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Theoretical and experimental analysis of a solar thermoelectric power generation device based on gravity-assisted heat pipes and solar irradiation

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ABSTRACT

Solar thermoelectric power generation has been widely used to solve the power supply limitation issue for low-power wireless sensors because of its light weight, high reliability, low cost, lack of noise, and environmental friendliness. A solar thermoelectric power generation system based on gravity-assisted heat pipes and solar radiation is devised in this paper, and its behavior is continuously measured in realistic outdoor circumstances. The effects of key parameters, including solar luminous flux, load resistance, a proportional coefficient, and a relative Seebeck coefficient, are analyzed. Related experimental results show that the device can output a voltage of 1057 mV and an electrical current of 343 mA, resulting in an output power of 362.56 mW. With a stable external energy conversion module under aluminous flux of 7.81×10^4 lx, the voltage converted from the nature solar radiation is boosted from 1057 mV to 4.40 V, which meets the rated operating voltage of low power consumption components, such as low-power wireless sensors and ZigBee modules. An economic analysis of the system shows that the solar thermoelectric power generation device is both economically and technically competitive when it is applied in a low-voltage wireless sensor network.

1. Introduction

Widely known as a clean, low cost, and quiet energy conversion strategy with no moving parts, thermoelectric power generation (TEG) and the capabilities and efficiencies of TEG systems have received wide attention due to their flexibility, economics and high stability, especially in fields such as solar energy conversion, thermal figure-of-merit study, and exhaust heat energy conversion. Selvan and Ali [1] indicated that the advantages of TEG devices are ecologically safe, cost effective and smaller dimensions. Candadai et al. [2] pointed out that using solar thermoelectric device comprised of solar absorbers, solar energy can be directly harnessed for power generation. Aswal et al. [3] demonstrated that an efficient TEG device requires the availability of thermoelectric materials with high figure-of-merit and management of maximum heat transfer. Zhang realized the performance measurement of a thermoelectric power generation (TEG) device designed to convert engine exhaust heat directly into electricity under different operating conditions [4,5]. As a prevalent energy conversion method, TEG technology provides an effective renewable solution for thermoelectric energy conversion and management both in outer space, e.g., hybrid PV/TEG outer space systems, and on Earth through Bi_2Te_3-based modules and concentrated photovoltaic-thermoelectric systems. Kwan and Wu [6] presented a study of the dynamics and the operation of the hybrid PV/TEG system in an outer space environment. Zhang et al. [7] focused on the optimization of Bi_2Te_3-electrode joints and fabrication of Bi_2Te_3-based TEG device. Lamba and Kaushik analyzed performance of a concentrated photo voltaic–thermoelectric generator hybrid system [8]. A famous application example of TEG in outer space is the radioisotope thermoelectric generator presented by Woerner [9], which has been applied in widespread fields ranging from satellites to space probes. In addition, following the principles of Peltier cooling and the Seebeck effect, thermoelectric power generation devices designed for cooling or heating were extensively studied by Yilmazoglu for prototype performance analysis [10]. And studies of stove-based thermoelectric generators used for collecting wasted biomass stoves energy were carried out by Gao et al. [11].

However, the popularity of TEG technology has been largely constrained by its low power output problem, which is mainly caused by losing energy to the surroundings and the material

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characteristics of conventional bismuth telluride. Singh et al. [12] stated that the heat energy lost to the surroundings from thermal processes is considerable. Brito et al. [13] proved that the application of TEG device is limited due to the low efficiency of its materials such as bismuth telluride. To mitigate this limitation, the structural optimization of TEG devices has been widely studied. Examining the geometric structure of TEGs, Zhang et al. [14] showed that by matching and optimizing the heat exchanger and thermoelectric power generation module (TEM) array, a stable maximum output power can be obtained from the interior of the thermoelectric generator system, which can be connected to an external maximum power point tracking system. Liang et al. [15] studied the performance of parallel TEGs through theoretical analysis and experimental testing; they demonstrated that the thermal contact resistance decreases the output power by decreasing the temperature difference between the two sides of the thermocouples. Wang et al. [16] investigated the performance of a TEG combined with an air-cooling system designed using two-stage optimization and suggested that the TEG power density can be further improved by scaling down the TEG when the heat sink length is shorter than14.5 mm. Rezania and Rosendahl [17] applied a parallel heat sink to a TEG device and obtained an optimum pumping power by considering the maximum temperature limitation for Bi_2Te_3material and using the heat sink to cool the TEG system. In addition, Rezania et al. [18] focused on applying a micro plate-fin heat exchanger to a TEG to maximize the output power and the cost performance of generic TEG systems; they illustrated that there is a unique pumping power for a fixed fin and ceramic substrate thickness that minimizes the cost performance of TEG systems. Moreover, Rezania et al. [19] compared a micro-structure plate-fin heat sink to a modified design of a cross-cut heat sink applied to a TEG device over a range of temperatures and thermal conductivities; they showed that the net power output of a TEG device can be significantly improved by optimal heat sink design.

