Thermal simulation optimization of RTG prototype

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Abstract. In this paper, a structural prototype of an isotope thermoelectric power supply is designed based on thermal simulation experiments. Through software thermal analysis technology optimization, the heat transfer efficiency of the prototype is increased to 78%. The simulation results show that the temperature of the cold end of the thermoelectric module is about 396 K, and the temperature of the hot end is about 933 K, the temperature difference is about 440 K. The simulation results have reference significance for the application of the structural prototype to the actual radioisotope thermoelectric power source.

Keywords: RTG, thermal simulation, heat radiation.

1. Introduction

With the development of deep space exploration technology and the expansion of deep space exploration activities, the detector's demand for energy is also increasing, especially when working under certain long-term low-light or harsh environmental conditions, conventional solar cells cannot be used. In the case of limited function or battery power supply capacity, there is an urgent need for long-term, highly reliable energy supply. The isotope power source has the characteristics of being unaffected by sunlight, strong environmental adaptability, long life, and high reliability. It is an ideal energy source for deep space exploration tasks. It is also the most mature nuclear battery currently developed.

In 1954, Jordan and Birden prepared the first RTG with ²¹⁰Po as the radiation source and Bi₂Te₃ as the thermoelectric conversion material [1]. In 1961, the United States used ²³⁸Pu as a radioactive source, successfully launched a navigation satellite powered by RTG, and used RTG for the first time in outer space. In 1965, the Soviet Union used ²¹⁰Po as a radioactive source and used RTG to power the "Cosmos" series of military satellites. In the early 1970s, the micro-RTG with ²³⁸Pu as a radioactive source was successfully used in cardiac pacemakers, the rate can reach 700 μW [2]. In 1971, China's first RTG with ²¹⁰Po as a radioactive source was born in Shanghai Institute of Nuclear Research, Chinese Academy of Sciences. In 2004, the China Institute of Atomic Energy began to conduct in-depth research on RTG, and two years later developed a RTG that can be used in space equipment with a power of several hundred mill watts. In 2008, Sandia National Laboratory in the United States developed an RTG with a power density of 104 μW/cm² [3]. The KTG uses ²³⁸PuO₂ as a radioactive source and Bi₂Te₃ as a thermoelectric material. In 2018, China installed a better-performance RTG on Chang'e 4, with a continuous output power of up to 2 W [4].
Due to the complex shell structure of the high-power isotope thermoelectric power supply, it has high requirements for heat transfer efficiency, and the environment in outer space is difficult to simulate on the ground. Therefore, when determining the structure, it is necessary to perform thermal simulation to determine the thermal design of each part reasonable. A structural prototype of an isotope thermoelectric power supply originally designed, optimized by software thermal analysis technology, and increased the heat transfer efficiency of the prototype to about 78%.

2. Experiment

2.1. Modelling
The heat should be dissipated as much as possible to reduce the temperature of the cold end and increase the temperature difference between the cold and hot ends. The thermoelectric module contains multiple modules, as shown in Figure 1(a). From bottom to top, they are a cooling block, a copper block, a ceramic substrate, a thermal insulation filling block, 15 electrical couple pairs, a ceramic substrate, and then pass through an insulating gasket, the high temperature elastic pad is connected with the internal high temperature collector ring. Because it contains too many parts and layers, in order to simplify the simulation model and improve the calculation efficiency, the thermoelectric model is simplified into a whole with equal area and weight [5], as shown in Figure 1(b). The density, heat capacity and thermal conductivity required for the simulation calculation are calculated to obtain equivalent values.

![Figure 1. (a) The thermoelectric module; (b) the simplified thermoelectric model.](image)

The structure of the thermoelectric power supply prototype is shown in Figure 2. The thermoelectric module is mainly used to convert heat energy into electrical energy to supply the load. The structure adopts a cylindrical central radiation type. The heat source is in the center of the cylinder. The heat is radiated from the center to the surroundings. After the thermoelectric module to the structural shell, a temperature difference is formed between the two end faces of the thermoelectric module. The thermoelectric module generates an output voltage from the temperature difference. Therefore, the internal heat transfer design should make the heat pass through the thermoelectric component to make it fully utilized, and the rest is filled with insulation material.

