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Research Paper

Innovative design of a thermoelectric generator of extended legs with tapering and segmented pin configuration: Thermal performance analysis

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HIGHLIGHTS

- Maximum efficiency depends on segmented and tappering configurations of pins.
- External load resistance and temperature ratios have effect on maximum device efficiency.
- Extended leg configuration enhances thermoelectric efficiency upto 8% increase.
- Output power is influenced by tappering, external load and temperature ratios.
- Output power corresponding to new innovative design remains higher than single material configurations.

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ABSTRACT

New design of a thermoelectric generator with extended pin configuration is introduced and its performance is assessed incorporating the pin tapering parameter and the operating conditions including external load and temperature ratios. The segmented configuration of device pins is also incorporated in the thermodynamic analysis. The device maximum efficiency and output power are formulated and analyzed for various values of the device design and operating parameters. It is found that the maximum efficiency of new innovative design of the thermoelectric generator remains higher than those previous designs incorporating single material pin configuration without tapering. Tapering of the pin geometry increases the maximum efficiency of the thermoelectric generator, particularly for low values of the external load parameter. The device output power of the extended leg thermoelectric generator with segmented configuration remains higher as compare to the thermoelectric generator with single pin material. A new innovative design of a pin configuration is presented in the study, which provides high performance of thermoelectric generator, this makes the thermoelectric generator one of the promising renewable energy devices for possible applications in future.

1. Introduction

A large scale and effective utilization of renewable energy sources is essential to slow down the climate change and lower its adverse effect on the environment. Although several research studies have been carried out to develop efficient renewable energy devices, such as photovoltaic panels, volumetric receivers, wind turbines, thermoelectric generators, etc., the research studies on the development of high efficiency renewable energy devices and multi-generation systems meeting the challenges of investment, cost-effective operation, and maintenance are still in progress. Improving the efficiency of renewable energy systems through enhancing waste heat recovery and utilization is also challenging in terms of the innovative design of high efficiency devices and minimization of operational cost at device level. Thermoelectric generators are the devices, which convert thermal energy directly into electrical energy without involving combustion and rotating parts. The innovative design of a thermoelectric generator becomes necessary because of its low thermal efficiency and narrow operational temperature ranges. The innovative design of a thermoelectric generator with the consideration of extended legs with pin tapering is promising for efficient operation of the device.

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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 semiconductor (W/mK)
$k_{eff,p}$	effective thermal conductivity of *p*-type semiconductor (W/mK)
k_n	thermal conductivity of *n*-type semiconductor (W/mK)
k_p	thermal conductivity of *p*-type semiconductor (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 semiconductor (Ω)
R_p	electrical resistance of *p*-type leg of semiconductor (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)
$T_{\mathrm{int},n}$	temperature at the interface of two *n*-type materials (K)
$T_{\mathrm{int},p}$	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 semiconductor (V/K)
$\alpha_{n,eff.}$	effective Seebeck coefficient of *n*-type leg of semiconductor (V/K)
α_p	Seebeck coefficient of *p*-type semiconductor (V/K)
$\alpha_{p,eff.}$	effective Seebeck coefficient of *p*-type leg of semiconductor (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 semiconductor (S/m)
σ_n	electrical conductivity of *n*-type semiconductor (S/m)
θ	$(= T_2/T_1)$ dimensionless ratio of the low and high temperature of thermoelectric generator

This is because of the fact that extended pins can operate independently at two low temperature sinks. This arrangement can improve the thermal efficiency of the system while tapering of the segmented pin configuration further contributes to the device efficiency enhancement. Consequently, it becomes necessary to perform the thermal analysis of a thermoelectric generator having extended legs with segmented and tapered pin configuration.

Considerable research was performed to study the thermoelectric generator performance under the different operating conditions. Thermoelectric power generator with segmented leg configuration was studied by Li et al. [1]. They showed that the electrical resistance of the segmented legs was dramatically increased in comparison with that of the bulk materials, which was due to the large interfacial resistance between different segments in the thermoelectric generator legs; therefore, the interfacial resistance was one of the key factors limiting the output power of the segmented thermoelectric generator. Segmented thermoelectric generator with tapered pin configuration was studied by Ali et al. [2]. They observed that segmentation of thermoelectric generator enhances the thermal performance of thermoelectric generator as compared with the non-segmented thermoelectric generator. In addition, they introduced the shaped factor related to the tapering of the pin of the thermoelectric generator. Their study revealed that increasing the tapering of pin thermoelectric result in the enhancement of the efficiency of the thermoelectric generator. However, at the same time, the device output power adversely effected by an increment in the shape factor. The design configuration of a thermoelectric generator incorporating the length ratio of segmented pins was performed by Zhang et al. [3]. Their finding reveals that for specific operating condition and configuration there exist a segmentation ratio which can provide the maximum thermal efficiency of thermoelectric generator. The comparative study for the performance assessment of the segmented and the traditional thermoelectric generators was carried out by Tian et al. [4]. Their results indicated that the increment in the pin length effect adversely on the device thermal efficiency and output power. The maximum output power varied linearly with the pin cross-sectional area. For the waste heat recovery application, the segmented thermoelectric generator is more effective as compared to the traditional thermoelectric generator. Tian et al. [5] introduced the thermal analysis of a segmented thermoelectric generator, which designed for the heat recovery from diesel engine exhaust. They simulated the effect of operating temperatures, geometric configuration, and segmentation ratio on the device efficiency and power output. Their finding reveals that for high temperature heat source the thermoelectric generator with segmentation performed better as compared with to the traditional thermoelectric generator. Ming et al. [6] carried out the study to assess the thermal performance of the segmented thermoelectric generator. The findings from the thermal analysis reveal that their thermoelectric design provides the steady voltage, and maximum thermal efficiency is around 11.2%. The thermoelectric generators with segmentation were examined for their mechanical performances by Jia and Gao [7]. Their finding reveals that for given operating temperature of the segmented thermoelectric generator the requirements of mechanical strength is not satisfied. In addition, the segmented thermoelectric generator could not attain the design value of thermal efficiency. The design analysis of a thermoelectric generator with segmented was introduced by Kim et al. [8]. They assembled two-pair segmented π-shaped thermoelectric generator, contact resistance across the interface is low. The reported the peak specific power density as 42.9 W/kg for the temperature of 498 °C, their measurements and predicted analytical prediction are in good agreement. Hadjistassou et al. [9] presented the design configuration for high efficiency thermoelectric generators with segmentation. In the case of segmented Bi_2Te_3–PbTe the Seebeck coefficient is higher as compare to traditional thermoelectric generators made of Bi_2Te_3 and PbTe. El-Genk et al. [10] studied the segmented thermoelectric generators for space power applications. Their study reveals that thermoelectric generator with segmentation can attain the 14.7% thermal efficiency for the cold side temperature of 300 K. The performance of a flat-plate