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Behavior of a thermoelectric power generation device based on solar irradiation and the earth's surface-air temperature difference

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ABSTRACT

Motivated by the limited power supply of wireless sensors used to monitor the natural environment, for example, in forests, this study presents a technical solution by recycling solar irradiation heat using thermoelectric generators. Based on solar irradiation and the earth's surface-air temperature difference, a new type of thermoelectric power generation device has been devised, the distinguishing features of which include the application of an all-glass heat-tube-type vacuum solar heat collection pipe to absorb and transfer solar energy without a water medium and the use of a thin heat dissipation tube to cool the earth surface air temperature. The effects of key parameters such as solar illumination, air temperature, load resistance, the proportional coefficient, output power and power generation efficiency for thermoelectric energy conversion are analyzed. The results of realistic outdoor experiments show that under a state of regular illumination at 3.75×10^4 lx, using one TEG module, the thermoelectric device is able to boost the voltage obtained from the natural solar irradiation from 221 mV to 4.41 V, with an output power of 4.7 mW. This means that the electrical energy generated can provide the power supply for low power consumption components, such as low power wireless sensors, ZigBee modules and other low power loads.

1. Introduction

In the last two decades, with the increasing scarcity of fossil fuels worldwide, energy transmission and the conversion of thermodynamic materials and energy sources have been extensively studied [1,2], which has led to centralized research on the thermoelectric phenomenon in the fields of renewable and green energy application [3–6]. Thermoelectric studies mainly focus on three aspects: the nanostructure of thermoelectric materials, the conversion and recycling of waste heat [7,8] and thermoelectric utilization based on environmental energy [9–11].

As a key measurement to improve the energy conversion efficiency of thermoelectric modules, nanostructure research on thermoelectric materials started with the birth of thermoelectrics, the aim of which is to increase the Seebeck coefficient and electrical conductivity [3]. With the relative maturity of thermoelectric material technology, heat waste is a widespread concern, motivating the rapid advancement of waste heat conversion and recycling technologies. These thermoelectric generators produce electricity from a heat absorption generator [7,8] that is powered by either the residual heat of fossil fuels or radioactive isotopes [12]. Due to energy shortages, the cost of power resources has soared rapidly, promoting research concentrated on the thermoelectric utilization of environmental energy [5,13]. As a result, the low cost, rich reserve and convenient acquisition of this energy source have driven the rapid technological development of thermoelectric power generation devices powered by environmental energy sources [5,14,15].

As indicated by the information above, the application fields for thermoelectric power generators are mainly restricted to places where waste heat produced by fossil fuels or radioactive isotopes exists. However, with the development of wireless sensor technology, large-scale electrical components of miniature sensor networks are applied in complex conditions, especially in harsh environments with no electricity supply [9–11]. Consequently, a power supply problem for the components of miniature sensor networks has emerged. In this paper, the extension of the application area of thermoelectric generators is achieved, making it possible to supply energy to components and miniature sensor networks in remote, hard to reach natural areas with no electricity supply. The device structure is unique, and the data are acquired using a realistic outdoor experimental measurement, which has thus far seldom been investigated. In this study, the parametric measurement method of the TEG device is considered in

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conjunction with realistic conditions of no electricity and with solar irradiation dependent properties of endothermic materials. The maximum output power generation, maximum thermoelectric voltage and optimal power efficiency in the thermoelectric generator are explored at the matched load condition and over a wide range of temperature differences, while the temperature differences vary with unstable weather conditions. Moreover, different values of the load resistance are imposed on the external energy conversion module of the device to consider the effects of varying load conditions on the results of the study. The thermoelectric characteristics of TEG are implemented in a natural environment and are solved by using an anemometer and illumination measuring instrument. The results of this study are generated based on the optimum temperature difference produced at both ends of the thermoelectric module that provides the maximum power for the constant load conditions, which provides a reference for future thermoelectric conversion research using the Seebeck effect to convert heat directly into electricity under harsh, remote circumstances with no electricity.

