Applied Energy 228 (2018) 873–880

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Multi-parameter optimization design of thermoelectric harvester based on phase change material for space generation

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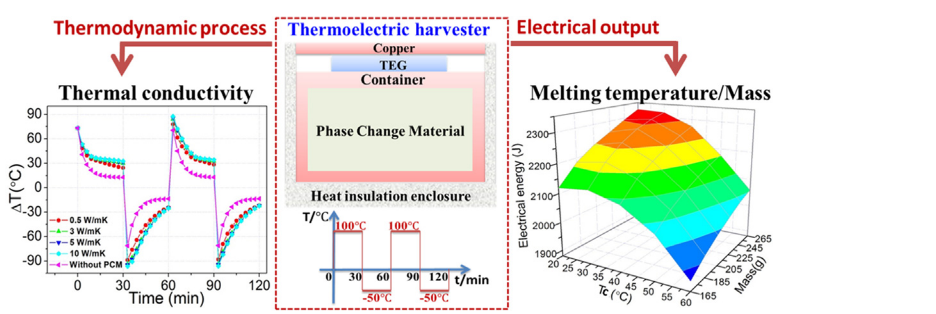
HIGHLIGHTS

- PCM based thermoelectric harvester is proposed applied in space environment.
- Multi-parameter optimization design is implemented for thermoelectric harvester.
- Choosing PCM with proper melting point is quite essential to enhance the output.
- The optimized design can realize mass-saving of harvester for space application.
- Generalized design rules are provided for PCM based thermoelectric harvester.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Thermoelectric energy harvesting
Phase change material
Multi-parameter optimization design
Space power supply

ABSTRACT

In this study, a thermoelectric energy harvesting device based on phase change material is presented which can be applied with large temperature variation in space for power supply. Aiming at multi-parameter optimization of thermoelectric harvester, an assessment of the generalized design rules for the proposed harvester has been implemented. The effect of thermal conductivity, melting temperature and mass of phase change material on the thermodynamic process were investigated to obtain the design criterion for thermoelectric harvester. Besides, both simulation and experiment validated that choosing PCM with a suitable melting temperature is quite essential to the temperature control by balancing the heat storage and release process, consequently enhancing the power output. This work offers a unique powering solution for wireless sensor involving location with temperature variation in space application.

1. Introduction

The numerous electrical components or wireless sensor networks on the spacecraft present power-supply challenges, where using batteries always requires accessibility and periodic replacement [1]. Hence, energy harvesting becomes a rapidly developing technology which addresses this limitation by exploitation of local ambient energy [2–4]. Systems comprising energy harvesting and storage have been demonstrated to improve autonomy and reliability, and reduce maintenance requirements [5,6]. To date, a number of approaches have been proposed with available energy sources of heat [4], vibration [7,8], sunlight [9] and so on. In space missions, variable spacecraft thermal environment would be encountered for landing vehicles on planets without atmosphere, where the day/night cycle presents a radically

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https://doi.org/10.1016/j.apenergy.2018.06.151
Received 12 March 2018; Received in revised form 24 June 2018; Accepted 30 June 2018

alternating temperature change. Similarly, satellite orbiting Earth is confronted with drastically different thermal environments cyclically as it passes in and out of Earth's shadow. Therein, a promising alternative power-supply technology for such applications is the thermoelectric energy harvesting with effective conversion from heat energy to electricity [10–12]. In addition, the thermoelectric generators (TEGs) are easy to integrate and own advantages of no noise, no moving part and environment friendly without extra waste, which is particularly suitable for space generation. However, the primary limitation of the thermoelectric power generation is its relatively low conversion efficiency, that depends largely on the available temperature difference ($\Delta T = T_h - T_c$) across its hot and cold sides. The applicability of thermoelectric energy harvesting has been greatly broadened by the introduction of a heat storage that allows the exploitation of temperature changes. In particular, the introduction of phase change materials (PCMs) to induce temperature hysteresis and transform into a spatial temperature difference has created an artificially increased temperature difference across TEGs [6,13,14].

PCMs, while undergoing a phase change, absorb or release thermal energy additional to their specific heat, known as latent heat, without obvious temperature change. For spacecraft operation, combining PCM with TEG exhibits great advantage of continuous production of electrical power during the night portion due to the capability of the PCM to release the heat stored in the day. In the reported by Samson et al. [15], an aircraft-specific thermoelectric generator module consisting of water as PCM and TEG element was designed and simulated, and then wireless sensor node powered by thermoelectric energy harvester is tested for aircraft applications [16]. Besides, Kiziroglou et al. presented a framework of design and analysis for heat storage thermoelectric harvesting devices [6], where the water was chosen as the PCM and output energy of 105 J was achieved from a temperature sweep from +20 °C to −21 °C, then to +25 °C. They further considered the scaling, super-cooling and dynamic response delay in heat storage harvesting devices [5,17]. Generally, water is regarded as a very effective expendable coolant in space applications. However, it also has such disadvantages as supercooling and liquid leakage, which requires extra nucleating agent and complicated package technology. Additionally, space environment certainly encounters sharper diurnal temperature change (much larger than 100 °C) and proposes more strict requirements for thermal reliability of PCM.

