF cathode model utilizes Shapal, a material with superior thermal conductivity, as the dielectric component.

METHODOLOGY

To estimate the temperature of the RF cathode, a thermal numerical simulation was conducted using ANSYS software, focusing exclusively on heat transfer through radiation and conduction. The basic operation of the RF cathode involves placing a coil around a dielectric chamber connected to an RF power supply operating at a frequency of 13.56 MHz and transmitting a power of 30 W. The RF frequency and power are transferred to the gas injected into the dielectric chamber, resulting in its ionization. The ionized gas was modeled as the primary heat source, with a thermal power of 30 W (see Figure 4).

To ensure the permanent magnets in the Hall-type thruster remain unaffected by excessive heat, thermal simulations were performed using two different ceramic materials: Macor and Shapal. These simulations aimed to determine whether the replacement of Macor with Shapal could reduce the temperature gradient and mitigate thermal risks. The thermal properties of the materials used in the simulations are provided in Table 1.

Materials	Emissivity [-]	Isotropic Thermal Conductivity [*W/m. °S*]	Specific Heat Constant Pressure [*J/kg.°C*]	Density [kg/m^3]
Macor	0.62	1.56	805.00	2550.00
Shapal	0.93	55.00	780.00	2880.00
Stainless Steel	0.30	13.80	480.00	8055.00
Copper	0.03	400.00	385.00	8933.00

Table 1: Physical properties used in thermal simulation

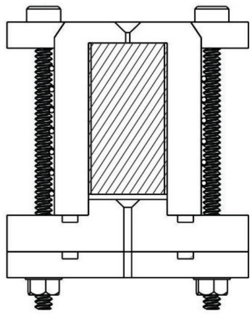
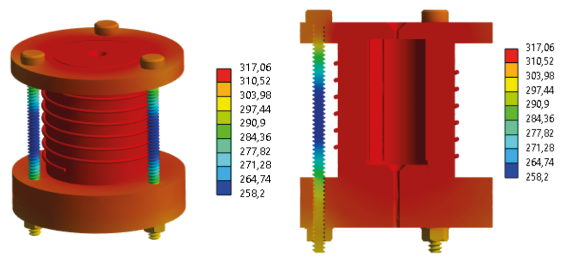


Figure 4: Hatching representing the area of the heat source at the RF cathode.



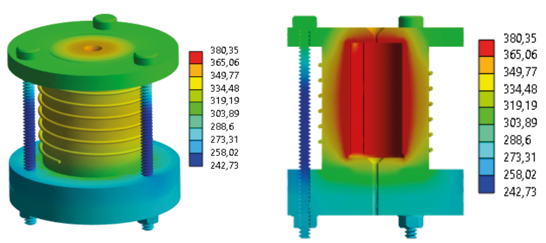
(a) External view of Shapal RF cathode thermal simulation.

(b) Internal view of Shapal RF cathode thermal simulation.

Figure 6: Thermal simulation of Shapal RF cathode.

RESULTS AND DISCUSSIONS

Figures 5 and 6 present the results of the thermal simulations. Figure 5 illustrates the thermal simulation using Macor as the dielectric material, showing a significant temperature gradient. This pronounced gradient is attributed to Macor's low isotropic thermal conductivity of only 1.56 *W/m.°C*. In contrast, Figure 6 depicts the thermal simulation with Shapal as the dielectric material, demonstrating a substantially smaller temperature gradient. This improvement is due to Shapal's superior thermal conductivity, approximately 36 times higher than that of Macor, with a value of 55 *W/m.°C*.



(a) External view of Macor RF cathode thermal simulation.

(b) Internal view of Macor RF cathode thermal simulation.

Figure 5: Thermal simulation of Macor RF cathode.

Both figures clearly show that, regardless of the material used, the temperature of the RF cathode remains well below the Curie temperature of the Sumarium-Cobalt permanent magnets, which is estimated to range between 700 and 800 °C. In Figure 5, which represents the use of Macor as the dielectric material, the external temperature of the RF cathode is approximately 335 °C, with a maximum internal temperature of 380.35 °C. In contrast, Figure 6, which represents the use of Shapal, demonstrates an average temperature of 317.06 °C, both externally and internally.

While both materials maintain the RF cathode's temperature well below the Curie threshold, replacing Macor with Shapal yields a significant thermal improvement. Specifically, the maximum temperature is reduced by nearly 64 °C, and the external temperature decreases by approximately 18 °C.

CONCLUSIONS

The thermal analysis of the RF cathode demonstrated that the selection of dielectric material plays a crucial role in managing the temperature profile of Hall thrusters. By replacing Macor with Shapal, a substantial reduction in the temperature gradient was achieved, attributed to Shapal's high thermal conductivity. The simulations confirmed that both materials keep the RF cathode's temperature well below the Curie temperature of the Samarium-Cobalt permanent magnets. However, the superior performance of Shapal ensures a more uniform and lower temperature distribution, which is critical for the reliability and efficiency of the thruster.

This improvement is vital for extending the operational life of the Hall thruster, as it minimizes the risk of demagnetization and thermal stresses. The findings of this study provide a significant step forward in the development of advanced propulsion technologies for nano and microsatellites, underscoring the necessity of integrating materials with enhanced thermal properties in the design of electric thrusters.

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