Based on the studies mentioned above, a thermoelectric power generation device powered by environmental energy is devised. The novel factors of the device include its particular structure, which is an indicator of the originality of the proposed apparatus, and its function in using the temperature difference between the solar energy collector module and the air to realize the electricity output for wireless sensor networks placed in environments with no electricity. After considering the physical models of thermoelectric generators and the specific application situations, the optimization of the device's internal structure and external energy conversion circuit has been realized, resulting in the achievement of a relatively high power efficiency [2,16–18]. By comparison with related thermoelectric studies, the distinguishing features of the device can be observed. First, the heat source of the device is solar energy, which is absorbed by an all-glass heat-tube-type vacuum solar heat collection pipe that has good solar irradiation transmission properties and thermal stability. Although similar types of solar energy heat sources have been widely discussed in research on solar installations, such as solar water heaters [15,19], there have been few realistic thermoelectric device applications capable of converting the thermal energy resulting from the absorption of solar energy directly into electricity. Second, the physical models of devices based on thermoelectric phenomena have been theoretically analyzed and experimentally tested, but only in stable situations within indoor laboratories or through ideal model simulations [20]. In the performance measurement experiments of the thermoelectric device, the main experiment components were tested in realistic outdoor conditions, which ensured the acquisition of a series of high quality data in real natural circumstances. Finally, in the design of the thermoelectric power generation device, a thin heat dissipation tube, which has not yet been applied in other similar devices, was chosen as a critical tool to decrease the temperature by cooling the earth surface-air, which is indispensable to the process of thermoelectric operation. As a particularly effective solution to the energy source problem of wireless sensor networks placed in situations with no electricity supply, this device was tested in a natural realistic outdoor environment, which provides convincing evidence for the feasibility of the device.

2. A theoretical model of a thermoelectric power generation device

A normal thermoelectric power generation device consists of a heat collector, heat transfer material, a thermoelectric module and a radiator, as shown in Fig. 1, where R_{load} is the load resistance

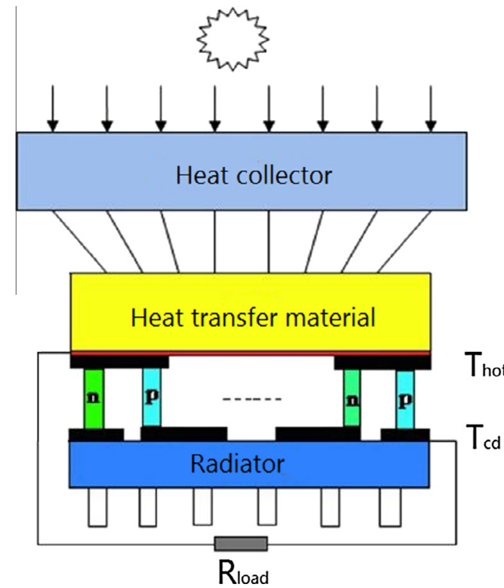

Fig. 1. A schematic diagram of a thermoelectric device.

and T_{hot} and T_{cd} are, respectively, the temperatures of the hot and cold sides of the thermoelectric module.

The thermoelectric effect occurs when a temperature difference exists between the two ends of a thermoelectric material, which causes the production of a thermal electromotive force and an electrical current. The Seebeck effect of thermoelectric materials describes the quantitative relationship between the thermal electromotive force and the temperature difference, resulting in the relation $\Delta V = \alpha\Delta T$. The Peltier effect describes the heat absorption or rejection that emerges from the intersection of two thermoelectric materials when an electrical current passes through them, with the direction (absorption or rejection) of heat decided by the electrical current direction. Thermoelectric effects have played an increasingly essential role in thermoelectric research, such as the Thomson effect, the Fourier effect, and the Joule effect. Among the above-mentioned TE effects, all are reversible except for the Joule effect, which is obviously not reversible.

Modern thermoelectric power generation devices are devised based on the Seebeck and Peltier effects. The basic unit of thermoelectric power generation is a thermoelectric couple consisting of one n-type semiconductor element and one p-type semiconductor element. When the temperature difference between the hot side and the cold side of the TE module varies, the thermal electromotive force produced by the TE module changes. Within a certain range, there is a linear relationship between the thermal electromotive force and the temperature difference between the hot and cold sides. The thermal electromotive force can be calculated as follows:

$$\Delta V = \alpha\Delta T \tag{1}$$

where ΔV, α and ΔT are, respectively, the difference in the thermal electromotive force, the relative Seebeck coefficient and the difference in temperature between the hot and cold sides of TE module. Therefore, the following relation is obtained:

$$\alpha = \frac{dV}{dT}, \tag{2}$$

showing that the Seebeck coefficient is determined by the thermal electromotive force and the difference in temperature. The most commonly used unit of the Seebeck coefficient is $\mu V/K$, and from Eq. (2), it is clear that the Seebeck coefficient can have