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Innovative design of a thermoelectric generator with extended and segmented pin configurations

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HIGHLIGHTS

- Segmented pin size maximizing efficiency changes with external load parameter and operating temperature.
- Cold junction temperature difference enhances maximum efficiency by 4.5–6.2%.
- New innovative design improves maximum efficiency as compared to classical design.
- Increasing cold junction temperature difference increases device output power.

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ABSTRACT

A thermoelectric generator is one of the key candidates for the renewable energy devices, which directly converts waste heat into electricity. The wide applications of the device are suppressed because of the device low efficiency. In this paper, a new innovative design of the thermoelectric generator incorporating the extended pin with segmented pin configuration is introduced. The new design allows the device operating at two different cold junction temperatures. The maximum efficiency and the output power for the innovative design of thermoelectric device are formulated. The performance of the thermoelectric device is evaluated using the operating parameters such as the hot and cold junction temperatures in terms of temperature ratio, and external load resistance ratio. The reveals that the innovative design improves the maximum efficiency and output power of the thermoelectric generator. Increasing the cold junction temperature difference increases the device maximum efficiency by 3.5–6.2%. The maximum device output power and maximum thermal efficiency occur at different values of external load parameter. However, the reduction in the efficiency is considerably small for the external load parameter maximizing the device output work.

1. Introduction

In the renewable energy devices, the thermoelectric generators are the promising candidates which can utilize waste heat or solar energy to generate electricity. The thermoelectric devices convert heat into electricity, but their practical applications are limited due to their low thermal efficiency. The energy conversion efficiency of a thermoelectric device depends on the thermoelectric figure of merit (Z), which is related to the material's Seebeck coefficient α, electrical conductivity k_{elct}, and thermal conductivity k_{th} via $Z = \alpha^2 k_{elect}/k_{th}$. Moreover, Z has the unit of 1/K and it is usually combined with the average temperature of material (T_{avg}), i.e. dimensionless figure of merit becomes ZT_{avg}. Improving pin material properties towards achieving high figure of merit and introducing innovative design of the device geometric features are the current research interest towards improving device efficiency [1]. Thermoelectric generator performance, in general, depends on the geometric features of the pin and operating conditions; as pin length and its cross-section [2], external load parameter, and temperature ratio [3]. The thermal efficiency and device power output are improved with the use of extended pin configuration. In addition, the device performance is enhanced with segmented pin configuration [4]. A new innovative design combining the extended pin length and segmented configuration of pin materials becomes fruitful for the wide utilization of the device in renewable energy applications. The thermal analysis of such innovative design becomes essential to optimize the device performance.

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Nomenclature

A_n	area of *n*-type leg of semi-conductor
A_p	area of *p*-type leg of semi-conductor
I	electrical current
$k_{n,eff}$	effective thermal conductivity of *n*-type semi-conductor
$k_{p,eff}$	effective thermal conductivity of *p*-type semi-conductor
k_n	thermal conductivity of *n*-type semi-conductor
k_p	thermal conductivity of *p*-type semi-conductor
$\overline{K}_{eff.}$	overall effective thermal conductance of thermoelectric generator
K_n	thermal conductance of *n*-type semi-conductor
K_p	thermal conductance of *p*-type semi-conductor
K_0	reference thermal conductivity for thermoelectric generator
L	total length of leg of thermoelectric generator
L_n	length of *n*-type semi-conductor leg
L_p	length of *p*-type semi-conductor leg
R_L	external load resistance
R_n	electrical resistance of *n*-type leg of semi-conductor
R_p	electrical resistance of *p*-type leg of semi-conductor
R_0	reference electrical resistance
R_{TEG}	overall electrical resistance in of thermoelectric generator
T_{high}	hot side temperature of the thermoelectric generator
$T_{low,n}$	cold side temperature on *n*-type leg of thermoelectric generator
$T_{low,p}$	cold side temperature on *p*-type leg of thermoelectric generator
$\Delta T_{low,p-n}$	temperature difference between cold side of *p*-type and *n*-type leg of thermoelectric generator ($\Delta T_{low,p-n} = T_{low,p} - T_{low,n}$)
$T_{int,n}$	temperature at the interface of two *n*-type materials
$T_{int,p}$	temperature at the interface of two *p*-type materials
V	voltage
W	power output of the thermoelectric generator
ZT_{avg}	dimensionless figure of merit
α_n	Seebeck coefficient of *n*-type semi-conductor
$\alpha_{n,eff.}$	effective Seebeck coefficient of *n*-type leg of semi-conductor
α_p	Seebeck coefficient of *p*-type semi-conductor
$\alpha_{p,eff.}$	effective Seebeck coefficient of *p*-type leg of semi-conductor
$\bar{\alpha}_{eff.}$	overall effective Seebeck coefficient of thermoelectric generator
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
η_{II}	second law efficiency
σ_p	electrical conductivity of *p*-type semi-conductor
σ_n	electrical conductivity of *n*-type semi-conductor
θ	dimensionless ratio of low and high temperature of thermoelectric generator

