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Nominal power density analysis of thermoelectric pins with non-constant cross sections

Yaoguang Shi [a,b], Deqing Mei [a,b,*], Zhehe Yao [b], Yancheng Wang [a], Haiyan Liu [b], Zichen Chen [a]

[a] The State Key Laboratory of Fluid Power Transmission and Control, School of Mechanical Engineering, Zhejiang University, Hangzhou 310027, China
[b] Key Laboratory of Advanced Manufacturing Technology of Zhejiang Province, School of Mechanical Engineering, Zhejiang University, Hangzhou 310027, China

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ABSTRACT

The investigation of the geometric structure of TEG (thermoelectric generator) pins is essential, as their geometry determines the performance of devices. In this study, nominal power density (NPD) is used to find a better geometric structure of thermoelectric pins of TEGs, since a comparison of maximum dimensionless efficiencies for different geometric pins cannot be used to identify the optimum geometry. The influence of shape parameter on NPD for TEG pins in linear, quadratic and exponential cross-sectional functions is studied. The NPD decreases when the shape parameter increases for different geometric pins, while the maximum values of NPD are the same. Then, the effects of dimensionless efficiency and the temperature ratio on the NPD are analyzed. The NPD decreases with the increase in dimensionless efficiency and temperature ratio. Pins with linear variation in cross section have the highest NPD among the three geometries of pins evaluated.

1. Introduction

In recent years, TEGs (thermoelectric generators) have attracted increasing attention because of their ability to convert thermal energy to electric power by the Seebeck effect. TEGs have advantages such as no moving parts, no waste and permanent energy gain [1,2]. However, it is necessary to improve the low efficiency and power generation of current devices. The performance of TEGs depends on many factors, such as the temperature difference, material properties, and the configuration or arrangement of thermoelectric pins. Among these factors, the geometry and configuration of TEG pins are crucial.

The design and optimization of the configuration and geometric structure of thermoelectric pins have been studied extensively. Yilbas and Sahin [3] found that, for a fixed thermal conductivity ratio, the external load parameter increases with an increasing slenderness ratio, while the electrical conductivity ratio reduces. Yamashita [4] developed thermal rate equations regarding temperature dependences of the electrical resistivity and the thermal conductivity, and the relative energy conversion efficiency was studied. They also developed thermal rate equations with both linear and non-linear components in the temperature dependences of the thermoelectric properties, including the Seebeck coefficient, the electrical resistivity and the thermal conductivity, assuming that these thermoelectric properties are a quadratic function of temperature [5]. Lavric and Daniela [6] developed a detailed one-dimensional model to characterize the operation of a TEG. The model analyzed the sensitivity of thermoelectric module performance with respect to geometry, electric and thermal contact resistances, and qualities of the heat source and sink. Meng et al. [7] implemented a multi-objective and multi-parameter optimization to design the optimal structure of a bismuth-telluride-based TEG module. With a weight factor of 0.5, the optimal design balanced output power and conversion efficiency to improve both simultaneously. Fateh et al. [8] developed a finite difference model to study the optimization parameters for thermoelectric elements. The numerical model predicted that a smaller number of shorter legs have the potential to achieve the same power per unit module area as a greater number of longer legs, when thermal contact resistance and the heat exchangers are considered negligible. Xuan et al. [9] carried out optimizations for two-stage TECs (thermoelectric coolers) with two design configurations, pyramid and cuboid. Cheng et al. [10,11] combined a TEC model and a genetic algorithm to optimize the geometry of single- and double-stage TECs. In their study, the maximum cooling capacity was defined as the objective function, and the leg length, leg area and the number of legs were taken as search variables and optimized simultaneously. In these studies, the cross sections of TEG pins were constant along the length direction, and the pin geometries were usually cuboid or cylindrical.

* Corresponding author at: The State Key Laboratory of Fluid Power Transmission and Control, School of Mechanical Engineering, Zhejiang University, Hangzhou 310027, China. Tel.: +86 571 87591906.
E-mail address: meidq_127@zju.edu.cn (D. Mei).

