Applied Energy 159 (2015) 19–27

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Influence of leg sizing and spacing on power generation and thermal stresses of thermoelectric devices

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HIGHLIGHTS

- Numerical and statistical methods are used to predict effect of dimensional parameters.
- Power output and conversion efficiency increase by increasing leg widths as well as decreasing height.
- Thermal stresses increase by increasing leg widths and spacing as well as decreasing height.
- There is an inverse relationship between power-generation performance and thermal stress levels.

ARTICLE INFO

Article history:
Received 8 April 2015
Received in revised form 22 August 2015
Accepted 24 August 2015

Keywords:
Thermoelectric device
Thermoelectric generator
Power output
Conversion efficiency
Thermal stress

ABSTRACT

The influence of leg dimensions and spacing on power-generation and thermo-mechanical performance of thermoelectric devices was investigated using numerical and statistical analyses tools. Bismuth-telluride based thermoelectric device models with rectangular-prism and cylindrical legs were simulated for a temperature range of 20–120 °C and various leg heights between 1 and 5 mm, widths/diameters between 1 and 2 mm, and spacing between 0.5 and 1.5 mm. Predicted power output, conversion efficiencies, and thermal stresses were validated with less than 8.9%, 1.2%, and 6.6% variations respectively. It is found that both leg width and height have a significant effect on power generation and thermal stresses: The relationship between power generation performance and thermal stress levels is inverse. Although leg spacing has effect on thermal stress and conversion efficiency, its effect on power output is negligible.

1. Introduction

Thermoelectric devices convert thermal energy into electrical energy and they are a unique solution for waste heat recovery and self-powered systems due to their solid-state structure [1,2]. Pyroelectric materials also harvest electrical energy from thermal energy, but they need temperature changes with time [3]. Existing thermoelectric power generation vary from low temperature (below 50 °C) to high temperature (above 650 °C) and micro-scale (μW) to macro-scale (kW). Thermoelectric power generation from motor vehicle exhaust systems, radioisotope materials (RTGs in space shuttles), human body heat, CPU heat, and solar collectors are some of the existing applications [2,4–7]. Thermoelectric devices are also used for various cooling applications due to the Peltier effect [8,9]. Thermoelectric devices typically consist of p- and n-type semiconductor—usually made of bismuth-telluride based alloys—couples, conductor layers, joint materials and ceramic plates. Performance of a thermoelectric material is defined by non-dimensional figure of merit $ZT = S^2T/\rho\lambda$ where S is Seebeck coefficient, T is temperature, ρ electrical resistivity, and λ is thermal conductivity of the material [1]. Massaguer et al. [10] developed a mathematical model to predict power generation behavior of thermoelectric couples.

Advantages of thermoelectric devices include silent and environmental friendly operation, small size, and minimal maintenance requirement. On the other hand, low conversion efficiencies (below 10%) and structural integrity related issues are their main disadvantages [1,11]. New thermoelectric materials—including nanostructured bismuth telluride, polymers, and crystal structures—with $ZT > 1$ have been developed recently through intensive research efforts focused on enhancing efficiencies with government-initiated support [1,2]. Although, recent improvements of thermoelectric properties are significant, insufficient research efforts on thermoelectric device-level challenges has created imbalance between material- and device-level researches. Since thermoelectric devices are composed of many dissimilar materials, thermo-mechanical and electrical properties of all

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http://dx.doi.org/10.1016/j.apenergy.2015.08.112
0306-2619/

Table 1
Material properties of p- and n-type legs, substrate, conductor, and solder [12,29–37].

Property	p-type Bi_2Te_3 leg	n-type Bi_2Te_3 leg	Al_2O_3 substrate	Cu-based conductor	63Sn–37Pb solder
d (kg/m^3)	6858	7858	3970	8940	8420
α (10^{-6}/K)	16.8	16.8	4.89–6.03 (−50–190 °C)	16.7–17.3 (−50–190 °C)	24
S (μV/K)	194.4–219 (20–120 °C)	−197–(−210.5) (20–120 °C)			
λ (W/m K)	1.22–1.37 (20–120 °C)	1.78–1.98 (20–120 °C)	37.7–25.8 (20–150 °C)	398–391 (20–150 °C)	53–46 (0–150 °C)
ρ (μΩ m)	1.22–5.24 (27–223 °C)	1.78–3.50 (27–223 °C)	1×10^{18}	0.18–0.38 (27–323 °C)	0.12–0.23 (20–200 °C)
E (GPa)	40.3 (Radial) 49.7 (Axial)	42.7 (Radial) 51.0 (Axial)	380	115	30
υ	0.28	0.28	0.26	0.31	0.40
σ_y (MPa)				70	20
σ_{UTS} (MPa)				250	40
%EL				69	40

materials are critical for performance and structural integrity [1]. For instance, significant stresses can be developed at the corners and edges of thermoelectric legs due to thermal expansion mismatch between thermoelectric materials and interface layers [12–16]. Internal and contact resistances of the layer materials in a thermoelectric device decrease conversion efficiencies [1,2,10].

