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Numerical simulations on the temperature gradient and thermal stress of a thermoelectric power generator

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ABSTRACT

Thermoelectric generator is a device taking advantage of the temperature difference in thermoelectric material to generate electric power, where the higher the temperature difference of the hot-cold ends, the higher the efficiency will be. However, higher temperature or higher heat flux upon the hot end will cause strong thermal stress which will negatively influence the lifecycle of the thermoelectric module. This phenomenon is very common in industrial applications but seldom has research work been reported. In this paper, numerical analysis on the thermodynamics and thermal stress performance of the thermoelectric module has been performed, considering the variation on the thickness of materials; the influence of high heat flux on thermal efficiency, power output, and thermal stress has been examined. It is found that under high heat flux imposing upon the hot end, the thermal stress is so strong that it has a decisive effect on the life expectation of the device. To improve the module's working condition, different geometrical configurations are tested and the optimum sizes are achieved. Besides, the side effects on the efficiency, power output, and open circuit voltage output of the thermoelectric module are taken into consideration.

1. Introduction

The thermoelectric phenomenon was first discovered as early as the 19th century. But further research on this phenomenon was not performed until the middle of the 20th when semiconductor materials with the Seebeck coefficient much higher than that of alloys were found. A basic unit of a thermoelectric power generator (TEG) is a thermocouple consisting of an n-type and a p-type thermoelectric element connected electrically in series by a conducting strip (usually copper). A typical thermoelectric device is constructed by these building-blocks connected electrically in series but thermally in parallel and sandwiched between two ceramic plates. The efficiency of the module highly depends on the temperature difference between the hot and cold end. Especially, as for the nearly 30 years, people have increasingly recognized un-sustainability and pollution of traditional energy sources, it makes much sense to have a better understanding of thermoelectric modules.

In the past three decades, the research work related to thermoelectrics has aroused much attention worldwide. The research group led by Sahin and Yilbas [1] investigated the influence of thermoelectric pin geometry on the module's efficiency and maximum power output. They showed that the pin geometry had obvious effect on the modules with various temperature difference applied on the two ends. The feasibility to use thermoelectric generators (TEG) to power a thermoelectric cooling device (TEC) was explored by Khattab and Shenawy [2]. They finally obtained a best match number of TEC and TEG and achieved the desired result using a solar thermoelectric generator to drive a small thermoelectric cooler in most times of the year. Thermodynamics and thermal stress analysis of a thermoelectric power generator with different pin geometry configurations was carried out by Merbati et al. [3] who managed to get the temperature and thermal stress field, and to test the thermal efficiency, maximum power output, and thermal stress in the modules. Their findings showed that the trapezoidal pins could alleviate thermal stress in the module and increase the efficiency at the same time. Rosado [14] gave a detailed description of a thermoelectric module. He especially advanced a mathematical method to estimate Thomson coefficient. A calculation model designed by Rodríguez et al. [4] was applied to examine the thermal and electrical properties of a thermoelectric module. Using the least boundary conditions, they managed to obtain a design method with better encapsulation characteristics. The research group led by O'Brien et al. [5] reviewed radioisotope

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thermoelectric systems (RTG) used in U.S. space missions and made comparisons between several radioisotope heat sources which were thought much easier to get than the traditional ones. They made a comprehensive analysis of the thermal characteristics and radiation barrier problems. The influence of dimensionless size and external load parameters on a thermoelectric module's efficiency was explored by Yilbas and Sahin [6] who showed that, when the ZT_{avg} value of the thermoelectric material was constant and the size parameters optimal, the module's maximum efficiency only depended on the temperatures on the hot and cold end. A two-stage solar concentrator designed by Omer and Infield [7] was applied to increase the temperature on a thermoelectric module's hot ends. The device improved the module's stability and efficiency by reducing its sensitivity to light angle as well as keeping the concentration ratio at 20. The two-stage structure not only enhanced the light-gathering efficiency but also confined the air convection intensity in the tube. A device integrating traditional rooftop solar isolation material and a thermoelectric power generator improved by Maneewan et al. [8] was applied to reduce indoor temperature in Thailand. Fans powered by thermoelectric module were used to cool the cold end of the thermoelectric module. The device reduced heat flux into the house and increased the efficiency of the thermoelectric module, which reversely affected the fan's total power and air convection intensity. An idea that incorporated commercially available thermoelectric generators (TEGs) to a water-fed heat exchanger was examined by Zhou et al. [9]. They demonstrated that, when reducing pin length while increasing the number of pins, the resulting reduction in flow resistance was found to facilitate increase in convective heat transfer, as well as in ΔT, and thus a great increase in conversion efficiency. A three-dimensional finite element model of a thermoelectric module based on low-temperature thermoelectric material bismuth telluride and medium-temperature thermoelectric material filled-skutterudite was built by Xiao et al. [10]. The numerical simulation results showed that a reasonable thermal design of multi-stage models would take full advantage of the characteristics of thermoelectric materials and effectively improve the performance of power generation.