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Nomenclature

A	cross section area of thermoelectric pins (m^2)
A_c	cross section area of cold side of thermoelectric pins (m^2)
A_{max}	maximum cross section area of thermoelectric pins (m^2)
A_0	average cross section area of thermoelectric pins (m^2)
K	overall thermal conductance of the thermoelectric generator (W/K)
K_0	reference thermal conductance of the thermoelectric generator (W/K)
L	length (height) of thermoelectric pin (m)
$\dot{Q}$	rate of heat transfer (W)
r_k	thermal conductivity ratio
r_σ	electrical conductivity ratio
R	overall electrical resistance of the thermoelectric generator (Ω)
R_0	reference electrical resistance of the thermoelectric generator (Ω)
R_L	external load resistance (Ω)
T_1	hot side temperature (K)
T_2	cold side temperature (K)
$\dot{W}$	power output (W)
ZT_{ave}	dimensionless figure of merit
β	dimensionless shape parameter
η	efficiency
θ	temperature ratio (T_2/T_1)
g	ratio of maximum and average area of thermoelectric pins
NPD	nominal power density

However, variation in cross section along the pin length also affects the TEG performance. Some studies have investigated the effects of thermoelectric pins with non-constant cross sections on the performance of thermoelectric devices. Boerdijk [12] gave two nonlinear differential equations describing the stationary distribution of the temperature and electrical potential of bars with variable shape. He found that the maximal values of the efficiencies obtained did not depend on the shape. Brandt [13] treated resistance heating and Thompson effects as non-uniformly distributed energy transfers. The computer solutions were presented graphically and the effects of variable currents, geometries, and radiative conditions were considered. Rollinger [14] presented differential equations describing the one-dimensional temperature distribution in a convectively cooled thermoelement with variable cross-sectional area. It was demonstrated that under certain conditions, shaping the element can enhance the performance gains. Semenyuk [15] studied the limiting efficiency of TEC when no limitations were imposed on the shape of the thermoelectric elements and their contact surfaces. Arenas et al. [16] studied the influence on the heat power absorbed and the coefficient of performance of pellets with variable cross sections. The values of the interchanged thermal powers and the efficiencies were not influenced by changes in geometry of the pellet, when the total "slimness" remained constant. The effects of cross sectional variation in the legs on TEG efficiency and output power in dimensionless form were investigated by Yilbas and Sahin et al. [17,18]. The variation functions were linear and exponential, respectively. The efficiency of a TEG was improved notably by increasing or decreasing the shape parameter, but the shape parameter had an adverse effect on power generation.

Many research studies have examined the thermoelectric performance of different geometric pins. But a better pin geometry cannot be obtained by these models or evaluation parameters. Also, a comparison of the maximum dimensionless efficiency of different geometric thermoelectric pins has not been made. In this study, we make such a comparison. Then, a model of nominal power density (NPD) is formulated to investigate and compare the performance of TEGs with different geometric pins. The effect of the geometric parameter on NPD is analyzed and the interdependencies among efficiency, temperature difference and NPD are examined.

2. Maximum dimensionless efficiency

TEGs usually consist of arrays of p-type and n-type semiconductor pins, connected electrically in series and thermally in parallel. In this study, and there is no heat loss caused by radiation and convection, and no external irreversibility or contact effects in the TEG. So a pair of n-type and p-type semiconductor pins is analyzed. The TEG is made from p-type and n-type bismuth-telluride, which are excellent thermoelectric materials widely used near room temperature. The material properties of the pins are assumed to be constant, and therefore the Thomson effect is neglected.

The volume, the thickness and the length of different geometric pins are assumed constant in this study. Fig. 1 is a schematic of the TEG with a pair of non-constant cross-sectional pins. We assume that the p-type and n-type pins of the TEG have the same dimensions [19–21], which is common in practical commercial thermoelectric module. Fig. 2 shows a schematic view of the thermoelectric pin with variation in cross section in quadratic function along the height direction x.

The cross sectional area $A(x)$ can be defined as:

$$A(x) = A_C + \alpha x^2 \quad (1)$$

where A_c is the cold side area of the thermoelectric pins, and parameter α is associated with the change in cross section along the length direction.

Assume that the heating situation is steady and the side surface of the pin is adiabatic. $\dot{Q}$ is the heat transfer rate through the thermoelectric pins. Then, we can obtain the thermodynamic equations:

$$\int_0^L \frac{\dot{Q}}{A(x)} dx = -k \int_{T_1}^{T_2} dT \quad (2)$$

$$\int_0^L A(x) dx = A_0 L \quad (3)$$

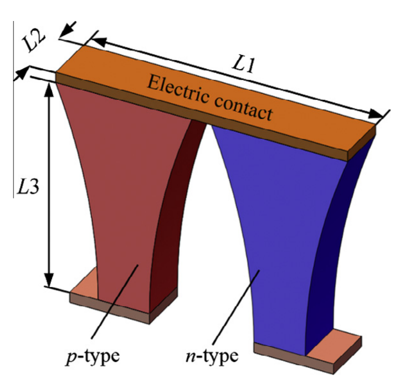

Fig. 1. Thermoelectric generator with a pair of non-constant cross-sectional pins.