Electromagnetic Thermal Coupling Simulation Analysis of Silicon Carbide Shock Absorber

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Abstract. This paper introduces a set of absorbing equipment used in 3.2GHz band vacuum high and low temperature environment. Through the finite element method modeling, COMSOL Multiphysics multi-physics simulation software analyzes the electromagnetic thermal coupling capability. The simulation results show that the absorbing properties of the silicon carbide pyramidal absorbing material are good. If the loss caused by the electrical conductivity of silicon carbide is considered, the absorbing performance of the silicon carbide pyramid will be greatly improved to -40dB. The simulation calculation model combines the electromagnetic field with the thermal, and gives the temperature curve and the isothermal contour dynamic diagram of the pyramid. It provides theoretical guidance for practical engineering applications.

1. Introduction

With the rapid development of communication satellite technology, transceiver sharing has become a common design method for communication satellite payloads. In this case, the problem of passive intermodulation is particularly prominent. If these weak interference signals enter the receiver with high sensitivity. It is very likely to exceed the thermal noise floor of the receiver, affecting the normal operation of the satellite [1-2]. In order to complete the PIM index test of the whole star and transponder subsystem in a hot vacuum environment, a low PIM absorbing heat sink was developed using silicon carbide absorbing materials, and the absorbing heat sink was used to establish an index of less than 150 dBm. Low PIM test environment with both heat flow simulation and microwave power withstand capability. The electromagnetic thermal coupling capability needs to be simulated and analyzed before the test [3-4].

In this paper, a set of absorbing equipment for vacuum high temperature and low temperature environment in 3.2GHz band is modeled by finite element method, and COMSOL Multiphysics multi-physics simulation software is used to simulate and analyze the electromagnetic thermal coupling capability[5]. The structure of the box is shown in Figure 1. The box body is made of stainless steel frame structure, and the absorbing module is installed inside. During the test, the antenna is facing the mouth of the absorbing device, radiating energy to the absorbing device, and the absorbing device ensures that the energy is absorbed to ensure the normal operation of the antenna.
2. Introduction to the absorbing box

The overall technical requirements for absorbing equipment:
1) Operating temperature range: -190°C ~ +100°C
2) Withstand power: greater than 1000 W/m²
3) Absorbing performance: 3.2G band absorbing performance is better than -30Db
4) Surface requirements: Coating hemisphere emissivity ε_h > 0.85
5) Vacuum suitability: TML (total mass loss) ≤ 1%; CVCM (condensable volatiles) ≤ 0.1%
6) Dimensions: Internal dimensions of absorbing equipment 1600mm * 700mm * 700mm

In order to improve the reliability, the microwave darkroom absorbing material installation idea is adopted, and the physical installation and the adhesive bonding method are adopted. The absorbing wave tip is stuck on the alloy aluminum plate to form the absorbing module by using the card slot structure (as shown in Fig. 2), and the card slot structure can be realized by extrusion molding.

![Figure 2 Absorbing module schematic](image2)

The silicon carbide absorbing tip is shown in Figure 3. The absorbing tip is connected by a card slot, and the absorbing tip is neatly arranged without gaps. In order to ensure that the heat in the absorbing body is effectively conducted to the wall surface, the heat-dissipating adhesive (usually silica gel) is used for reinforcement during assembly. The design of the absorbing tip cone is 40 mm (W) × 40 mm (L) × 115 mm (H), which is a hollow structure, and the inner hole is conical.

3. The principle of the method

COMSOL Multiphysics multi-physics simulation analysis software is a numerical calculation software based on finite element method, which can be applied to the simulation analysis of electromagnetics, thermal, mechanics, optics and other disciplines. Here is a brief introduction to the relevant basic principles of electromagnetic and thermal coupling.

![Figure 3 Single absorber shape](image3)
The essence of solving the electromagnetic problem is to solve the Maxwell equations. In order to facilitate the computer's solution operation, the Maxwell equations are simplified by a series of reasoning, as shown in the following equation.

$$\nabla \times \frac{1}{\mu_r}(\nabla \times E) - k_0^2(\varepsilon_r - \frac{j\alpha}{\omega \varepsilon_0})E = 0$$

(1)

The wave number $k_0=\omega/c$, $\varepsilon_r$, $\mu_r$ is the relative dielectric constant and the relative magnetic permeability, respectively, $\sigma$ indicating the conductivity.

