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Segmented thermoelectric generator: Influence of pin shape configuration on the device performance

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ABSTRACT

A segmented thermoelectric generator and thermal performance of the device is investigated in terms of the efficiency of the device and its output power. The influence of tapering of the device pins on the segmented thermoelectric performance is also analyzed. Modified Bismuth and lead tellurides are used as the pin materials. The performance characteristics of the segmented thermoelectric generator are compared with its counterpart, which has homogeneous material pin configurations. Various levels of the load and temperature ratios are incorporated to assess the performance of the device. The findings reveal that the segmented thermoelectric generator results in a higher efficiency and more output power than those with the homogeneous configurations. The shape factor, defining the pin tapering, influences the device efficiency significantly; in which case, increasing the shape factor enhances the device efficiency. The opposite is true for the device output power; in which case, the pin tapering lowers the device output power.

1. Introduction

Thermal energy conversion by a thermoelectric generator offers several advantages over the other conventional energy converging methods. Some of these advantages include the involvement of green energy conversion, non-rotating parts, low cost, and easiness of operation. However, thermoelectric generators have low thermal efficiencies because of the low figure of Merit of the thermoelectric materials, which is associated with the properties of the active materials used in the thermoelectric generation. The figure of Merit is directly proportional to the Seebeck coefficient and electrical conductivity of the material and inversely related to the thermal conductivity of the active material. Temperature difference across the thermoelectric device causes heat diffusion and the Seebeck current generation in the active element; in which case, the heat diffusion across the device junctions lowers the thermal efficiency of the device significantly. In addition, the maximum operational temperature of the thermoelectric device depends on the type of the active materials used in the device, for example, a device made from the bismuth telluride operates at around 250 °C–30 °C [1] while that made from the skutterudite operates at about 600 °C–30 °C [2]. However, the thermoelectric generator made from the skutterudite gives rise to a reduced thermal efficiency when used at low temperature ranges (~250 °C) [3]. In order to improve the thermal efficiency of the thermoelectric device and extend the operational temperature ranges, the use of the segmented thermoelectric pins becomes fruitful [4]. On the other hand, the geometric configuration of the thermoelectric generator plays an important role for the improvement of the device efficiency [5]. Consequently, investigation of the segmented thermoelectric generator with varying geometric pin configurations for maximizing the device efficiency and the output power becomes essential.

Considerable research studies were carried out to examine segmented thermoelectric generators. Segmented bismuth telluride thermoelectric generator system for a mid-temperature thermoelectric energy conversion system was studied by Liu et al. [6]. They showed that the segmented thermoelectric system operating at mid-temperature ranges could improve the device efficiency significantly; in which case, the leg efficiency of thermoelectric conversion for segmented elements based on the n-type materials could potentially reach 12.5%. The study on the power conversion efficiency in thin-film and segmented thermoelectric devices was carried out by Reddy et al. [7]. They indicated that the performance

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Nomenclature

A_0	Area of rectangular geometry of thermoelectric generator (m^2)
I	Electrical current (A)
$k_{eff,n}$	Effective Thermal conductivity of *n*-type semi-conductor (W/mK)
$k_{eff,p}$	Effective Thermal conductivity of *p*-type semi-conductor (W/mK)
k_n	Thermal conductivity of *n*-type semi-conductor (W/mK)
k_p	Thermal conductivity of *p*-type semi-conductor (W/mK)
$\overline{K}_{eff.}$	Overall effective thermal conductance of thermoelectric generator (W/K)
K_0	Reference thermal conductivity for thermoelectric generator (W/K)
L	Total length of the leg of thermoelectric generator (m)
R_L	External load resistance (Ω)
R_n	Electrical resistance of *n*-type leg of semi-conductor (Ω)
R_p	Electrical resistance of *p*-type leg of semi-conductor (Ω)
R_0	Reference electrical resistance (Ω)
R_{TEG}	Overall electrical resistance in of the thermoelectric generator (Ω)
s	Shape factor of the thermoelectric leg (m)
T_1	Hot side temperature of the thermoelectric generator (K)
T_2	Cold side temperature of the thermoelectric generator (K)
$T_{int,n}$	Temperature at the interface of two *n*-type materials (K)
$T_{int,p}$	Temperature at the interface of two *p*-type materials (K)
V	Voltage (V)
W	Power output of the thermoelectric generator (W)
ZT_{avg}	Dimensionless Figure of merit (1/K)
α_n	Seebeck coefficient of *n*-type semi-conductor (V/K)
$\alpha_{n,eff.}$	Effective Seebeck coefficient of *n*-type leg of semi-conductor (V/K)
α_p	Seebeck coefficient of *p*-type semi-conductor (V/K)
$\alpha_{p,eff.}$	Effective Seebeck coefficient of *p*-type leg of semi-conductor (V/K)
$\overline{\alpha}_{eff.}$	Overall effective Seebeck coefficient of the thermoelectric generator (V/K)
μ_n	($=L_{n,1}/L$) Dimensionless ratio of *n*-type material 1 to total length of thermoelectric generator
μ_p	($=L_{p,1}/L$) Dimensionless ratio of *p*-type material 1 to total length of thermoelectric generator.
η	Efficiency
ξ	Dimensionless shape factor
σ_p	Electrical conductivity of *p*-type semi-conductor (S/m)
σ_n	Electrical conductivity of *n*-type semi-conductor (S/m)
θ	($=T_2/T_1$) Dimensionless ratio of the low and high temperature of thermoelectric generator.