Generally, the research work related to thermoelectrics could mainly be classified into four categories: (1) The Carnot efficiency was enhanced by increasing the hot side temperature in order to obtain a larger temperature difference between the two ends [7,11]. (2) Researchers made a good effort on finding materials with high ZT value to improve conversion efficiency of thermoelectric materials. On the other hand, Thomson effect's influence on thermoelectric module efficiency aroused people's attention gradually [12–16]. (3) The structures of thermoelectric devices were optimized to achieve good designs with higher system efficiency. Mathematical analysis and numerical simulation both played important roles in the process [17,18]; and (4), where much research has been done, A lot of research [19–22,2,23–25] focused on thermoelectric devices applied on certain conditions, such as thermoelectric cooling device in remote desert, thermoelectric power generation device for automobile waste heat utilization, thermoelectric power generation device for space mission and application, which clearly indicates that the research and application of thermoelectric system blossom presently and become much more valuable in the future.

Much investigation has been carried out to examine the thermodynamic performance of thermoelectric devices. But thermal stresses generated in different layers of materials in TEM due to temperature gradients are neglected to a certain extent. Thermal stress induced by high temperature gradient in the device undoubtedly decreases the predicted lifecycle of the module. For solar thermoelectric module, much higher concentration ratio of solar energy will be applied to the hot end of TEM to achieve higher system efficiency. However, higher temperature of hot end will cause larger thermal stress within the material and among different materials, which will cause serious warp during different layers of materials and thereby significantly decrease the overall efficiency of the TEM. A better understanding of the operating feature of thermoelectric modules with different geometry configurations becomes essential, but seldom can similar work be found in the previous studies. The location of the maximum stress and the level of thermal stress intensity are obscure. Further, thermal stress intensity is the decisive factor for the predicted lifecycle of a thermoelectric device, especially the maximum stress value. To alleviate the hard working condition of the thermoelectric generator devices, a full investigation about the influence of geometry configurations on stress intensity of the module is of great importance. An optimum structure is the one that decreases thermal stress while having little impact or even positive effect on the device's thermoelectric performance. In this paper, a numerical modeling is presented to examine the effect of the conducting strip, ceramic plate and tin soldering geometry configuration on the module's stress level.

2. Model description

2.1. Physical model

The thermoelectric model tested in the paper is presented in Fig. 1(a), including ceramic plate, conducting strips (copper), thermoelectric pins, and tin soldering. It is considered that the basic parameters of the thicknesses of copper strip, ceramic plates, and tin solder are 0.5, 2.00, and 0.50 mm, respectively. The size of thermoelectric pins is $3.00 \times 3.00 \times 4.50\ mm^3$. The distance between the two pins is 1.00 mm. The parameters of the model, especially the size of the therm-pins, are chosen under the consideration of the common magnitude of commercial thermoelectric products available. The most commonly used Bi_2Te_3 is selected for the thermoelectric module and there is no difference in properties as a function of position. Aluminum oxide ceramics (Al_2O_3) is selected as the material of ceramic plate.

Actually, a single thermoelectric module's lifecycle is random, but the distribution of a large number of thermoelectric modules' lifecycles is ideally normal. In the condition that a large temperature gradient exists, the decisive factor for the lifecycle of a module is thermal stress intensity. As we all know, Young's moduluses of aluminum oxide ceramics (Al_2O_3) and Bi_2Te_3 vary greatly, the positions that most possible to crack are those of the interfaces of the copper strips and ceramic plates, and the edges of the thermo-pins. In this paper, we mainly pick up stress intensity data along the three lines shown in Fig. 1, which we respectively mark as Line 1, Line 2 and Line 3, to analyze the overall distribution of thermal stress intensity in the modules. The material properties used in the previous study [3,26] are incorporated in the present simulations, which are listed in Figs. 2–4 and Tables 1 and 2.

2.2. Mathematical model

The analysis pertinent to thermoelectric generator is divided into two-sub sections including the thermodynamic analysis and thermal stress formulations.

2.2.1. Thermodynamics and thermoelectricity analysis

(1) Governing equations

In this paper a finite element method using thermoelectric element in ANSYS 14.0 is employed to simulate the temperature and