For solid heat transfer, the temperature field is solved using the following formula,

$$\rho C_p \nabla T + \nabla \cdot \mathbf{q} = Q + Q_{\text{ed}}$$

(2)

$$\mathbf{q} = -k \nabla T$$

(3)

Among them $\rho$ is the density of the object, $C_p$ is the heat capacity of the object, $u$ is the velocity field, $\mathbf{q}$ is the heat flux density, and $k$ is the thermal conductivity. $Q_{\text{ed}}$ is the heat source and is the thermoelastic damping.

In addition to solving electromagnetic problems and heat transfer problems separately, there is also a need to solve the electromagnetic-thermal coupling problem. Considering that the energy of the heat source $Q$ in heat transfer can be composed of temperature boundary and electromagnetic heat loss, the electromagnetic-thermal multiphysics coupling problem can be solved.

$$Q_e = Q_{\text{rh}} + Q_{\text{ml}}$$

(4)

$$Q_{\text{rh}} = \frac{1}{2} \left| \mathbf{J} \cdot \mathbf{E} \right|$$

(5)

$$Q_{\text{ml}} = \frac{1}{2} \left| \text{Re}(\mathbf{J} \cdot \mathbf{B}) \right|$$

(6)

### 4. Simulation calculation modeling

The finite element method is a numerical calculation method that divides the model into a large number of grid subunits and then calculates the field functions in these small unit structures to obtain an approximate solution. The full size of the absorbing box is much larger than the minimum wavelength. Building a full-scale model will cause the number of grid cells to grow exponentially, consume a lot of computing resources, and the calculation efficiency is low. At the same time, according to the electromagnetic field and heat transfer theory, it is not difficult to find that the field function of each small quadrangular pyramid unit structure inside such a large-sized absorbing box structure is approximately periodic, so that only one of the pyramid structures can be analyzed.

The silicon carbide square pyramid has a size of 120 mm (W) × 40 mm (L) × 115 mm (H), and the inner hollow cone has a size of 12 mm (R) × 69 mm (H). The front, back, left, and right sides of the model are set to the period boundary (electromagnetic + temperature). The upper bottom surface is the incident wave port P1, the incident power $P=1.8$W (withstand power greater than 1000 W/m$^2$), and the lower bottom surface is a perfect electrical conductor. In this model, the temperature boundary conditions are set to the upper and lower bottom surfaces as constant temperature boundary conditions, $T=38$. In addition, the material parameters of the silicon carbide used in the calculation of the model are shown in Table 1 below. The constant pressure heat capacity $C$ (Fig. 4) and the conductivity $\sigma$ (Fig. 5) are the default values in the COMSOL material database. The thermal conductivity, density, relative permittivity, and relative magnetic permeability are the basic parameters of the test. The real and imaginary parts of the electrical constant are shown in Figures 6 and 7, respectively. In the solid heat transfer module, in addition to the temperature boundary conditions such as the above-mentioned upper and lower bottom surface temperature $T$ and the periodic boundary, it is also necessary to provide a silicon carbide pyramid as a total power dissipation density heat source, that is, electromagnetic loss heat generation.
Table 1. Silicon carbide material parameters

| Name                              | Value | Unit             |
|-----------------------------------|-------|------------------|
| Thermal conductivity             | 5.5   | W/(m·K)          |
| Heat capacity at constant pressure | C(T[1/K]) | J/(kg·K)      |
| Electrical conductivity          | 0 or sigma(T[1/K]) | S/m             |
| Density                          | 1700  | kg/m³            |
| Relative permeability            | 1     | 1                |
| Relative permittivity            | epsilonReal(freq)-i*epsilonImg(freq) | 1               |

Figure 4 Silicon carbide constant pressure heat capacity (sigma-temperature)

Figure 5 Silicon carbide conductivity (C-temperature)

