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Research Paper

Thermal and electrical analysis of SiGe thermoelectric unicouple filled with thermal insulation materials

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HIGHLIGHTS

- Crucial design parameters were evaluated for their impact on the SiGe thermoelectric unicouple performance.
- Thermal insulation filler is beneficial to avoid radiation heat loss and maintains conversion efficiency at ~7%.
- A thermoelectric generator consisted with SiGe unicouples and cooling fins is optimized.

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ABSTRACT

Thermoelectric performance of SiGe unicouple filled with four kinds of thermal insulation materials is simulated using finite element method. Crucial design parameters including thermoelectric leg length L, space t_i, hot side temperature T_h within 1073–1223 K and cold side temperature T_c within 573–773 K were evaluated for their impact on the unicouple performance. Unicouple models consisted of SiGe served in RTG on board Cassini spacecraft (Cassini SiGe) and home-made ball milled SiGe (BM SiGe) are analyzed, respectively. It is found that the power output per unit area P_A, heat absorption per unit area Q_{hA} and heat released per unit area Q_{cA} are inversely proportional to leg length and space area between legs. The conversion efficiency η of SiGe thermoelectric legs is ~7.5% at T_h = 1223 K (1173 K) and T_c = 573 K. η of unicouple will decrease to below 1% if there is no fillers in the space between legs. For unicouple filled with thermal insulation materials, radiation heat is shielded, and heat flow from filler will lead to a η decrease of 0.07–0.5%, where $\eta_{unicouple}$ of 7.09% and 6.89% can be obtained, respectively. A model calculating system mass and power density for thermoelectric generator is built, and is used to optimize the system.

1. Introduction

Thermoelectric modules conversing heat directly into electric is popular in deep space exploration as electrical power source, since it has the advantages of quiet, vibration free, maintenance free and long life [1–3].

Geometric parameters play a significant role on performance of thermoelectric devices as well as materials properties [4–6]. A thermoelectric unicouple is typically π shape and consists of 1N-type and 1P-type thermoelectric leg and electrodes. Space between legs in thermoelectric model is usually filled with thermal insulation materials for the purpose of mechanical support, shielding of radiation and formation of evaporation barriers [7]. Besides, the filler generates thermal bypass, due to which the heat flow is affected by the filler. Therefore, the efficiency of thermoelectric module is influenced by the filler. The thermal conductivity, density of thermal insulation materials and space area between thermoelectric legs will affect electrical power density, heat absorption at hot side and heat released at cold side dramatically. Accordingly, the thermal power density, heat flow at hot and cold sides, and size of fins will be varied. In other words, the design of the whole thermoelectric generator system will be decided partially by size and properties of thermal insulation materials. Thus, the properties and size of thermal insulation materials must be considered and analyzed carefully in the design of thermoelectric unicouple.

SiGe is one of the most maturely developed thermoelectric materials behaving good thermoelectric properties [8–11], and has been used successfully in Radioisotope Thermoelectric Generators (RTG) on board Cassini, Voyager and Galileo spacecraft [12,13]. In this paper, thermoelectric performance including power output density (P_A and P_m), heat absorption (Q_{hA}) and heat release (Qc_A) for thermoelectric unicouple models, built on both Cassini SiGe [13] and BM SiGe, and filled with thermal insulation materials, are simulated using finite element

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Nomenclature

L	length of SiGe legs (cm)
t_i	space between SiGe legs (cm)
T_h	temperature at hot side (K)
T_c	temperature at cold side (K)
ΔT	temperature difference between hot side and cold side (K)
S	Seebeck coefficient of thermoelectric materials (μV K^{-1})
P_0	electrical power output of the unicouple (W)
$P_{0(L)}$	electrical power output of the unicouple when leg's length is L (W)
P_A	electrical output of the unicouple per unit area (W cm^{-2})
P_m	electrical output of the unicouple per unit mass (W g^{-1})
Q_h	heat absorbed by unicouple at hot side (W)
Q_{hA}	the heat absorbed per unit area for unicouple at hot side (W cm^{-2})
Q_c	heat released by unicouple at cold side (W)
Q_{cA}	the heat released per unit area for unicouple at cold side (W cm^{-2})
Q_r	radiation heat (W)
A_i	area of space between thermoelectric legs (cm^2)

