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A novel thermoelectric harvester based on high-performance phase change material for space application

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HIGHLIGHTS

- A thermoelectric harvester is proposed applied in extreme environment in space.
- Paraffin/EG composite is optimized with enhanced thermal property and reliability.
- Both simulation and experiment are used to evaluate the performance of harvester.
- High-grade electrical energy is enhanced when using the paraffin/5 wt% EG composite.

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ABSTRACT

In this study, a thermoelectric energy harvesting device applied with extremely large temperature variation (from +100 °C to −50°C) for space application is presented using phase change material (PCM) for thermal control and storage. Aiming at developing a high-performance PCM to fill into the heat storage unit (HSU) of the device, the thermal conductivity, leakage and thermal reliability of paraffin-based composites with different loadings of expanded graphite (EG) were investigated. Results showed the form-stable paraffin/EG composite has enhanced thermal conductivity and maintainable latent heat storage capacity after repeated thermal cycling test. Furthermore, the prototype device of thermoelectric harvester was developed, where the proportion of EG in the PCM is key to balance the heat storage capacity and the heat transfer rate. Both simulation and experiment are used to evaluate the performance of the harvester. The experimental evidence verifies that the thermoelectric harvester with paraffin/5 wt% EG composite owns the largest total energy output and the most portion of high-grade electrical energy.

1. Introduction

The life span of the wireless sensor is a critical problem in Wireless Sensor Network, especially for space missions, such as satellite orbiting Earth or landing vehicles on planets, which would encounter drastically different thermal environments cyclically. Some reports have shown a promising alternative power-supply technology for such applications is the thermoelectric energy harvesting [1–4]. The devices own advantages of small size, no moving parts, simple structure, high reliability and being environment friendly. Various types of thermoelectric generator (TEG) for energy harvesting and electricity generation have been proposed [5–9]. However, low heat-to-electricity conversion efficiency has been identified as the main obstacle to the development of the thermoelectric power generation. The theoretical maximum efficiency of a TEG, i.e., η_{TEG}, can be written as a function of ZT and the temperature difference ($\Delta T = T_h - T_c$) between its hot (T_h) and cold (T_c) surfaces. Thus,

$$\eta_{TEG}(\Delta T) = \frac{\Delta T}{T_h}\cdot\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_c}{T_h}}$$

Most commercial thermoelectric materials, which are commonly telluride alloys, typically give a limited ZT of around 0.8 at room temperature. Thus, the efficiency of TEGs depends largely on the available temperature difference ΔT, and hence thermoelectric harvesting has been limited to applications where a large ΔT is available at the device location. Therefore, how to establish a large temperature difference has become the key to solve the low conversion efficiency of TEG, and then an alternative approach of using a heat storage unit (HSU) is employed to transform temperature variation in time into spatial difference ΔT which can then be appropriately exploited by a TEG [10–12].

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Phase-change material (PCM) has been the key component in the HSU, which can maximize the average temperature difference of thermoelectric harvesting [13]. During alternate changing temperature field, the application of PCM exhibits great advantage of continuous production of electrical power in the night due to the capability of the PCM to release the heat stored in the day. For example, Samson et al. [10] showed an energy output of 23.3 J from a temperature sweep from +20 °C and −20 °C and back corresponding to 10g of water as the PCM. Kiziroglou M E et al. [14] demonstrated output energy of 105 J into a 10 Ω matched resistive load, from a temperature sweep from +20 °C to −21 °C, then to +25 °C, using 23 g of water as the PCM. Water appears to be the best sensible heat storage (SHS) [15,16] liquid available because it is inexpensive and has a high latent heat (333 J/g) [17,18]. However, application of water as PCM has such disadvantages as supercooling phenomenon and liquid leakage, indicating poor thermal reliability in space environment [19]. Besides, the thermal conductivity of water is comparable to that of TEG, implying that a large fraction of ΔT is lost within the PCM. This effect significantly reduces the overall energy conversion performance of that particular implementation [20]. Additionally, space environment certainly means sharper temperature change and proposes more strict requirements for thermal reliability of PCM.

Paraffin is taken as a promising PCM because it has relatively high latent heat in heat storage application and proper thermal characteristics such as little or no supercooling, varied phase change temperature, good thermal and chemical stability and self-nucleating behavior [21–23]. However, there are still some common drawbacks such as low thermal conductivity and liquid leakage that exist in paraffin. To overcome the problem of low thermal conductivity, several methods based on addition of different thermal conductivity enhancers have been propose [24–29]. Among them has EG attracted much attention because of its high thermal conductivity, porous structure and adsorption capability, which are beneficial to solving the liquid leakage problem [30–33]. Meanwhile, it is certain that latent heat of the composite PCMs gets reduced largely as mass fraction of EG increases. Thus, a proper proportion of EG was required as a compromise to balance the heat storage and the heat transfer requirements of latent heat thermal energy storage (LHTES) system using the composite PCMs [34].

