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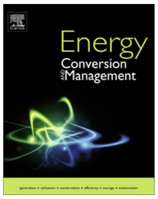

Thermoelectric generator performance analysis: Influence of pin tapering on the first and second law efficiencies

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ABSTRACT

Thermoelectric generators are the important candidates for clean energy conversion from the waste heat; however, their low efficiency limits the practical applications of the devices. Tailoring the geometric configuration of the device in line with the operating conditions can improve the device performance. Consequently; in the present study, the influence of the pin geometric configuration on the thermoelectric generator performance is investigated. The dimensionless tapering parameter is introduced and its effect on the first and second law efficiencies is examined for various operating conditions including the external load resistance and the temperature ratio. It is found that the first and second law efficiencies are significantly influenced by the pin geometry. The dimensionless tapering parameter (a), increasing tapering of the thermoelectric pins, within the range of $2 \leqslant a \leqslant 4$ results in improved first and second law efficiencies. However, the dimensionless tapering parameter maximizing the first and second law efficiencies does not maximize the device output power. This behavior is associated with the external load resistance which has a considerable influence on the device output power such that increasing external load resistance lowers the device output power.

1. Introduction

Thermoelectric power generation from the waste heat sources offers advantages over the other conventional energy generation systems when the low power is required. This is mainly because of simplicity of the operations, which does not involve with rotating parts and the carrier fluids. Although the thermal efficiency of the generator is low, its low cost and simplicity make it attractive for the practical applications. The development of new thermoelectric materials for high figure Merit increases the usage of thermoelectric generators in practical applications. However, further studies are required for the cost effective utilization of thermoelectric generators in practical applications. The thermal conversion efficiency of thermoelectric elements can be improved through proper designing of thermoelectric active elements via altering the device geometric configurations [1]. Thermal analysis incorporating geometric configurations of the thermoelectric generators provides useful information about the optimum design of the device for the improved performance. The design configuration also depends on the operational conditions including temperature range, internal and external load parameters, and active elements material, which can be characterized through the figure of Merit [2]. Consequently, further investigation into the influence of active elements geometric configuration on thermal characteristics of the thermoelectric generator within the frame of different operating conditions becomes essential.

Considerable research studies were carried out to examine thermoelectric generation and thermal system characteristics [3–17]. Thermal analysis of a segmented thermoelectric generator was carried out by Ming et al. [3]. They indicated that the segmented thermoelectric pins could increase the efficiency and voltage output of the device in most situations. Thermal analysis of a thermoelectric device and the influence of geometric features on device characteristics were investigated by Ibrahim et al. [4]. They showed that the device output power could increase significantly with a small change in the shape factor; however, further increase in the shape factor did not influence output power of the device. In addition a unique design configuration was present for a fixed operating condition of a thermoelectric generator; in which case, thermal efficiency and output power of the device attained the high values. Thermodynamic analysis of thermoelectric power generator and influence of pin geometry on device performance was studied by Al-Merbati et al. [5]. They showed that thermal efficiency improved for certain geometric configuration of the device; in which case, the maximum thermal stress developed in the pins