![Figure 2. The simplified thermal simulation model of the RTG prototype.](image)
2.2. Simulation

On the basis of the simplified thermoelectric module model, the installation gap and contact thermal resistance of each component are ignored; the internal radiation heat transfer of the power supply is ignored, and only the external radiation heat of the shell is considered. The space background temperature is 20 K, and the surface emissivity is set to 0.85; simulation The heat source is an evenly distributed body heat source with a constant calorific value of 2000; high thermal conductivity filler is filled between the heat source and the high temperature sleeve, and the thermal conductivity is set to 50 W/(m·K); the bottom mounting surface of the power supply is insulated.

The construction of unstructured tetrahedral grids, local details such as fins and thermoelectric modules are refined, and the total number of grids is 8.52 million. The steady-state heat conduction adopts the Fourier heat conduction model and uses FLUENT 17.2 thermal simulation software to calculate. Select the steady-state laminar flow model, the second-order upside-down style of the SIMPLE algorithm, and the boundary conditions are set as follows: external radiant heat emissivity is 0.85, external temperature is 20 K; simulated heat source: uniform constant body heat source as 1406200 W/m²; the rest of the wall is adiabatic.

According to Fourier's law of heat conduction, the thermal resistance analysis of the thermoelectric module is carried out, and the thermal conductivity is calculated according to the equivalent thermal resistance. There is only the heat transfer method of heat conduction in the thermoelectric module, and only the heat conduction thermal resistance exists. The heat of each part of the heat transfer process resistance calculation formula [7]:

\[ R = \frac{\delta}{A\lambda} \]  

Where \( R \) is the heat transfer resistance, \( \lambda \) is the thermal conductivity. \( \delta \) is the thickness in the heat transfer direction, \( A \) is the normal phase area perpendicular to the heat transfer direction.

3. Result and discussion

After processing the simulation results after thermal equilibrium, the cross-sectional temperature distribution cloud diagram of the power supply is shown in Figure 3 (a). It can be seen from the figure that the overall temperature difference of the power supply is relatively large. The highest temperature of the entire heat source module is 1122 K, located inside the simulated heat source; the lowest value is about 408K, located at the end of the radiator fin. In addition, the heat leakage from the calcium silicate board at the bottom of the simulated heat source is relatively large. Thermal insulation support materials with lower thermal conductivity could be chose in next project, or increases the thermal conductivity of the thermoelectric module to minimize heat leakage. The temperature of the aluminum alloy shell is about 450 K; the temperature of the radiator fin is in the range of 408–448 K, the temperature difference is 40 K, and the temperature uniformity is good, as shown in the figure 3 (b). The thermoelectric module adopts equivalent simplified processing, and combines the two connected modules into a whole, and its temperature cloud diagram is shown in the figure below. The cold end temperature is about 483–490 K, the hot end temperature can reach up to 965 K, and the temperature difference is about 470 K.
According to the simulation results, the temperature of the cold end of the thermoelectric module exceeds 473 K. The reason is that the radiator fin is small and the radiation area is insufficient, which results in a higher temperature. According to the calculation results of the previous radiation surface, the length of the fin and the embedded heat pipe is extended, and the radiation area is increased without increasing the temperature difference, thereby reducing the cold end temperature. The length of the radiator fins and heat pipes is increased from the original 189 mm to 500 mm, and the total area of radiation heat dissipation is about 2.5 m. The model was established as Figure 4 shown, and the unstructured tetrahedral grid was divided. The number of grids was 11.56 million, and the temperature of each component dropped as Figure 5 shown. The cold end temperature of the thermoelectric module is about 396 K, the hot end temperature is about 933 K, and the temperature difference is about 440 K. The radiator temperature is between 358–402 K, and the heat pipe temperature difference is 15 K (length 500mm).
Figure 5. (a) The cross-sectional temperature distribution cloud diagram of the optimized RTG prototype; (b) temperature distribution cloud diagram of the optimized RTG prototype.

4. Conclusions
The thermal simulation result of this isotope power source principle prototype achieves 78% heat conduction efficiency, which can ensure thermoelectric conversion of thermoelectric devices under temperature difference conditions of more than 400 K. By optimizing the structure of the radiant heat sink, the cold junction temperature can be further reduced, so that in order to meet the requirements for the development of the isotope power principle prototype, the subsequent completion of the electrical performance test and the environmental verification test also needs to be reliable in the long-term operation of the heat source module (real source) Further related work has been carried out in terms of performance, mechanical stability of thermoelectric components, and reliability of integrated structural insulation components.

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