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The effect of the full-spectrum characteristics of nanostructure on the PV-TE hybrid system performances within multi-physics coupling process

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HIGHLIGHTS

- A multi-physics coupling mathematic model is developed for the PV-TE hybrid system.
- Full-spectrum characteristics of nanostructure is found and summed up.
- Output power of the PV-TE system is increased by optimizing heat transfer structure.
- Dynamic analysis on effect of the full-spectrum characteristics of nanostructure.

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ABSTRACT

Nanostructured surface is an important way to improve the efficiency of solar energy by absorbing more solar irradiance. However, due the bandgap of semiconductor material, more absorbed irradiance results in more waste heat. As for photovoltaic-thermoelectric (PV-TE) hybrid system, more waste heat reduces the efficiency of PV module due to the increased temperature, but is beneficial for TE module. There are complex and coupling physical processes (near-field optics, photovoltaic conversion, thermoelectric effects, and heat transfer) in the PV-TE hybrid system. Therefore, a multi-physics coupling mathematic model is developed for investigating the effect of full-spectrum characteristics of nanostructure on the PV-TE hybrid system performances. At first, the full-spectrum characteristics of nanostructure is found and summed up. As an example, the II set of the cone nanostructures have two cone nanostructure (II-1 cone nanostructure and II-2 cone nanostructure) with different dimensions. They have the same average reflectance of the wavelength range from 0.35 µm to 1.1 µm (0.05), however the average reflectance of the wavelength range from 1.1 µm to 2.5 µm ($R_{a,1.1\text{-}2.5}$) of the II-1 cone nanostructure is 74.8% lower than that of the II-2 cone nanostructure, which results in that the output power density of the PV-TE hybrid system with the II-2 cone nanostructure being 8.4 W/m^2 more than that with the II-1 cone nanostructure when the concentration ratio is 10. Thus, the cone nanostructures with as high $R_{a,1.1\text{-}2.5}$ as possible are more beneficial for the hybrid system. Then, by optimizing the heat transfer structure of the PV-TE hybrid system, the output power density is increased by 9.1%. At last, through dynamic analysis, it is found that the annual power generation per square meter of the PV-TE hybrid system with II-2 cone nanostructure is about 17 kW·h/m^2 greater than that with the II-1 cone nanostructure. As a result, combined with the structural analysis of the cone nanostructure, the bottom diameter should be as short as possible for the cone nanostructure.

1. Introduction

Increasingly serious environmental problems have led to more and more attention in renewable energy research [1–6]. Due to low cost, easy installation, and high photoelectric conversion efficiency, the photovoltaic (PV) device is considered to be the technology with great development potential in solar energy utilization. However, the bandgap of the semiconductor causes the PV device to not utilize the full-spectrum solar energy. In response to this problem, a tandem photovoltaic-thermoelectric (PV-TE) system is proposed.

In the tandem PV-TE hybrid system, the TE module is attached to the backside of the PV module. In this case, the TE module can not only utilize the dissipated heat from the PV module to generate electricity, but also can be used as a photovoltaic cooling system to improve the PV module's efficiency. Therefore, the PV-TE hybrid system is receiving more and more attention in the study of full-spectrum solar energy

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utilization. For example, Wang et al. [7] proposed a novel PV-TE hybrid device that is composed of a sensitized solar cell, a solar selective absorber and a TE module. Zhou and He et al. [8] presented a MC-FDTD coupled method to analysis the absorbed irradiance distribution on the nanostructured front surface of PV-TE hybrid device. Li and Xuan [9] designed a novel PV-TE hybrid system that employs a phase change material to maintain the system operating at the ideal working temperature for obtaining higher efficiency. Kil and Choi et al. [10] demonstrated a highly-efficient concentrated PV-TE hybrid system, whose conversion efficiency is large than the single CPV system by 3% at the concentration ratio of 50. Rezania and Rosendahl [11] established a thermally coupled model of the PV-TE hybrid system to analyze feasibility of the hybrid system over wide range of concentration ratio and effects of different types of heat sinks.

Moreover, nanostructured surface has become an important way to improve the efficiency of solar energy utilization. Nanostructure not only has excellent antireflection for a wide range of wavelengths, but also can reduce the manufacturing costs because it is not necessary to deposit the antireflection layer on the front surface of PV device. Thus, there is a lot of studies about nanostructure. For example, Gaucher and Collin [12] designed an ultrathin c-Si solar cell with a front texturation based on an inverted nanopyramid array, which makes the absorption reach 80% at short wavelength, and the short-circuit current density be 35.3 mA/cm^2. Kuang and Lin et al. [13] demonstrated experimentally a teepee-like photonic crystal structure on c-Si, whose average reflectance is only 0.7% for $\lambda = 400–1000$ nm. Ortega et al. [14] demonstrated a high-efficiency interdigitated back contacted solar cell with the reflectance below 0.7% in the 300–1000 nm wavelength range, and the outstanding photovoltaic efficiencies over 22% have been achieved both in p-type and n-type 9 cm^2 cells. Savin et al. [15] demonstrated that efficiencies above 22% can be reached in thick black silicon solar cells with interdigitated back-contacts, where the reflectance is less than 1% between 300 and 1000 nm. Proust and Bonod [16] optimized the square pillars to make its average reflectance remain under 5% in the visible spectrum for both polarizations in a wide angular range.

