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Numerical power output predictions for low-bandgap thermophotovoltaic cells coupled with a latent-heat energy storage system

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ABSTRACT

The thermal energy storage and thermal-to-electric conversion components of a satellite power system were analyzed computationally. A phase- change material provided the energy storage while thermophotovoltaic cells converted the thermal energy to electrical. The phase-change mechanics were modeled and the associated system temperatures determined throughout the orbit. Using an equivalent circuit model for low-bandgap thermophotovoltaic diodes, those temperatures were then used to predict the maximum power output of the thermophotovoltaic cells. The system was modeled at five different altitudes. Two different thermophotovoltaic cells, gallium antimonide (GaSb) and gallium indium arsenide antimonide (GaInAsSb), were evaluated, and the system was analyzed when there were no voids in the phase-change material and when there were voids present. For all situations evaluated, the GaInAsSb cell produced significantly more power, but experienced greater variation in performance. The presence of voids in the phase-change material significantly lowered the power available during eclipse.

1. Introduction

Solar energy technologies that require direct sunlight to generate electricity are inherently limited. Electricity is commonly needed when sunlight is not available. By combining a thermal-to-electric conversion device with an energy-storage system, solar electricity can be a viable alternative to traditional sources. In this work, a satellite power system, in which solar energy is stored in a latent-heat energy storage system and converted to electricity using thermophotovoltaic cells, was evaluated. The power output of this system was quantified numerically. Two different thermophotovoltaic cells were evaluated for several different orbits. In addition, the effect of voids in the phase-change material of the energy storage system on power output was also predicted.

2. Background

The proposed satellite power system collects and concentrates solar energy on a phase-change material, where it is stored in the latent heat of fusion. In this case, the phase-change material is silicon. The thermal energy stored in the silicon is converted to electrical energy using either gallium antimonide (GaSb) or gallium indium arsenide antimonide (GaInAsSb) thermophotovoltaic cells. In this work, the phase-change mechanics of the proposed system were modeled and the associated system temperatures determined throughout the orbit. The temperature of the emitter of the system was then used to predict the power output of the thermophotovoltaic cells. The proposed system would be an alternative to systems currently in use which employ solar panel arrays and batteries.

At the core of the proposed system is a phase-change material. While a sensible-heat storage system would be less expensive and simpler than one using latent heat, the larger storage capacity, constant temperature performance, and higher storage efficiency [13] of the latent system were desirable. Silicon was chosen for its thermal properties and phase-transition temperature. The thermophysical, kinetic, and chemical properties essential for a successful thermal-energy storage design are summarized in

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[19]. Key properties identified by the authors include large latent heat, good thermal conductivity, high density, small volume changes, and stability. Current state-of-the-art phase-change materials meeting these requirements include paraffin wax and salt hydrates. The energy density and thermal conductivity of silicon are an order of magnitude larger than either the wax or salt [4,11]. Additionally, silicon has a much higher phase-transition temperature, which proves significant when trying to convert the thermal energy of the phase-change material to electricity using thermophotovoltaic cells. The bandgaps of GaSb and GaInAsSb thermophotovoltaic cells operating at 323 K are 0.802 eV [10] and 0.55 eV [20] respectively. The emitter temperatures that result from the silicon phase change process produce photons with energy equal to or greater than these bandgaps. Wu et al. [23] predicted the power density of GaSb cells as a function of emitter temperatures. For temperatures between 1000 K and 1800 K, GaSb TPV performance was better at the higher end of the range. While the thermal properties and melt temperature of silicon make it an excellent choice for this system, it is by no means a perfect choice. A 7.5% change in silicon volume with phase change is expected [9] and therefore voids are anticipated. The presence of a void has been shown to decrease the utility and the thermal-storage ability of the phase change material (PCM) [22] and was therefore included in this study.

In the proposed, power-system design, the silicon phase-change material is housed in a silicon- carbide container. The container top acts as an emitter for thermophotovoltaics located above it. Predicting the emitter temperatures requires the phase-change process and associated heat transfer be modeled. Verma and Varun [21] reviewed the first and second law mathematical models of phase change commonly used. The fifteen different first law models presented looked at an assortment of geometries and phase-change materials and made a variety of different simplifying assumptions. In general, for all the studies, either the energy conservation or the enthalpy method was used, and both methods were shown to match experimental results well. The enthalpy method is a fixed grid technique that may experience temperature oscillations while predicting the temperature history of the device. To avoid this issue, Cao and Faghri [1] proposed a modified temperature transforming method (TTM). The TTM uses the enthalpy-based energy equation and adjusts the thermodynamic properties of the material to simulate phase change. This model was shown to be accurate, simple, and efficient by Dutil [7]. The current study employs the TTM method. The phase-change process along with the associated heat transfer is modeled in COMSOL Multiphysics, a finite element multiphysics simulation platform. A variety of different studies using this modeling package have employed the TTM to successfully incorporate the effects of phase change. For example, Ogoh and Groulx [15] presented two different studies, a one-dimensional model (2010) and a cylindrical finned (2009) [12] model, where the phase change process was modeled in COMSOL using the TTM. Their results compared well to an analytical evaluation of the problem.