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Nomenclature

a	dimensionless tapering parameter
$A_{upper}(x)$	area variation in upper proration of thermoelectric generator leg (m^2)
$A_{lower}(x)$	area variation in lower proration of thermoelectric generator leg (m^2)
A_a	constant in exponential variation of area (m^2)
A_0	area of rectangular geometry of thermoelectric generator (m^2)
C_H	thermal conductance at high temperature reservoir (W/K)
C_L	thermal conductance at low temperature reservoir (W/K)
I	electrical current (A)
k	thermal conductivity (W/mK)
k_n	thermal conductivity of n-type semi-conductor (W/mK)
k_p	thermal conductivity of p-type semi-conductor (W/mK)
K	overall thermal conductivity of the thermoelectric generator (W/K)
K_0	reference thermal conductivity for thermoelectric generator (W/K)
L	length of leg of thermoelectric generator (m)
$\dot{Q}_H$	heat flux at hot reservoir (W/m^2)
$\dot{Q}_L$	heat flux at cold reservoir (W/m^2)
r_k	thermal conductivity ratio
r_σ	electrical conductivity ratio
R	overall electrical resistance of thermoelectric generator (Ω)
R_L	external load resistance (Ω)
R_0	reference electrical resistance (Ω)
R_{leg}	overall electrical resistance in single leg (Ω)
T_0	ambient temperature (K)
T_1	hot side temperature of the thermoelectric generator (K)
T_2	cold side temperature of the thermoelectric generator (K)
T_H	temperature of hot reservoir (K)
T_L	temperature of cold reservoir (K)
$\dot{S}_{gen}$	total entropy generation (W/K)
S^*	dimensionless entropy generation
$\dot{W}$	work output from the thermoelectric generator (W)
ZT_{avg}	dimensionless Figure of merit (1/K)
α	net Seeback coefficient (V/K)
α_p	Seeback coefficient of p-type semi-conductor (V/K)
α_n	Seeback coefficient of n-type semi-conductor (V/K)
λ_H	dimensionless thermal conductivity for hot junction
λ_L	dimensionless thermal conductivity for cold junction
η_I	first law efficiency
η_{II}	second law efficiency
σ_p	electrical conductivity of p-type semi-conductor (S/m)
σ_n	electrical conductivity of n-type semi-conductor (S/m)
θ	dimensionless ratio of cold and hot reservoir temperature
θ_0	dimensionless ambient temperature
θ_2	dimensionless cold side temperature
θ_H	dimensionless hot reservoir temperature
θ_L	dimensionless cold reservoir temperature

reduced slightly. Temperature field and thermal stress developed in a thermoelectric power generator was examined by Wu et al. [6]. They demonstrated that due to the high heat flux, the thermal stress remained high, which had a decisive effect on the life expectation of the device. The performance analysis of a thermoelectric cooling and heating system was investigated by He et al. [7]. They indicated that the energetic efficiency of the system in summer operation mode was higher than that of it in winter operation mode, but the exergetic efficiency in summer operation mode was lower than that in winter operation mode, on the contrary. The performance improvement for micro-thermoelectric energy generator based on system analysis was presented by Yu et al. [8]. They investigated the thermal matching requirement for thermocouples dimension and array density to maximize the output power. They demonstrated that the wristwatch-thermoelectric application produced 0.32 μW output power, realizing an improvement of three orders of magnitudes for the reported wristwatch-thermoelectric device of the similar materials. The design and thermal analysis of a two stage solar concentrator for combined heat and thermoelectric power generation was studied by Omer and Infield [9]. They showed that the use of thermoelectric generators improved the overall performance of the solar concentrator system. Analysis of a thermoelectric generator incorporating variable material properties and heat losses were carried out by Meng et al. [10]. Their findings revealed that usage of thin ceramic plates increased the junction temperature difference and hence enhanced the thermoelectric generator performance. In addition, there were two optimal leg lengths which corresponded to the maximum output power and the maximum conversion efficiency, respectively. Effect of various leg geometries on thermo-mechanical and power generation performance of thermoelectric devices was investigated by Erturun et al. [11]. They demonstrated that significant differences in magnitudes and distributions of the thermal stresses were developed in the legs due to changing leg geometries. The thermoelectric power generation using a passive cooling system was studied by Date et al. [12]. They introduced a theoretical model to determine the maximum theoretical heat flux capacity of thermoelectric generator and verified the findings with the experimental data. Thermal characteristics of a combined thermoelectric generator and refrigeration cycle were studied by Yilbas and Sahin [12]. They demonstrated that the location of the thermoelectric generator in between the condenser and the evaporator decreased coefficient of performance of the combined system; however, the location of thermoelectric device in between the condenser and its ambient enhanced coefficient of performance of the combined system. Waste energy utilization using a thermoelectric generator in automobiles was examined Karri et al. [14]. They showed that the thermoelectric power generator system weight was one of important issue for the sport utility vehicles. Effects of environmental factors on the conversion efficiency of solar thermoelectric co-generators comprising parabola trough collectors and thermoelectric modules without evacuated tubular collector were studied by Li et al. [15]. The findings revealed that although the electrical efficiency of the system increased with increasing solar insolation, it decreased with increasing ambient temperature and wind velocity. Investigation of exhaust-based thermoelectric generator system for internal combustion engines was carried out by Niu et al. [16]. They showed that a single exhaust-based thermoelectric generator design might not be suitable for all the engine operating conditions; however, introducing the number of exhaust channels and adjustable bafflers, according to different engine operating conditions, could improve the thermal performance. The thermoelectric power generator and the effect of leg geometry on the efficiency and power generation were