Energy Conversion and Management 78 (2014) 634–640

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Thermodynamic analysis of a thermoelectric power generator in relation to geometric configuration device pins

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ARTICLE INFO

Article history:
Received 2 October 2013
Accepted 21 November 2013
Available online 18 December 2013

Keywords:
Thermoelectric
Power
Leg geometry
Efficiency
Exponential area variation

ABSTRACT

Thermoelectric generators (TEG) are cost effective solid-state devices with low thermal efficiencies. The limitations, due to the operational temperature of the thermoelectric materials, suppress the Carnot efficiency increase of the device. Although thermoelectric generators have considerable advantages over the other renewable energy devices, low convergence efficiency of the device retains thermoelectric devices behind its competitors. In order to keep up with the competition, improvement of device efficiency becomes crucial for the practical applications. The design configuration of the device pin legs, lowering the overall thermal conductance, can improve the device efficiency. Therefore, in the present study, the influence of pin leg geometry on thermal performance of the device is formulated thermodynamically. In this case, the exponential area variation of pin legs is considered and dimensionless geometric parameter 'a' is introduced in analysis. The influence of dimensionless geometric parameter on efficiency and power output is demonstrated for different temperature ratios and external load resistance ratios. It is found that increasing dimensionless geometric parameter improves the thermal efficiency of the device; however, the point of maximum efficiency does not coincide with the point of the maximum device output power.

1. Introduction

Thermoelectric generators (TEG) are a solid-state, which are used to convert thermal energy into electrical energy. The conversion of waste heat into electricity takes place in the device pins due to the Seebeck effect. A thermoelectric generator (TEG) creates voltage because of charge carriers in semiconductor pins, which are free to move much like gas molecules while carrying charge as well as heat. A potential difference is produce because of the buildup of charge carriers, which result in a net charge at the cold end. Since TEG does not contain any moving part and no require combustion, they can be considered as one of the alternative renewable energy resources. TEG can be used to recover waste heat and convert it into electrical power, which becomes important with awareness of the environmental impact on global climate change. The TEG efficiency depends upon the operating temperature, figure of merit, and design configuration of the device. Geometric configuration of thermoelectric is one of the important factors affecting the thermal efficiency and the power output of thermoelectric generator. Therefore, investigation of geometric configuration of TEG is becomes essential.

Considerable research studies were carried out to examine thermoelectric device performance. Hoder [1] studied the thermoelectric generator characteristics to find the optimum arrangements of semiconductor pellets. He discussed the effect of number of pellets and their heights on the maximum output power and efficiency of the thermoelectric generator. Yilbas and Sahin [2] introduced the dimensionless parameters, namely, slenderness ratio and the external load parameter to maximize the efficiency and the output power of a thermoelectric generator. Their finding revealed that the efficiency attains high values for the slenderness ratio less than 1 for almost all the cases considered in the study. Lavric [3] performed 1-D thermal analysis to investigate the thermoelectric performance with respect to geometry for the practical applications. She concluded that power output depended on two opposite effects including: (i) reduction in the leg length reduces the electric resistance and (ii) larger legs ensured the higher temperature difference between the two ends of the legs. Sahin et al. [4] studied the effect of thermoelectric generator on the performance of the topping cycle. They showed that the overall efficacy of the system increased slightly for some range of operational conditions. The thermoelectric generator performance analysis was carried out by Chen et al. [5]. They considered the fixed number of thermoelectric elements of the combined device in order to optimize the system heat load and the coefficient of performance. They indicated that the location of the thermoelectric device was critical to

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0196-8904/$ - see front matter
http://dx.doi.org/10.1016/j.enconman.2013.11.029

Nomenclature

a	dimensionless geometric parameter	r_σ	electrical conductivity ratio
$A(x)$	exponential variation of area (m^2)	R	total electrical resistance (Ω)
A_a	constant in exponential variation of area (m^2)	R_L	external load resistance (Ω)
A_H	area of high temperature side (m^2)	R_o	reference electrical resistance (Ω)
A_L	area of low temperature side (m^2)	R_{leg}	overall electrical resistance in leg (Ω)
A_0	area of rectangular geometry of thermoelectric generator (m^2)	T_1	temperature of hot side (K)
A_R	area ratio of high temperature and cold temperature side	T_2	temperature of cold side (K)
I	electrical current (A)	V_o	constant volume of thermoelectric material (m^3)
k	thermal conductivity (W/m K)	W	thermoelectric power generation (W)
k_n	thermal conductivity of n-type semi-conductor (W/m K)	ZT_{avg}	dimensionless figure of merit
k_p	thermal conductivity of p-type semi-conductor (W/m K)	α	total Seeback coefficient (V/K)
K	overall thermal conductivity of the thermoelectric generator (W/K)	α_p	seeback coefficient of p-type semi-conductor (V/K)
K_o	reference thermal conductivity for thermoelectric generator (W/K)	α_n	seeback coefficient of n-type semi-conductor (V/K)
L	length of leg of thermoelectric generator (m)	η	efficiency
$\dot{Q}$	rate of heat transfer (W)	σ_p	electrical conductivity of p-type semi-conductor (S/m)
r_k	thermal conductivity ratio	σ_n	electrical conductivity of n-type semi-conductor (S/m)
		θ	dimensionless temperature = T_1/T_2

