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Effect of various leg geometries on thermo-mechanical and power generation performance of thermoelectric devices

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HIGHLIGHTS

- Thermoelectric modules with various leg geometries were modeled and analyzed for two different temperature gradients.
- Disparities in temperature distributions, power outputs, and conversion efficiencies were limited.
- Magnitudes and distributions of thermal stresses in the legs were significantly affected by changing leg geometries.
- Thermal stress levels were smaller in the cylindrical and trapezoidal prism legs compare to the rectangular prism legs.

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ABSTRACT

This study aims to investigate possible effect of various thermoelectric leg geometries on thermo-mechanical and power generation performances of thermoelectric devices. For this purpose, thermoelectric modules with various leg geometries were modeled and finite-element analyses for two different temperature gradients were carried out using ANSYS. Temperature distributions, power outputs, conversion efficiencies, thermal stresses in the legs were evaluated for each model. Significant differences in magnitudes and distributions of the thermal stresses in the legs occurred due to changing leg geometries. Thermal stresses in the rectangular prism and the cylindrical legs were 49.9 MPa and 43.3 MPa respectively for the temperature gradient of 100 °C.

1. Introduction

Environmental challenges, such as global warming, growing demand on energy, and diminishing oil sources have accelerated research on alternative energy conversion methods. Meanwhile, significant amount of energy is wasted during energy conversion processes due to technological limitations. Particularly in vehicles, more than 50% of the fuel energy [1] dissipates to the environment through exhaust and cooling systems as heat. Recovering some amount of wasted heat and converting it into useful energy such as electricity could increase overall efficiency of energy conversion systems and reduce demand on fossil fuels and natural resources. Thermoelectric power generation is an appropriate and promising method to convert wasted heat into electrical energy. Imposed temperature gradient through a thermoelectric device (module) produces electrical potential through the Seebeck effect, discovered by Thomas J. Seebeck. Thermoelectric devices can also be used for cooling/heating purposes utilizing Peltier effect.

Based on the application, thermoelectric devices can be used for cooling, heating, power generation, and sensing [2]. The benefits include being solid state (no moving parts), silent, maintenance free and light weight. These characteristics attract attention to thermoelectric devices from industries including defense, aerospace, electronics, and automotive. Temperature controlled car seats, electronic device cooling, thermal management, waste heat recovery from hot chimneys, thermoelectric cogeneration systems and energy harvesting from human body heat are some of the existing and potential future applications of thermoelectric systems [1–10]. Thermoelectric generators (TEGs) have the capability to convert wasted exhaust heat into useful electric power in vehicles [11]. Thus, automotive companies have begun developing prototypes. Nonetheless, thermoelectric devices have not been broadly used particularly for power generation due to some of their deficiencies. Low conversion efficiencies, usually around 3–10% [1], due to the small non-dimensional figure of merit ZT value, is the major drawback of thermoelectric devices. New thermoelectric

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materials (with values of ZT~1 and more) including thin-film superlattices, advanced bulk semiconductor alloys, and crystal structures with rattlers have been developed recently through intensive research efforts focused on enhancing efficiencies [12]. Contrary to the material level challenges, research on device-level challenges is small. This resulted as an imbalance between material and device level developments of thermoelectric devices.

Thermoelectric devices are typically consists of electrically in series and thermally in parallel connected p- and n-type thermoelectric legs, commonly fabricated with BiTe-, PbTe- or SiGe-based semiconductors. Conductor shunts, cold/hot substrates and solder joints are the other parts of a thermoelectric device. In either power generation or cooling applications, they are subjected to a temperature gradient. This causes thermal stresses in the devices due to differential thermal expansions and mismatching of thermal expansions of the bonded components [13]. Dislocations and cracks might arise due to the thermal stresses. Further, fatigue fractures may occur and finally the device may fail due to repeated thermal stresses in cyclic heating applications [14,15]. Potential failure mechanisms of thermoelectric devices were evaluated by Choi et al. [15]. More seriously, failure of even only one thermoelectric element may cause the entire device to fail since all the elements are connected electrically in series. Consequently, thermal stresses are critically important for reliability; operation life-time and expected performance of thermoelectric devices. Therefore, it is crucial to investigate developed thermal stresses in thermoelectric devices and the factors that influence them.