Subscripts

i	thermal insulation materials
SiGe	SiGe legs

Greek symbols

σ	electrical conductivity of thermoelectric materials (S cm^{-1})
κ	thermal conductivity of thermoelectric materials (W m^{-1} K^{-1})
δ	Stefan–Boltzmann constant (W m^{-2} K^{-4})
ρ	density (g cm^{-3})
ε	emissivity value
η	conversion efficiency (%)
Φ	radiation heat (W)

Abbreviations

RTG	radioisotope thermoelectric generator
TE	thermoelectric
AFC	aerogels/fibrous ceramic composites
BM	ball milling
SYS	system

method (FEM). Effects of four kinds of thermal insulation materials including areogel, traditionally Min-K, ceramic fiber, and aerogels/fibrous ceramic composites (AFC) on unicouple performance have been investigated thoroughly under conditions that the legs length, space, T_h and T_c are varied.

2. Model

The simulation was carried out using the steady-state thermal and thermoelectric modules in the finite element package, ANSYS. Multiphysics procedure was conducted using a direct coupled field solution and account for the full set of thermoelectric relevant effect (Joule, Thomson, Peltier, Seebeck) [4,14–16]. A unicouple with P and N type rectangular prism SiGe legs with dimension of $0.5 \times 0.5 \times 1$ cm^3 was modeled. The distance between legs was 0.2 cm, and the space between legs was filled with thermal insulation materials. This model was defined as the original model, as shown in Fig. 1(a) and (b). As to other models, leg length L and space t_i are varied between 0.5–2.5 cm and 0.05–0.5 cm, respectively, with leg cross sections remain the same with the original model. As only the effects of thermal insulation fillers and geometric were considered, both electrodes and contact resistivity were ignored. The voltage was coupled at hot side.

With regard to the finite element (FE) models that were built in ANSYS, both the thermoelectric materials and the thermal insulation materials were meshed with PLANE 226 element, and the meshing size was set to 1 mm. Preferred thermoelectric materials parameters of $Si_{0.8}Ge_{0.2}$ are $Si_{0.8}Ge_{0.2}$ used in Cassini RTG (Cassini SiGe) [13] and $Si_{0.8}Ge_{0.2}$ prepared by ball milling and SPS (BM SiGe). Thermal insulation materials are Min-K [17], aerogel [18], ceramic fiber [19], and aerogels/fibrous ceramic composites (AFC) [20]. Temperature-dependent thermoelectric properties are shown in Fig. 2. The resistor was meshed with CIRCU 124 element in the FE model. The load resistivity was set as the same with inner resistivity, namely, P_0 was always maximum [21]. The thermal insulation material was meshed with SOLID 226 element, which has both thermal and structural properties. To simulate the properties of the pellet-thermal insulation, contact pairs (CONTA 174/TARGE 170 elements) were established on the interface between the implemented thermoelectric unicouple (including legs) and the insulation filler, with the contact thermal conductivity was set to be 2 W m^{-1} K^{-1}, as shown in Fig. 1(c). Once the model was built, the performance of the unicouple was simulated by a variation of the temperature load. The efficiency was calculated as ratio of the output power and nodal heat flow at the hot side of unicouple.

For the Cassini SiGe unicouple model, four kinds of thermal insulation materials including Min-K, areogel, ceramic fiber, and AFC were chosen. For the BM SiGe unicouple model, AFC was chosen as thermal insulation materials. The boundary conditions are list in Table 1.

3. Result and discussion

Temperature distribution of the unicouple is shown in Fig. 3(a). The temperature gradient between hot side and cold side is the main driving force for heat flux, thermal exchange is ignorable at the interface of thermoelectric materials and thermal insulation filler, according to the calculation result. However, there is a temperature difference between TE legs and insulation fillers, as the temperature in insulation filler is a little bit higher than that in the TE legs, compared in Y direction. It is mainly because that the κ of SiGe is larger than that of the thermal insulation filler. Electrical potential distribution for $T_h = 1223$ K and $T_c = 573$ K is plotted in Fig. 3(b). As can be seen, electrical potential decreases rapidly from maximum value of 0.124 V to minimum value of 0 V, indicating most electrical power is consumed by the load resistivity.

The simulated P_0, Q_h, Q_c, Q_{hi}, Q_{ci} and η_{SiGe} are list in Table 2. Since there is no heat flux exchange between thermoelectric legs and thermal insulation materials, the properties and thickness of thermal insulation materials have no effect on electrical power output P_0 of SiGe legs.