A good PCM should possess the characteristics of high heat fusion per unit mass, proper melting temperature, high thermal conductivity, thermal stability, non-toxicity and non-corrosiveness. Organic compounds e.g. paraffin (CnH2n + 2) have adjustable melting points, large latent heat, good thermal and chemical stability and self-nucleating behavior, which become new promising candidate for thermal storage applied for the space mission [18,19]. Although the drawbacks of low thermal conductivity still existed in paraffin, which may affect the heat transfer rate, several methods based on addition of different thermal conductivity enhancers have been propose to overcome this problem [20–24]. In most spacecraft applications, criteria for design selection boil down to that one has the lowest mass and meets power requirements. A substantial mass savings could be rather valuable which has been rarely considered in PCM based thermoelectric harvesting. Additionally, the PCM should own a proper melting point temperature well within the range of temperature variation to ensure the maximization of power output.

The thermodynamic process is equally vital to establish large temperature considering both the alternating cooling and heating processes. The numerical simulation based on finite element method becomes a useful tool for optimization and prediction, being a possible substitute for high-cost and complex experimental work [25]. Thermodynamic analysis has been frequently reported in many literatures [26–28]. Thermal simulation can effectively predict the performance of various device designs, guide experimental test and analyze thermodynamic response [29,30], which was limited conducted on the phase change based energy harvesting domain previously. In our previous work, a thermoelectric harvester has been presented to upgrade the output characteristics of TEG system by introducing high-performance paraffin based composite with enhanced thermal conductivity and stability [31]. However, the transient thermal process and its performance will be influenced by various parameters, including thermal conductivity, mass, melting point of PCMs and also alternating temperature. Hence in this work, we further focused on a multi-parameter optimization of PCM based thermoelectric harvester for space generation. When on the sun-lit side of the earth, the temperature on the spacecraft or space station can reach over 100 °C. While during a night pass through earth's dark shadow, temperatures can plunge to −100 °C. However, considering the practical application conditions inside the space shuttle and modules of the space station, the device will experience a smaller range of temperature. Hence, a novel prototype device is presented and applied with the temperature variation from +100 °C to −50 °C. Meanwhile, its performance is analyzed using experimental evidence.

2. Theoretical principle and numerical models

2.1. Thermoelectric basis

The figure of merit ZT is generally used to evaluate the properties of the thermoelectric materials, which is defined as

$$ZT = \frac{\alpha^2\sigma}{\lambda}T \tag{1}$$

where α, σ, λ, and T are the Seebeck coefficient, the electrical conductivity, the thermal conductivity of the thermoelectric material and the absolute temperature, respectively. The theoretical maximum efficiency of a TEG, i.e., η_{TEG}, can be written as a function of ZT and the temperature difference ($\Delta T = T_h - T_c$) across its hot and cold sides [31]. Thus,

$$\eta_{TEG}(\Delta T) = \frac{\Delta T}{T_h}\cdot\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_c}{T_h}} \tag{2}$$

Generally, the maximum power output for TEG is given by

$$P_{max} = \frac{(S\Delta T)^2}{4R_{in}} \tag{3}$$

where S is the Seebeck coefficient of the thermoelectric device, which is dependent on the Seebeck coefficient (α) of thermoelectric materials and pairs of thermocouples integrated in the device. R_{in} is the internal electrical resistance of TEG. It is apparent that the materials with a higher ZT value can be employed to improve the efficiency of TEG. Meanwhile, the other important concern to improve the performance of TEG is to establish a large ΔT.

2.2. Governing equations of ANSYS thermal analysis

ANSYS can solve the underlying governing equations and the associated problem-specific boundary conditions based on the finite-element method, which supports thermal analysis, including phase change issues. According to the energy conservation principle, transient thermal equilibrium equation without the presence of internal heat source is expressed as [32]

$$[C]\{\dot{T}\} + [K]\{T\} = 0 \tag{4}$$

where $[C]$ and $[K]$ represent the thermal capacity and conductivity matrix, respectively. $\{T\}$ is the location-time dependent temperature vector and $\{\dot{T}\}$ is the derivative of temperature with respect to time. When solving phase change problems, the effect would be included in $[C]$. In general, a simplified effective heat capacity approach is commonly employed to model the phase change effect in the numerical