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Influence of pin material configurations on thermoelectric generator performance

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ABSTRACT

Thermoelectric generator with new pin configurations is considered to enhance device efficiency and output power. The thermal and the electrical conductivities of the thermoelectric generator pins are modified to vary along the pins length. Thermodynamics analysis of the thermoelectric generator with new pin configurations is carried out and device efficiency and output power are compared with those of uniform pin material thermoelectric generators. The performance of purposed thermoelectric generator is assessed incorporating the operating temperature parameter ($\theta = \frac{T_2}{T_1}$, where T is the junction temperature of thermoelectric generator, and T_1 corresponds to the high temperature source and T_2 is the low temperature source) and the external load parameter (R_L/R_0, where R_L is the external resistance, and R_o is the reference electrical resistance of the device - $R_0 = \frac{L}{\sigma_{0,n}A}$ is the reference resistance, in which L is the pin length, $\sigma_{0,n}$ is the reference electrical conductance, and A is the pin cross-sectional area). It is found that the purposed pin configuration enhances the thermoelectric efficiency and the output power. The external load parameter maximizing the output power does not maximize the thermal efficiency of the device for given temperature parameters. In this case, the value of the external load parameter becomes small as the device efficiency and output power increases.

1. Introduction

A thermoelectric generator is one of the clean energy devices that generate electricity from waste heat without hazardous emission. Although the thermoelectric generator has a simple design, its low efficiency limits the practical application of the devices. The most critical parameters influencing the device output power is the Figure of Merit, operating temperature ratio, and external load. The Figure of Merit can be improved through increasing the Seebeck current while lowering the thermal conductivity of the device active parts such as pins. Operating conditions depend on the source and sink temperatures where thermoelectric device operates in between. External load is associated with the electrical resistance of the external device, which drives current from the thermoelectric generator. Operating conditions are influenced by the external parameters, which become device parameters dependent to achieve high performance. This is because of the fact that the Seebeck coefficient and thermal conductivity depend on operating temperature range and internal heat generation because of the current flow through the pins due to the external load. Several considerations were made to improve the device efficiency and the output power. Some of these considerations include resetting the geometric features of the device such as pins [1,2], pin material modifications [3,4], and improvement of the device operational conditions such as optimizing external load parameters [5]. One of the alternative approaches is to consider the design of active materials, such as pins materials, incorporating the geometric feature of the pins. In this case, gradually varying of the thermal and electrical conductivities of the pin material along the pin length may improve the device performance in terms of the efficiency and the output power. Consequently, investigation of the effects of gradual change of pin material properties along the pin length of thermoelectric device on the thermal efficiency and the output power becomes essential.

Considerable research studies were carried out to examine thermoelectric generator performances. Design and performance analysis of a thermoelectric generator were carried out by Orr et al. [6]. They introduced simplified equations to assess the thermoelectric generator and demonstrated that the equations introduced were valid for low temperature ranges of device operation. Power and efficiency factors affecting thermoelectric generator performance were investigated by Zhang et al. [7]. They indicated that the effect

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Nomenclature

a_n	constant which represents the linear variation of thermal conductivity for n-type semi-conductor (1/m)
a_p	constant which represents the linear variation of thermal conductivity for p-type semi-conductor (1/m)
A	cross-section Area of the thermoelectric generator (m^2)
b_n	constant which represents the linear variation of electrical conductance for n-type semi-conductor (1/m)
b_p	constant which represents the linear variation of electrical conductance for p-type semi-conductor (1/m)
I	electrical current (A)
k_n	thermal conductivity of n-type semi-conductor (W/m K)
k_p	thermal conductivity of p-type semi-conductor (W/m K)
$k_{0,n}$	reference thermal conductivity of n-type semi-conductor (W/m K)
$k_{0,p}$	reference thermal conductivity of p-type semi-conductor (W/m K)
$[K]$	total thermal conductance in of thermoelectric generator (Ω)
K_n	thermal conductance of n-type semi-conductor (W/K)
K_p	thermal conductance of p-type semi-conductor (W/K)
K_0	reference thermal conductivity for thermoelectric generator (W/K)
L	length of leg of thermoelectric generator (m)
R	total electrical resistance in of thermoelectric generator (Ω)
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)
T_1	hot side temperature of the thermoelectric generator (K)
T_2	cold side temperature of the thermoelectric generator (K)
W	power output of the thermoelectric generator (W)
ZT	dimensionless Figure of Merit (–)
α	net seebeck coefficient of thermoelectric generator (V/K)
α_n	seebeck coefficient of n-type semi-conductor (V/K)
α_p	seebeck coefficient of p-type semi-conductor (V/K)
η	efficiency
σ_n	electrical conductivity of n-type semi-conductor (S/m)
σ_p	electrical conductivity of p-type semi-conductor (S/m)
$\sigma_{0,n}$	reference electrical conductivity of n-type semi-conductor (S/m)
$\sigma_{0,p}$	reference electrical conductivity of p-type semi-conductor (S/m)
θ	dimensionless ratio of low and high temperature of thermoelectric generator