Consequently, investigation of innovative design of thermoelectric generator resulting in high performance is necessary.

Considerable research were carried out to study the performances of thermoelectric generator. The optimization study of a waste heat recovery system with presence of thermoelectric generators was carried out by Huang et al. [5]. They showed that proper selection of operating parameters increased the power generation efficient; however, optimal design of a waste heat recovery system was necessary for further improvement of the system performance. The assessment of thermal performance of building along with installed photovoltaic thermoelectric was investigated by Luo et al. [6]. Their simulation relieved that heat gain was reduced around 70% in case of building integrated with photovoltaic thermoelectric wall for simulated day. Thermal performance of two heat exchangers for thermoelectric generators was studied by Li et al. [7]. They indicated that the coupled heat exchanger design resulted in improved thermal performance of the thermoelectric generator than that of a single heat exchanger design. In this case, the coupled heat exchanger was more compact and efficient than the single heat exchanger. The heat transfer analysis of internal plate fin structured thermoelectric generator was carried out by Kim et al. [8]. They demonstrated that the plate fins on the hot surface of each thermoelectric module provided the most effective temperature fields for improved output power generation. Performance analysis of an integrated solar concentrated power based thermo-electric and desalination system was realized by Aberuee et al. [9]. They showed that the maximum energy and exergy efficiency of the integrated system is about 46% and 15%, respectively while demonstrating the suitability of purposed system for residential applications. Energy and exergy efficiencies of solar heat pipe based annular thermoelectric generator system were examined by Manikandan and Kaushik [10]. They confirmed that in comparison of solar flat plate thermoelectric generator the solar annular thermoelectric generator system provides better heat transfer characteristics along with the easy installation and maintenance. Design, fabrication and feasibility analysis of a thermoelectric wearable helmet was investigated by Lv et al. [11]. They demonstrated that the wearable thermoelectric generation system was visible; however, the future improvement of the wearable device was necessary for outdoor applications. High-performance photovoltaic-thermoelectric hybrid power generation system with optimized thermal management was studied by Zhu et al. [12]. They indicated that the copper plate served as thermal concentrator and conductor guaranteed a large temperature difference in both sides of thermoelectric module, which contributed extra electrical energy of 648 J even during the absence of sun light. Thermal modeling and exergetic analysis of a thermoelectric assisted solar still was carried out by Dehghan et al. [13]. The results indicated that thermoelectrically assisted solar still is having higher energy efficiency as compared to simple passive solar still; however, the exergy efficiency of simple passive solar still was higher. A thermal system for self-cooling applications incorporating the thermoelectric devices was examined by Kiflemariam and Lin [14]. They developed a strategy that the device temperature was kept at an optimum value while being able to run the cooling system. Analysis of a dry condenser and dry cooling towers integrated with a thermoelectric generator was carried out by Benn et al. [15]. They presented the performance analysis for five water-saving heat exchanger and demonstrated that hybrid arrangement of the dry condenser and dry cooling towers with the conventional wet cooling components result in the reduction of cost along with enchantment in water saving. Performance analysis of a concentrated solar thermo-electric generator was investigated by Sudharshan et al. [16]. They confirmed that the setup developed could be used effectively as an alternative to optically concentrated solar thermoelectric generator, which required extra power for the solar tracking system. Performance of the thermoelectric generator system used in diesel engines investigated by Temizer and Ilkilic [17]. They