of a small-scale segmented device was better than that of the thermoelectric device with a single material configuration. The segmented thermoelectric multi-couple converter was investigated by Fleurial et al. [8]. Their findings revealed that segmented thermoelectric multi-couple converter arrays could achieve more than 8% system efficiency. The model study for building blocks of segmented thermoelectric power generators was carried out by Crane et al. [9]. They demonstrated that over 10% efficiency of the segmented thermoelectric generator could be designed for various loads and temperature ranges. Hadjistassou et al. [10] performed the theoretical modeling of segmented thermoelectric generators for improving the thermal efficiency. They indicated that the overall Seebeck coefficient of the segmented thermoelectric generator can sustained a higher values electrical load as compare to a homogeneous thermoelectric generator. High efficiency segmented thermoelectric uni-couple was examined by El-Genk and Saber [11]. They showed that segmented thermoelectric uni-couples having a total contact resistance ~50 $\mu\Omega cm^2$ per leg and being well insulated on the sides could potentially achieved a peak conversion efficiency of 15% when operated between 973 K and 300 K. An optimization study for a segmented thermoelectric generator operated using exhaust of a diesel engine was carried out by Tian et al. [12]. They demonstrated that the segmented thermoelectric generator was more suitable than the traditional thermoelectric generator for a high-temperature heat source and for large temperature differences. Segmented thermoelectric uni-couples for space power applications were investigated by El-Genk et al. [13]. They indicated that the segmented thermoelectric uni-couples could achieve peak efficiencies of 7.8% and 14.7% when operated at a cold side temperature of 573 K -typical of that in current radioisotope thermoelectric generators- and 300 K, respectively. The high efficiency segmented thermoelectric uni-couples were studied by Ngan et al. [14]. They showed that the conversion efficiency and working temperature range could be greatly improved by segmenting multiple materials, which in turn increased the device efficiency. Generator modules of segmented thermoelements were studied by Vikhor and Anatychuk [15]. They demonstrated that the efficiency of modules of double-segmented legs was approximately 7.5% and exceeded the power efficiency of homogeneous material generators. High performance *p*-type segmented leg of misfit-layered thermoelectric generator was examined by Hung et al. [16]. They indicated that the maximum conversion efficiency was ~5%, which was about 65% of that expected from the materials without parasitic losses. In addition, the long-term stability investigation for two weeks at the hot and cold side temperatures revealed that the segmented leg had good durability as a result of stable and low electrical resistance contacts.

Although thermal performance of the segmented thermoelectric electric generators were studied previously [17], the influence of the thermoelectric pin configuration on the thermal performance was left for a future study. Therefore, in the present study, thermal analysis of the segmented thermoelectric generator is introduced and the influence of the pin geometric configuration on the device performance is examined. In the analysis, modified lead telluride (*n*-type - $Ag_{0.8}Pb_{19+x}SbTe_{20}$: *p*-type - $Ag_{0.9}Pb_9Sn_9Sb_{0.6}Te_{20}$) and modified bismuth telluride (*n*-type -$Bi_2Te_{3-x}Se_x$: *p*-type - $Bi_xSb_{2-x}Te_3$) are incorporated to design the thermoelectric generator pins. The comparison between the segmented and homogeneous material thermoelectric generators is made for the same geometric configuration of the pins. The maximum device efficiency and its output power were analyzed for various external load parameters and temperature ratios.