Researchers carried out numerical analyses to determine power generation and thermo-mechanical characteristics of thermoelectric devices and effect of geometric factors. Russel and co-workers [8,9], numerically and experimentally studied performance characterization of a thermoelectric cooling-based (TEC) thermal management system while considering parameters include geometric factor of the thermo-elements. Jang and co-workers [5,6], studied power generation performance of thermoelectric modules using numerical methods to find optimum performance parameters. Li and co-workers [13] showed that the thickness of the copper pad does not have an effect on the power output of the thermoelectric device under defined conditions. Jiang and co-workers [16] studied effect of thermoelectric leg size and variable physical parameters on power generation and conversion efficiencies of thermoelectric modules. Furthermore, Nguyen and Pochiraju [17] studied power generation performance of thermoelectric modules under transient temperature gradient conditions.

Studies on thermo-mechanical performance revealed that the maximum thermal stresses are developed at the interface between the hot side conductor and the legs of BiTe-based modules [14.18,19]. The corners of the legs are more critical through the concentrated stress levels. Researchers showed that varying leg lengths and widths changes the thermal stresses developed in the modules [19–21]. Nakatani and co-workers [22] observed that increasing conductor thickness lowers the stress caused by macroscopic deformation despite increases in the strain caused by CTE mismatches. The influence of various trapezoidal prism leg geometry configurations on thermal stress, power generation, and the device efficiency of the thermoelectric modules was also studied [23,24]. Al-Merbati and co-workers [23] showed that lower thermal stresses can be acquired by changing leg geometry and the consequence of this can enhance operation life. Investigation led by researchers showed distribution of thermal stresses in segmented thermoelectric legs [25–27]. Li and co-workers [25] observed maximum tensile stress of 180 MPa due to mismatching of thermo-mechanical properties. Consequently, thermal stresses are critically important for durability, operation life-time, and expected performance of thermoelectric devices. We agree with several researchers [28,29], that thermoelectrics needs more device-level research. For this reason, it is crucial to investigate the factors that have impact on thermal stresses in the legs, in particular their geometry.

It is the aim of this study to investigate the possible effect of thermoelectric leg geometries on thermo-mechanical and power generation performance of thermoelectric devices. For this purpose, thermoelectric modules with various leg geometries including rectangular prism, trapezoidal prism, cylindrical and octagonal prism were modeled. Finite-element analyses were carried out for specific configurations. Power generation through an imposed steady-state temperature gradient was considered as operation mode of the thermoelectric modules. Moreover, modules with segmented thermoelectric legs were modeled considering a larger temperature gradient. Temperature distributions, magnitude of generated power outputs, conversion efficiencies, magnitude and distribution of thermal stresses were evaluated.

2. Finite element modeling

2.1. Method

In order to predict temperature distribution, power generation and thermal stresses with varying leg geometry, finite-element methods are used. Power generation and thermo-mechanical behavior of a 4-leg thermoelectric module is considered. Steady-state temperature gradients of 100 °C and 300 °C were applied since most commonly used thermoelectric devices are usually designed to operate around these temperatures. Steady-state thermal, thermoelectric, and static structural modules of ANSYS® Workbench (Academic Research, Release 14.0) were utilized to carry out temperature, power generation, and thermo-mechanical analyses, respectively. ANSYS finite element software has multi-physics coupled simulation capabilities to model and analyze thermoelectric effects with accurate solutions and is recognized by the thermoelectric device manufacturers [30].

2.2. Module geometries

Various thermoelectric leg geometries were considered. First, a 4-leg module with p- and n-type rectangular prism BiTe-based legs with dimensions of 1.4 mm × 1.4 mm × 3.0 mm was modeled. The legs were spaced with 1.0 mm distance between each other. This module was defined as the original model since thermoelectric modules are typically made of rectangular prism legs. Other modules were modeled with cylindrical and trapezoidal- and octagonal-prism leg geometries. Ease of fabrication was considered when choosing the leg geometries. Leg geometries were modeled with equal cross-sectional areas in x-y plane and heights. Cross-sectional area at mid-height was considered for the trapezoidal prism model. Modeled thermoelectric modules with their respective dimensions are shown in Fig. 1. Thicknesses of ceramic substrates, conductor pads, and solder strips are 0.8 mm, 0.15 mm, and 0.1 mm respectively. Geometries of the copper pads and solder strips were modified to match leg geometries. However, their thicknesses remained the same for all models. Segmented leg structure was considered for the temperature gradient of 300 °C. Modules with rectangular prism- and cylindrical-segmented legs were modeled. Segmented models share the same dimensions with the rectangular prism and the cylindrical non-segmented models.

2.3. Material properties

Thermoelectric modules are usually composed of p- and n-type thermoelectric legs (or so-called pins), ceramic substrates,