of thermal conductivity was underestimated in the traditionally used Figure of Merit; however, the traditional power factor and Figure of Merit could be corrected via incorporating the convection losses from thermoelectric junctions. Performance analysis of thermoelectric generator and influence of pin tapering on the first and second law efficiencies were studied by Yilbas and Ali [8]. They showed that the dimensionless tapering parameter had a significant influence on the first and second law efficiencies, and the output power of the device. This behavior was associated with the external load resistance which had a considerable influence on the device output power such that increasing external load resistance lowered the device output power. A plate-type thermoelectric power generator operating under a small temperature difference was investigated by Tohmyoh and Daimon [9]. They demonstrated that oxidizing the bi-metal interface was effective in enhancing the performance of the thermoelectric power generator. Thermal performance of thermoelectric generators coupled with solar pond was examined by Ding et al. [10]. They indicated that the thermal-electrical conversion efficiency was low, which was in the range of 1–1.5%. A waste cold recovery from the exhausted cryogenic nitrogen using thermoelectric generator was studied by Weng et al. [11]. They showed that a power generation rate as high as 0.93 W was obtained by the proposed prototype thermoelectric generator using four two-layer cascades and a mass flow rate of cryogenic nitrogen of 3.6 g/s. A review on development of thermoelectric power generators was presented by Aswal et al. [12]. They discussed the status on the development of thermoelectric generators, which were suitable for operation at different temperature ranges including <250 °C, 250–650 °C and >650 °C. Energetic and exergetic performances of a solar energy-based integrated system for multi-generation including thermoelectric generators were analyzed by Islam et al. [13]. The findings revealed that the energy and exergy efficiencies of the photovoltaic panels and the overall system were improved significantly after incorporating thermoelectric generation unit in the thermal system. High-performance nanostructured thermoelectric generators for micro-combined heat and power systems were studied by Zhang et al. [14]. They showed that thermoelectric system harnessed the untapped exergy between the combustion gas and water, and converted thermal energy into electric power with 4% heat-to-electricity efficiency based on the total heat input into the thermoelectric generator. A design configuration of a segmented thermoelectric generator was examined by Zhang et al. [15]. They indicated that there existed an optimal length ratio corresponding to the highest maximum output power or thermoelectric conversion efficiency, which was not only dependent on the material properties but also the heat transfer conditions and geometric structure. Optimization study of a hybrid solar panel and thermoelectric generators was carried out by Kwan and Wu [16]. They demonstrated that the optimized photovoltaic/thermoelectric generator system achieved better efficiencies than that of the monolithic counterparts. In addition, single stage thermoelectric generator was more beneficial than the two stage thermoelectric generator in terms of achievable high performance. High-temperature and high-power-density nanostructured thermoelectric generator for automotive waste heat recovery was introduced by Zhang et al. [17]. They demonstrated that a high-performance thermoelectric generator, by combining high-efficiency nanostructured bulk materials with a novel direct metal brazing process, increased the device operating temperature. In this case, a 1 kW thermoelectric system could be operational through recovering the exhaust waste heat from an automotive diesel engine. Analysis of thermoelectric generators for various configurations was carried out by Favarel et al. [18]. They presented the thermoelectric generator for various operating states of hot inlet gas airflow rate and of cold inlet source temperature. Power density optimization for micro thermoelectric generators was investigated by Dunham et al. [19]. They showed that different combinations of thermal and electrical conductivities, and Seebeck coefficient resulting same Figure of Merit (ZT) gave rise to different