In addition, various new features have been added to traditional TEG devices to achieve better output. Wang et al. [20] added a solar selective absorber (SSA) and a series-connected dye-sensitized solar cell (DSSC) to a TEG device to use the energy surrounding the TEG device more efficiently. As a result, a novel photovoltaic-thermoelectric (PV-TE) hybrid device was created. Yang and Yin [21] utilized solar materials, hot water through a multilayered building envelope and thermoelectric modules to construct a hybrid TEG system that is superior to traditional TEG systems. Jaworski et al. [22] used a phase change material (PCM) module as the cooling/heating media in a TEG device; this PCM module absorbs heat as it melts, thus stabilizing the TEG cool side temperature. Weng and Huang [23] investigated an energy-harvesting system that extracts heat from an automotive exhaust pipe and turns the heat into electricity using TEG. The influences of the number of heat exchangers and the heat exchanger coverage rate on the TEG device were explored through simulations. Deng et al. [24] successfully fabricated an integrated design consisting of a silicon thin-film solar cell (STC), a heat collector and TEGs; they showed that the TEG and STC performance are both improved by the integrated design.

According to the researched mentioned above, the physical structure and energy transfer media significantly affect the TEG output, which greatly interested our team and moved our research towards this aspect. This study proposes a TEG structure optimization method of adding a solar energy collector and a series of gravity-assisted heat pipe components to a TEG device. In this method, during the whole energy transfer and conversion process, the energy transfer is circulated within the heat transfer components of the TEG device, significantly reducing the energy loss between the TEG device and the outside environment. Similar research has been proposed by Armijo and Carey [25] with PV solar cells; they achieved a high heat flux of 114.8 W/cm^2. Moreover, Riffat et al. [26] applied heat pipes and PCMs to TEG modules, showing the importance of using a heat pipe system to prevent reverse heat flow in the event of a power failure. Lee et al. [27] employed two two-phase loop thermosyphons in an experimental and analytical study on a TEG system and presented high heat transfer rates for the system. Filippeschi et al. [28] combined a highly compact periodic two-phase thermosyphon (PTPT) cooling device with a TEG cooler to allow wide flexibility in the TEG system design.

The core heat transfer component in this paper is a gravity-assisted heat pipe, which is still the most commonly used high thermal conductivity energy transfer mechanism in both cooling and heating energy transfer and conversion systems. As an efficient solution for waste energy during the energy transfer period, gravity-assisted heat pipe takes full advantage of the waste energy, which is critical in low-efficiency energy generating systems, especially TEG systems designed for cooling or heating.

The optimized TEG device works as follows: As shown in Fig. 1, solar radiation is collected by an all-glass heat-tube-type vacuum solar heat collection pipe from the natural environment and is then transferred as a heat source to the hot surface of the TEG module through a series of heat transfer components such as an aluminum flake, a heat conduction block and a gravity-assisted heat pipe. As a result, a high temperature difference is achieved between the hot surface and the cold surface of the TEG module, causing the TEG device to produce and output electricity and providing a power supply for an external electric appliance. During this process, when the energy is transferred through the gravity-assisted heat pipe, the transformation media inside the pipe changes state from a liquid to a vapor in the evaporator and from a vapor to a liquid in the condenser, making the continuous stable working conditions of the TEG device possible.

According to the references mentioned above, in order to exert the maximum extent of thermoelectric energy conversion output power in the realistic environment, the solution to the problem of low output power thermoelectric energy conversion still needs further research. Motivated by the constraint of the low power output from the thermoelectric energy conversion process mentioned above, this study aims to solve this problem by building a physical structure and an optimized energy transfer media TEG experimental set-up considering both the physical model for the thermoelectric energy conversion process and unique practical applications. The detailed aim is to achieve a power output of hundreds of Watts with only one TEG module in realistic outdoor conditions; such an output has seldom been realized in energy conversion fields and other related interdisciplinary studies because of the large amount of energy wasted during the energy conversion process and the low energy conversion efficiency of TEG materials. Compared to the previous work of [29] and similar energy studies, new features are included in this optimized TEG device. For instance, the unique structure of the proposed TEG device was designed to contain a new energy transfer strategy using an aluminum flake, a heat conduction block and a gravity-assisted heat pipe, which improves the heat transfer and decreases the energy lost in the energy transfer process. To fully use the energy collected by the TEG device, as shown in Fig. 1, the aluminum flake attaches perfectly onto the inner surface of the solar collector and the outer surface of the gravity-assisted heat pipe; similarly, the heat conduction block and the gravity-assisted heat pipe fit closely together through the cylindrical surface. Moreover, unlike similar studies that use the photovoltaic-thermoelectric (PV-TE) method or other hybrid means to obtain a larger energy output result, this study concentrates on efficient energy acquisition by minimizing energy loss within a single TEG structure. The output parameters of the device presented in this paper clearly show the potential of a simple TEG