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Proposal and assessment of a solar thermoelectric generation system characterized by Fresnel lens, cavity receiver and heat pipe

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ABSTRACT

A solar thermoelectric generation system characterized by Fresnel lens, cavity receiver and heat pipe, i.e., FCH-STGS, was proposed. To analyze the performance of FCH-STGS accurately, a comprehensive theoretical model was built, where a finite element method was employed to consider the Thomson effect and temperature-dependence of thermoelectric materials. With this model, the influences of emissivity of ceramic plate and environment factors such as solar irradiation, optical concentration ratio, wind speed, wind incident angle, system tilt angle and ambient temperature were discussed. Results show that the FCH-STGS has the potential to reach the output power and efficiency of 45.73 W and 3.289%. Both output power and efficiency of FCH-STGS can be improved by decreasing the emissivity of ceramic plate or ambient temperature, or increasing the total solar irradiation (product of solar irradiation and optical concentration ratio). However, the efficiency reduces slightly when the total solar irradiation exceeds a certain value. As the wind speed increases, both output power and efficiency rise firstly and then fall. Due to the high thermal efficiency of cavity (exceeding 85%), the effects of wind incident angle and system tilt angle are approximately negligible. Compared with the previous STGSs, the FCH-STGS is excellent in the perspectives of performance, economy and practicability.

1. Introduction

Environmental pollution and energy crisis are two of severe challenges for human survival and social development [1]. Considering solar energy sharing advantages of abundant, accessible and environmentally friendly, how to utilize it efficiently may become the key to cope with these challenges. Thermoelectric generator, which converts thermal energy into electrical energy directly with no moving parts, high-reliability, compactness, environmental friendliness and light weight [2–5], has received much attention in the fields of solar energy utilization. Solar thermoelectric generation system (STGS) refers to a kind of system that harnesses the sun to fuel thermoelectric generator. Solar absorber, thermoelectric module (TM) and heat radiator are the main components of STGS. In a concentrated STGS, an optical concentrator is also included. Obviously, the performance of STGS is determined jointly by the above mentioned four components.

The first recorded STGS with black absorber surface was patented by Weston [6,7] in 1888. The first experiment on STGS was conducted by Coblentz [8] in 1913. However, the experimental efficiency of STGS was not reported until 1954 by Telkes [9]. For the STGS with optical concentration ratios of 0 and 50, 0.6% and 3.35% efficiency were measured respectively [9]. After that, a number of studies [10–14] on STGS were carried out, but the efficiency did not exceed that of Telkes [9]. This situation was changed by Kraemer et al. [15] in 2011. Kraemer et al. [15] pointed out that with optical concentration ratios of 0 and 1.5, the efficiencies of STGS were 4.6% and 5.2% respectively. The use of high performance nanostructured material to enhance the performance of TM, selective solar absorber to maximize the ratio of absorption and re-radiation, as well as evacuated enclosure to suppress convective heat loss were the main measures responsible for efficiency improvement. Hence, these measures, especially the latter two, were employed widely in subsequent studies. STGSs with trough collector and solar vacuum tube were experimented by Lesage's team [16–18] and Özdemir et al. [19]. The efficiencies were 1.32–1.53% [18] and 0.46% [19], and the output power was less than 1 W [16–19]. Pereira et al. [20]

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experimentally studied a STGS working at high optical concentration ratio and high temperature, where the selective solar absorber and evacuated enclosure were used. The maximum efficiency and output power were about 1.6% and 0.48 W. The performance of STGS with selective solar absorber was researched by Candadai et al. [21]. The experimentally obtained maximum efficiency and output power were 1.25% and 0.67 W. The effect of vacuum enclosure pressure on the performance of STGS was conducted by Sudharshan et al. [22]. The lower the vacuum enclosure pressure was, the higher the efficiency and output power were.

To reduce the research cost and accelerate the research progress, numerical simulation and theoretical analysis were also performed. He et al. [23] theoretically analyzed the effects of various parameters. The maximum efficiency of STGS increased with increasing solar irradiation and it was 3.346% under the solar irradiation of 1000 W/m^2. Through theoretical calculation, Chen [24] and Kraemer et al. [25] proved that the efficiency of STGS with selective solar absorber under evacuated enclosure can exceed 5%. Taking the same type STGS as an object, Chen et al. [26] numerically studied the influence of thermal concentration ratio and found its effect was related to the geometrical parameters of thermoelectric couple. The output power of STGS was less than 0.5 W, and the maximum efficiency was 4.15%. Using numerical method, the impact of concentration type (optical and thermal) on the performance of STGS was analyzed by Kossyvakis et al. [27]. On the basis of energy and exergy analysis, a STGS with annular TM was theoretically studied by Manikandan et al. [28]. The maximum output power and efficiency were 1.92 W and 2.63%.