Figure 6 SiC dielectric constant real part

Figure 7 SiC dielectric constant imaginary part

5. Simulation results and analysis

Figure 8 S11 reflection coefficient curve, sigma=0

Figure 9 S11 reflection coefficient curve, sigma=default

After the simulation model is established as described above, the reflection coefficient is first calculated using the steady-state frequency domain solver. Since the silicon carbide type absorbing material is a dielectric loss absorbing material, the dielectric constant and conductivity sigma are the key parameters of the material, but the sigma parameter value of silicon carbide is not given at present, here sigma= 0 and sigma=default (material library) are calculated. The silicon carbide in the material library in COMSOL is alpha polycrystalline silicon carbide, sigma ≠ 0. The silicon carbide in practical application is a ceramic material, and the electrical conductivity of the material is not zero compared
with the silicon carbide in the material library, and tends to be doped to increase the loss and enhance the absorbing effect. Figure 8 shows the S11 reflection coefficient curve for \( \sigma = 0 \). S11 is less than \(-10 \) dB in the 2.65-4 GHz band and decreases as the frequency increases. This is consistent with the results of Figures 6 and 7, because as the frequency increases, the loss tangent angle increases correspondingly, resulting in increased losses. However, if the influence of the material sigma is considered, the S11 reflection coefficient curve will undergo a large change. As shown in Fig. 9, the absorbing effect of the material is significantly enhanced, and the enhancement is 30 dB. It can be seen that the sigma value has a great influence on the absorbing performance. Therefore, in order to obtain more accurate simulation data, further testing of the material and obtaining the accurate value of sigma is an indispensable link.

The thermodynamic analysis of the model is performed using a frequency domain transient solver. Fig. 10 is a graph showing the average body temperature \( \text{Avg} \) of the hollow silicon carbide pyramid and the maximum temperature \( \text{Max} \) in the body as a function of the electromagnetic wave irradiation time. Regardless of whether the parameter value of the material sigma is 0, the temperature of the pyramid increases rapidly under the irradiation of strong electromagnetic waves, but then the increase of the pyramid temperature tends to be stable due to the existence of the heat sink, and finally reaches the thermal equilibrium state. When the conductivity of the silicon carbide is set to the default value of the material library, i.e. \( \sigma = \text{default} \), the average temperature and the maximum temperature of the pyramid are significantly larger than the corresponding \( \sigma = 0 \). This phenomenon is easier to understand. When \( \sigma = \text{default} \), the loss of electromagnetic waves in the silicon carbide pyramid increases, and the corresponding coupling generates higher thermal energy, so the corresponding average temperature and maximum temperature are greater than the temperature when sigma is zero. In addition, it is not difficult to find that the average temperature difference in the two cases \( \Delta \text{Avg} < 5^\circ\text{C} \), but the maximum is close to \( 25^\circ\text{C} \), which indicates that the transient warming effect caused by sigma is very strong, further illustrating the big influence of sigma value on absorbing performance and temperature change.

**6. Summary**

The basic principle of electromagnetic-thermal coupling simulation calculation and the modeling and simulation process are introduced above. The simulation results show that the absorbing properties of the silicon carbide pyramidal absorbing material are good, and the reflection coefficient of the absorbing body is less than \(-10 \) dB even without considering the loss effect caused by sigma. But this still has not reached the technical requirement of \(-30 \) dB. If we consider the loss caused by the conductivity of silicon carbide, the absorbing performance of the silicon carbide pyramid will be greatly improved to \(-40 \) dB. Therefore, it is very effective to dope in the silicon carbide material to enhance the loss effect caused by the conductivity, thereby improving the absorbing properties of the silicon carbide material, which is very consistent with the methods reported so far. In addition to the absorbing properties of the absorbing box, the temperature field changes are also the data of interest to
the model. The simulation calculation model combines the electromagnetic field with the thermal, and gives the temperature curve and the isothermal contour dynamic diagram of the pyramid. Although the radiation time and temperature conditions of the port (antenna) in the model are not actively controlled, that is, the electromagnetic boundary conditions and temperature boundary conditions are not accurate experimental temperature conditions, but also provide theoretical guidance for practical engineering applications.

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