Hence in this paper, paraffin-based composites (m.p.: 42–44 °C) with different loadings of EG were prepared. Thermal characterizations such as thermal conductivity, energy storage capacity, thermal reliability and liquid leakage after repeated thermal cycles were also investigated. A novel prototype device which can be used as sustainable power supply is presented applied with extremely large temperature variation (from +100 °C to −50 °C) inside the space shuttle and modules of the space station, and its performance is analyzed using both numerical simulation and experimental evidence. Thermal simulation can effectively predict the performance of various device designs, analyze thermodynamic response, and guide experimental test [35,36], which was limited to conduct on the phase change domain previously. Through comparing the thermodynamic response and total electrical energy of different thermoelectric harvesters, it illustrated that, for a given temperature cycle, capacity of thermoelectric energy harvesting device has been largely enhanced by introducing the paraffin/5 wt% EG composite as PCM. Furthermore, considering the alternate environment of space applications, reliability evaluation of both material and device after repeated thermal cycles was discussed as well in this work.

2. Experimental section

2.1. Preparation of Paraffin/EG composite

Paraffin with melting temperature of 42–44 °C was obtained from Fushun Wenai Company, China, which has a relatively proper phase transition temperature corresponding to the temperature variation (from +100 °C to −50 °C) in space application. EG with 50 mesh size microparticles was supplied by Qingdao Hengruida Company, China. The paraffin/EG composites with the mass fraction of 5% and 10% EG were prepared by absorbing liquid paraffin into the EG at 80 °C for an hour through electrical oven. The samples were then cooling under ultrasonic irradiation for 20 min. Hence, samples of paraffin/EG composite allowing no liquid paraffin leakage were considered as form-stable composite PCM.

2.2. Tests and techniques

Field emission scanning electron microscope (FE-SEM) images were collected on FE-SEM, Sirion 200 systems. Thermal energy storage and melting temperature of pure paraffin and paraffin/EG composite have been determined by means of differential scanning calorimeter (Mettler Toledo DSC 1) at heating rate of 2 °C/minute under atmosphere of nitrogen. Thermal diffusivity (D) of the samples was measured by the laser flash method (LINSEIS LFA 1000), and the specific heat (C_p) was determined by differential scanning calorimetry (Mettler Toledo DSC 1). The sample density (ρ) was determined by measured mass and volume ($\rho = m/V$). The thermal conductivity (κ) was calculated by $\kappa = D \times C_p \times \rho$.

In order to determine the change in thermal properties of the composite PCMs, thermal cycling test was performed by a thermal shock chamber (GDC-50, Weidatx Co., Ltd.). The thermal shock chamber was separated into two temperature zones, high-temperature zone (150 °C) and low-temperature zone (−40 °C), respectively. The samples were transferred from one zone to the other and stayed in one zone for 2 min. One test cycle consists of a warm-up phase and a cooling-down phase.

The output performances of the heat storage thermoelectric harvester were monitored by a paperless recorder (GP10, Yokogawa Co. Ltd.). The environmental and PCM temperatures were measured using type-T thermocouples. The two TEGs were electrically connected in series, and the open circuit voltage was monitored during the temperature cycle.

2.3. Fabrication of thermoelectric harvester

The thermoelectric energy harvesting system reported in this paper is illustrated in Fig. 1. The HSU comprises PCM inside a container, which provides thermal contact to TEGs and is otherwise thermally insulated from the environment. An insulation layer prevents heat leakage to the environment through the rest of the HSU surface. A finned heat sink is used on the outside TEG surface to improve thermal contact with the environment. When the environmental temperature fluctuates, heat flows in and out of the HSU through the TEGs, resulting in generation of electrical energy. Measurements were performed by applying a temperature cycle (T1) between +100 °C and −50 °C to the surrounding environment. During tests, the harvester was positioned inside a chamber for the heating and cooling phase. Measurements

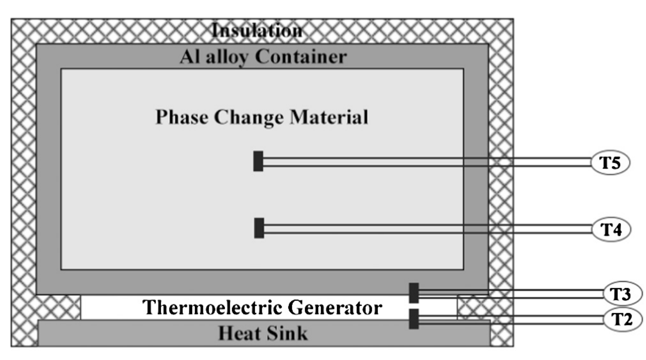

Fig. 1. Schematic of the device structure.