Chubb et al. [4] used a steady-state, one-dimensional model to predict the performance of a solar-thermophotovoltaic system using latent-heat energy storage. Emitter temperatures as well as component and total efficiencies were predicted for different silicon phase-change material geometries. Datas et al. [6] used a one-dimensional model of a storage integrated solar thermophotovoltaic (SISTPV) system using silicon as the phase-change material. Achieving large system efficiencies and energy-storage densities concurrently was shown to require system operation at the highest possible concentration ratio while maintaining a PCM temperature as close as possible to the melt point of silicon. Unlike the three-dimensional, transient study that is the subject of this paper, both these evaluations were one-dimensional and steady state. Additionally, the previous studies assumed thermal losses from the system to be negligible or very small while this study includes these losses. Finally, those investigations were terrestrial based while this work is for low earth orbit.

3. Model

Fig. 1 provides a basic overview of the cylindrical power system that was modeled computationally. At the center of the system was a phase-change material of silicon housed in a silicon- carbide inner container. The inner container was separated from high temperature insulation by a vacuum gap. In the remaining area between the inner container and the insulation were three tantalum radiation shields. The top of the inner container, delineated with a dashed line, acted as an emitter for the thermophotovoltaic cells located directly above it, marked with a dot-dashed line. An insulation standoff connected the lid of the inner container to the high-temperature insulation above it.

In this system, concentrated solar energy was focused on the lid of the inner container, which coupled the solar radiation to the silicon storage material. As was just mentioned, the lid of the inner container also acted as an emitter for the thermophotovoltaic cells located above it. For this design to be truly functional, a solar concentrator and an aperture would be required for solar input. Obviously, this is a crucial component of the real design, but its exclusion does not affect the analysis and it was therefore neglected for simplicity. In the simulations it is assumed the solar energy irradiates the inner container top. It should be noted that the overall system design included a positional concentrator that was 80% efficient. Assuming 1367 W/m^2 available heat flux, a 4.6 m^2 concentrator was determined to be required.

A two-dimensional, axisymmetric computational model, generated in COMSOL Multiphysics 4.3, was used to model the power system heat transfer during both the sunlight and the eclipse phases of low earth orbit. Of particular interest were the phase-change process and the associated emitter temperature. The energy added to the system was in the form of concentrated solar irradiation. This irradiation was modeled as a constant power input of 5000 W applied to the inner container lid during the sunlight

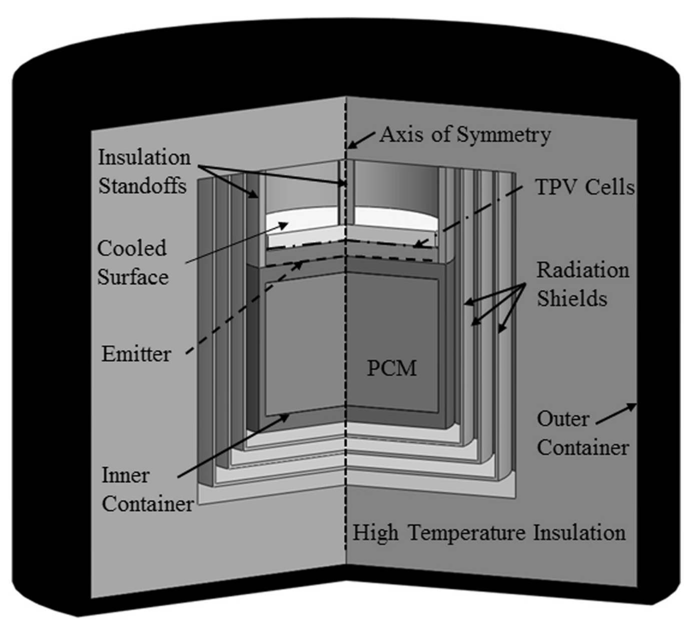

Fig. 1. Three-dimensional image of the system geometry with a wedge removed.