As the above described studies, most studies have focused on the nanostructure with as low reflectance as possible in order to enhance the absorption of solar irradiance for improving the PV efficiency. However, there is a serious deficiency. For example, the bandgap of silicon is 1.11 eV, and the corresponding wavelength is 1.1 μm. Thus, the wavelength ranges of 0.35–1.1 μm that can be utilized by the PV module become a major concern, and the effect of the wavelength ranges from 1.1 μm to 2.5 μm is overlooked. The solar irradiance of the wavelength ranges from 1.1 μm to 2.5 μm is converted into heat to increase the temperature, which reduces the output power of the PV module. Nevertheless, in the PV-TE hybrid system, the higher temperature is beneficial for the TE module. Therefore, it is very important to investigate the full-spectrum characteristics of nanostructure, and its effect on the PV-TE hybrid system performances.

In addition, coupling multi-physics problem is involved in this study. There are already some studies on multi-physics in PV module or the hybrid system. For example, Teo and Hawlader et al. [17] developed a heat transfer simulation model of PV/T hybrid system, and achieved the good agreement between the simulation and experimental results. Sohel et al. [18] presented a dynamic model of the air-based PV/T system for simulating real operating conditions. Oruc and Kenis [19] proposed a new photovoltaic thermal water electrolyzer, and perform the comprehensive energy analysis. Su and Fang et al. [20] presented the performance of PV/T solar collector with dual channels for different fluids, and analyzed the electrical and thermal characteristics.

In the above studies of multi-physics, the main concern was the coupling of electricity and heat. In the meantime, the relationship between the efficiency and temperature of the PV module is often described by a linear empirical equation, and the concentration ratio is used as a coefficient of the equation. In this case, there are three deficiencies: (1) the full-spectrum characteristics of nanostructure is ignored; (2) the relationship between the efficiency and the temperature is assumed to be linear; (3) the effect of the series resistance on the PV module performances is ignored as the concentration ratio increases.

In this study, a low concentrated PV-TE hybrid system model is built, which employs an all-back-contact silicon photovoltaic device with nanostructured front surface, a thermoelectric device, and a plane fins heat sink. A multi-physics coupling mathematic model is developed for dealing with the coupling physical processes in PV-TE hybrid system, which include the propagation of solar electromagnetic radiation on the nanostructured surface, the photovoltaic conversion in PV module, thermoelectric effect in TE module, and the heat transfer throughout the PV-TE hybrid system. At first, the full-spectrum characteristics of nanostructure is proposed. Based on the coupling mathematic model, the effect of the full-spectrum characteristics of nanostructure on the PV-TE hybrid system performances is investigated under the ideal conditions. Then, the heat transfer structure of the PV-TE hybrid system is optimized. At last, the dynamic analysis on the effect of the full-spectrum characteristics of nanostructure is performed.

2. Description of the PV-TE hybrid system

In this study, as shown in Fig. 1, the PV-TE hybrid system is tandem, which mainly includes a concentrator, a PV module, a TE module, and a heat sink. The hot side of the TE module is attached to the bottom of the PV module to utilize the heat dissipation from it, and the heat sink is placed underneath the TE module for cooling the cold side of TE module.

The PV module is an all-back-contact N-type silicon solar cell with nanostructured front surface, and Fig. 2 shows its schematic illustration. The cover glass is assumed to be with ideal transmittance. The n++ phosphorus high-doped, n+ phosphorus low-doped, and p+ boron low-doped are 7.010^{19} cm^{-3}, 1.010^{19} cm^{-3}, and 1.010^{19} cm^{-3} respectively. In addition, the cone nanostructures are chosen to be periodically distributed on 2.2 Ω cm N-type crystal silicon substrate because of its widely application. Their dimensions are determined by the bottom diameter *D*, the height *H*, and the spacing *S* between two adjacent cone nanostructures.

Moreover, as shown in Fig. 1, the TE module mainly consists of the hot side ceramic plate, the hot side electrode, the 127 pairs of thermoelectric legs, the cold side electrode, and the cold side ceramic plate. The heat sink is an aluminum plane fin heat sink. The parameters associated with the simulation are stated in Table 1, and include the PV-TE hybrid system geometry and the related material properties.

3. Multi-physical field coupling mathematic model

During the operation of the PV-TE hybrid system, there are complex physical processes, which are the propagation of solar electromagnetic radiation on the nanostructured front surface, photovoltaic conversion in PV module, thermoelectric effect (Seebeck effect, Peltier effect, and Thomson effect) in TE module, and the heat transfer throughout the hybrid system. Moreover, they are coupled to each other. Therefore, a multi-physical field coupling mathematic model is developed in this study, and described in details in the following.

3.1. Near-flied optics

Finite Difference Time Domain (FDTD) is used to deal with the interaction between the sun light and the nanostructured surface of the PV module in the hybrid system. As presented in Fig. 2, the cone nanostructures are periodically distributed on the PV surface, thus the periodic boundary conditions can be used to truncate a periodic unit for simulation. In the meantime, the periodic computational domain is truncated by two convolutional perfect matched layers at top and