maximize the efficiency of the heat pumps. Design and thermal analysis of solar thermoelectric power generation system was carried out by Vatcharasathien et al. [6]. They incorporated the truncated parabolic collectors with a flat receiver, conventional flat-plate collectors, and thermoelectric power generator modules in the analysis. The simulation study for the performance analysis of the thermoelectric power generation with multi-panels was carried out by Suzuki and Tanaka [7]. They demonstrated that the proper arrangements of the thermoelectric panels could shorten significantly the device area despite the fact that the output from the multi-panels could decrease a few percent. Gou et al. [8] carried out experimental study for low temperature waste heat thermoelectric system. They developed a mathematical model for the system. They indicated that use of the thermoelectric generator could save energy from the low temperature waste heat system. Amatya and Ram [9] analyzed the thermoelectric generator for practical applications. Thermodynamic analysis was presented to predict the thermal-to-electric conversion efficiency of the generator. Weinberg et al. [10] studied the thermoelectric power conversion from heat re-circulating combustion systems. They found that the efficiency of thermoelectric devices could be improved for certain arrangements of the locations of the devices around the heat transferring surface. Freunek et al. [11] presented a physical model for a thermoelectric generator. They investigated the influence of heating conditions and load resistance on the thermoelectric power generation. Extensive amount of work has been done in literature [12–20] for studying the thermodynamic analysis of thermoelectric devices performance. In some work the influence of the geometric configuration on thermoelectric devices is considered [21–28]. However, the effect of leg geometry on the performance of the thermoelectric generator has received very little attention. In the present study, the theoretical analysis of thermoelectric generator performance is carried out by considering the effects of leg geometry configuration, operating parameters such as temperature ratio, external load and device resistances. One dimensionless geometric parameter is introduced which defines the effects of leg geometry on power output and efficiency of thermoelectric generator. The study is extended to include the effects of the device leg geometry on the maximum output power and the maximum efficiency of the thermoelectric generator. In the process of the performance optimization the volume of the leg material is kept constant. Thus the geometry of the legs (i.e. the cross sectional area of the legs) is varied by re-distributing the available constant amount of thermoelectric material along the legs of the generator.

2. Thermal analysis

Consider the thermoelectric element of variable cross section as shown in Fig. 1. The properties of leg material are assumed to be temperature independent so that the Thomson effect is inherently neglected. After introducing the Dirichlet boundary conditions, the efficiency of the thermoelectric power generator with legs of variable cross-section (Fig. 1), can be written as:

$$\eta = \frac{I^2 R_L}{\alpha I T_1 + K(T_1 - T_2) - \frac{1}{2} I^2 R} \quad (1)$$

where K is the thermal conductance and R is the electrical resistivity of the thermoelectric generator. The current I is a function of the net Seebeck coefficient $\alpha = \alpha_p - \alpha_n$ (the difference between the Seebeck coefficient of p and n junctions), the upper and lower temperature (T_1 and T_2), the electrical resistance R and the external load resistance R_L as:

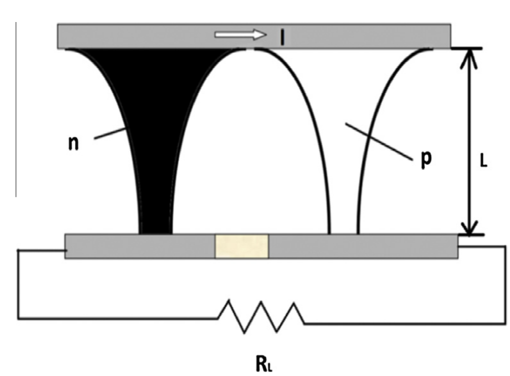

Fig. 1. A schematic view of a thermoelectric power generator with variable cross section legs (pins).