Geometric parameters also play a significant role on performance of thermoelectric devices as well as the material properties. Researchers have investigated the impact of dimensional factors on the thermo-mechanical and power-generation characteristics of thermoelectric devices [12,13,15,17–19]. Gao et al. [15] have found that power output is significantly affected by leg length. Mackey et al. [20] performed thermoelectric couple optimization considering dimension parameters such as leg length and cross-sectional area. Jia and Gao [16] evaluated the effect of segment lengths on thermoelectric and thermo-mechanical performances of segmented thermoelectric generators. Effect of leg geometries has also been investigated thoroughly [14,21–23]. To examine the influence of conductor thicknesses on thermal stresses in the thermoelectric legs, finite-element analyses has been carried out by some investigators [24,25]. Li et al. [24] studied the effect of varying conductor thickness on the power generation and showed that it is not affecting the power output. Furthermore, at the systems level, researchers [26–28] analyzed the effect of heats sink and spreader dimensions and thermoelectric module spacing for improving power-generation performance. They concluded that proper size of heat sink and heat spreader can increase power output. Although, studies for dimensional analysis of thermoelectric devices exist in the literature, consideration of both power-generation and thermal stresses together is rare. Optimizing a thermoelectric device considering only power-generation parameters may cause issues related to thermo-mechanical integrity.

In the present study, statistical models are developed to determine the influence of leg dimensions and spacing on both power-generation performance and thermo-mechanical integrity of thermoelectric devices simultaneously. For this purpose, typical thermoelectric devices with rectangular-prism and cylindrical legs are modeled and analyzed using 3D Finite Element Analysis (FEA) and statistical methods. Thermoelectric and structural FEA were carried out using Design of Experiments (DOE) theory. Full-factorial designs were implemented for various leg heights between 1 and 5 mm, widths/diameters between 1 and 2 mm, and spacing between 0.5 and 1.5 mm. Power output magnitudes, conversion efficiencies, and the maximum equivalent stresses developed in the legs were defined as outputs. To predict the output responses for other input factors, mathematical models were developed using Response Surface Methodology (RSM) and Artificial Neural Networks (ANNs). To maximize power output and conversion efficiency while simultaneously minimizing thermal stresses in the legs, these models were used.

2. Methods

2.1. Finite-element model

In this study, BiTe-based thermoelectric devices operating at a temperature range of 20–120 °C are considered, because these are the most commonly used thermoelectric devices. In our previous study [14], a finite-element thermoelectric device model was validated using an experimental method and comparison with a study in the literature. Models with rectangular-prism and cylindrical legs used in this study were designed based on this validated original model.

Preferred materials were $(Bi_{0.5}Sb_{0.5})_2Te_3$, $(Bi_{0.95}Sb_{0.05})_2(Te_{0.95}Se_{0.05})_3$, Al_2O_3, 63Sn–37Pb, and Cu-based alloys for the p- and n-type legs, substrates, solder joints, and conductor pads respectively and their properties are listed in Table 1. Hot- and cold-side temperatures were defined as 120 °C and 20 °C and imposed to the surfaces of the modeled devices. Calculated Seebeck electric potential of 45 mV for the defined temperature gradient was applied to the conductor pads (see Fig. 1). Power outputs P, conversion efficiencies η, and maximum equivalent (von Misses) stresses σ_υ, in the legs were defined and predicted as the responses of the model. Power output P and conversion efficiencies η were calculated using the simulation outputs, which are electric current I and absorbed heat Q_H, and Eq. (1) where N is number of thermoelectric couples, T_H and T_C are hot- and cold-side temperatures, I is electric current, S, A, h, and ρ are Seebeck coefficient, cross-sectional area, length, and electrical resistivity of the legs respectively.

$$\eta = \frac{P}{Q_H} = \frac{N\left[S(T_H - T_C)I - I^2 \frac{h}{A}(\rho_n + \rho_p)\right]}{Q_H} \tag{1}$$

2.2. Design of experiments

Desired output responses for the given input factors were calculated with help of Design of Experiments (DOE), which is an objective method used to analyze processes depending on many input factors [38]. In these analyses, two different DOE data sets were used. First, a full-factorial design with 2 factors at 3 levels and 1 factor at 5 levels, making the required number of runs 45, was implemented for the rectangular-prism leg models. Another $3 \times 3 \times 5$ full-factorial design was also implemented for the models with cylindrical legs. The variables were labeled as h for