Apart from the use of high performance thermoelectric materials, selective solar absorber and evacuated enclosure, another measure, i.e., segmented or cascaded TM with different materials was proposed. Considering the four measures above, Kraemer et al. [29] experimentally demonstrated a peak efficiency of 7.4% for a segmented STGS under an optically concentrated normal solar irradiance of 211 kW/m^2. Besides, theoretical studies on segmented and cascaded STGSs were carried out by McEnaney et al. [30] and Baranowski et al. [31]. The results of Ref. [30] showed that both segmented and cascaded STGSs can have efficiencies exceeding 10% with existing materials. While Ref. [31] pointed out that with current materials, the efficiency of segmented STGS ran up to 15.9%. To experimentally demonstrate the potential of a segmented STGS with efficiency of 15%, a project has been undertaken and some preliminary results have been given in Olsen et al. [32]. Xiao et al. [33] numerically investigated a segmented STGS. The performance of STGS was enhanced with an increase in optical concentration ratio and number of segments.

The stability of selective absorber is lower in air in comparison with that in vacuum [34]. In addition, the cost of selective absorber is high. Therefore, alternative measures should be found out in order to reduce the cost and promote the commercialization of STGS. Cavity receivers, which absorb solar radiation effectively and experience lower heat loss than external receivers such as flat-plate receiver [35], have been employed extensively. STGSs with cavity receiver as solar absorber were studied by some researchers. Experiments on STGSs with cavity receiver were performed by Tomeš et al. [36] and Suter et al. [37]. Compared with the flat-plate receiver, the cavity receiver reduced the radiative heat loss from 60% to 4% [37]. Experiments showed that the efficiency of STGS was 0.13% under an optical concentration ratio of 620 [37], and the output power was 1.42 W under an optical concentration ratio of 998 [36]. Low figure merit of materials was the main reason responsible for the low efficiency. A theoretical study conducted by Baranowski et al. [38] showed that above 85% thermal efficiency can be achieved for a thermally insulating cavity, and 15% efficiency of STGS can be realized. Ohara et al. [39] performed field tests on a cavity receiver based STGS, which can produce electricity and thermal energy simultaneously. Test results demonstrated 0.59% electrical efficiency and 32% overall efficiency.

In a STGS, especially in an optical concentrated STGS, solar irradiance on the solar absorber and then temperature on the hot side of TM are non-evenly distributed. Both Admasu et al. [40] and Montecucco et al. [41] suggested that compared with the uniform temperature distribution, the output power of TM decreased significantly for the non-uniform one. To solve this problem, two methods were put forward. The one was inserting the heat spreader with high thermal conductivity between solar absorber and TM. Jang et al. [42] discussed the effect of heat spreader. The performance of TM was improved by increasing heat spreader thickness. However, the effectiveness of this method was very limited, since the performance of TM could deteriorate as long as the heat spreader owned excessive thickness [42]. On account of that heat pipe shared the benefit of high thermal conductivity and could keep temperature uniform and constant [43], adopting it was the other method. STGSs with heat pipe as heat transfer medium were studied by Refs. [19,23,28,44,45].

The choice of optical concentrator is crucial for a concentrated STGS, because the cost, mass, concentration ratio and so on should be considered at the same time. The present optical concentrator mainly includes parabolic trough [16–19], parabolic dish [12,39] and Fresnel lens [20,21,27,45]. Among them, the former two were widely used in solar thermal power plants. The latter one, Fresnel lens, featured in light weight, low cost, simple fabrication and good optical properties, has received ever-increasing attention recently [46,47].

In this paper, combining the merits of Fresnel lens, cavity receiver, heat pipe and TM, a novel STGS, i.e., FCH-STGS, is proposed. This system can be used as a stand-alone power source to provide reliable power for zones without electricity supply such as rural areas in developing countries. The organization of this paper is as follows. Section 2 describes the main structure and principle of FCH-STGS. A theoretical model analyzing the performance of FCH-STGS is constructed in Section 3. In this model, not only Peltier effect, Joule effect, Fourier heat conduction, Thomson effect and temperature-dependence of thermoelectric materials are incorporated, but also the heat transfer between two sides of TM without covering thermoelectric couple, i.e., the heat transfer in the air gap of TM, is taken into account. Section 4 presents and discusses the effects of various factors (emissivity of ceramic plate of TM and environmental factors). Also the performance comparisons with previous STGSs are carried out in order to highlight the characteristics or advantages of FCH-STGS. Main conclusions of this study are summarized in Section 5.

2. FCH-STGS

2.1. Schematic view of FCH-STGS

The schematic diagram of FCH-STGS is shown in Fig. 1. The dish-shaped Fresnel lens (1#) and cylindrical cavity are employed as optical concentrator and solar absorber respectively. According to the geometrical features of cavity, the flat-plate thermoelectric generation module (FTGM, 8#) and the annular thermoelectric generation module (ATGM, 7#) are arranged on the outer bottom and side walls of cylindrical cavity (4#) respectively. The FTGM (8#) or ATGM (7#) is composed of a number of flat-plate thermoelectric couples (FTCs) or annular thermoelectric couples (ATCs) thermally in parallel and electrically in series. To solve the harmful effect caused by non-uniform solar irradiation, a heat pipe is designed between the inner and outer walls of cylindrical cavity (3#, 4#). Heat pipe, inner and outer walls of cylindrical cavity (3#, 4#)