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Modeling and analysis of the effect of thermal losses on thermoelectric generator performance using effective properties

Heonjoong Lee[a,*], Jeff Sharp[b], David Stokes[c], Matthew Pearson[d], Shashank Priya[a,*]

[a] Center for Energy Harvesting Materials and Systems (CEHMS), Department of Mechanical Engineering, Virginia Tech, Blacksburg 24061, USA
[b] Marlow Industries, 10451 Vista Park Rd, Dallas, TX 75238, USA
[c] Electronics and Applied Physics Division, RTI International, Research Triangle Park, NC 27709, USA
[d] Thermal Fluid Sciences Department, United Technologies Research Center, East Hartford, CT 06118, USA

HIGHLIGHTS

- Modeling captures the contributions from thermal losses and interfacial resistance.
- The effective properties provide a precise description of the transport properties.
- Quantification of actual figure-of-merit with thermal losses is performed.
- The performance of TEG is explained quantitatively through effective properties.
- The modeling method is applied to various materials to confirm the feasibility.

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ABSTRACT

A mathematical model for a thermoelectric generator (TEG) based on constitutive equations has been developed to analyze temperature dependent performance in terms of output power and efficiency. Temperature dependent material properties and thermal losses, which occur as conductive and radiative heat transfer, were considered in the finite element model. Effective material properties were invoked for understanding the influence of temperature dependence of material parameters and related adverse effects on the model TEG. It is shown that analytical equations with effective properties can provide excellent estimation of the performance of a TEG over a broad operating range. The model was simulated, analyzed and validated to examine the effects of different operating conditions and geometry that interact with thermal losses inside the TEG. We believe that this model will further expedite the optimization of TEGs being developed using new material compositions.

1. Introduction

Currently, conventional fossil fuels meet most of the energy demands, which has raised concern about increasing ambient temperature and resulting climate change [1]. Therefore, significant effort is being placed on identifying and developing sustainable energy harvesting methods to provide new renewable energy sources [2]. There are many types of ambient and kinetic energy sources from which energy can be harvested, such as thermal energy, ocean waves, wind, solar and mechanical vibrations. Thermal energy is available everywhere and is one of the most attractive energy sources due to the fact that every thermodynamic process is accompanied by the release of wasted energy as heat. Thus, there is a strong interest in developing high efficiency solid state thermal-to-electrical energy harvesting devices that can be utilized in wide ranges of temperature. Thermal energy harvesters are also desired for remote power applications, for example, soldiers camping in remote areas require portable power generators that can convert liquid fuel into electricity. Thermoelectric generators show promise in such applications due to their low weight, noise, and vibration as compared to mechanical systems.

Semiconductor-based thermoelectric (TE) devices utilize the Seebeck effect in order to generate electricity directly from heat without chemical reactions, noise, or harmful byproducts, and thus have attracted much attention as a prospective energy conversion technology. In past, thermoelectric generators (TEGs) have been modelled and characterized to quantify key parameters influencing the performance and understand the quantitative correlation between material/device parameters and performance of the device [3–7]. Internal electrical resistance and thermal conductance causes TEG performance to fall far below the Carnot limit, and their effects on TEGs

* Corresponding authors.
E-mail addresses: leehnj@vt.edu (H. Lee), spriya@vt.edu (S. Priya).

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Nomenclature

A	cross sectional area (m^2)
A_n	cross sectional area of the n type leg (m^2)
A_p	cross sectional area of the P type leg (m^2)
E	energy (J)
G	mutual radiation (W)
g	function
Gr_L	Grasshof number
h	heat transfer coefficient ($W\,m^{-1}\,K^{-1}$)
I	current (A)
k	conductive heat transfer coefficient ($W\,m^{-1}\,K^{-1}$)
k_{avg}	averaged conductive heat transfer coefficient ($W\,m^{-1}\,K^{-1}$)
K_{couple}	thermal conductance of the TEG couple ($W\,K^{-1}$)
K_{eff}	effective thermal conductance ($W\,K^{-1}$)
$K_{eff,couple}$	effective thermal conductance of the TEG couple ($W\,K^{-1}$)
$K_{eff,device}$	effective thermal conductance of the device ($W\,K^{-1}$)
$k_{n,avg}$	conductive heat transfer coefficient of the n type TEG leg ($W\,m^{-1}\,K^{-1}$)
$k_{p,avg}$	conductive heat transfer coefficient of the p type TEG leg ($W\,m^{-1}\,K^{-1}$)
L	length of the TEG leg (m)
L_n	length of the n type TEG leg (m)
L_p	length of the p type TEG leg (m)
N	number of couple
P	power
P_{max}	maximum power (W)
Pr	Prandtl number
Q_c	heat transfer rate at the cold side (W)
Q_{gen}	heat generation rate (W)
Q_h	heat transfer rate at the hot side (W)
Q_{loss}	thermal loss (W)
Q_p	heat transfer rate by the Peltier effect (W)
Q_t	heat transfer rate by the Thomson effect (W)
$Rcouple$	electrical resistance of the TEG couple (Ω)
$Reff,couple$	effective electrical resistance of the TEG couple (Ω)
$Reff,device$	effective electrical resistance of the TEG device (Ω)
RI	internal resistance (Ω)
RL	load resistance (Ω)
T	temperature (K)
$Tamb$	ambient temperature (K)
Tc	temperature at the cold junction (K)
Th	temperature at the hot junction (K)
Voc	open circuit voltage (V)
Vs	voltage by the Seebeck effect (V)
Z	figure of merit
$Zeff$	effective figure of merit

Greek symbols

α	Seebeck coefficient ($V\,K^{-1}$)
αavg	averaged Seebeck coefficient ($V\,K^{-1}$)
$\alpha couple$	Seebeck coefficient of the TEG couple ($V\,K^{-1}$)
αeff	effective Seebeck coefficient ($V\,K^{-1}$)
$\alpha eff,couple$	effective Seebeck coefficient of the TEG couple ($V\,K^{-1}$)
$\alpha eff,device$	effective Seebeck coefficient of the TEG device ($V\,K^{-1}$)
ε	emissivity
η	efficiency (%)
λ	thermal conductivity
μT	Thomson coefficient
π	Peltier coefficient
ρ	electrical resistivity (Ω m)
ρavg	averaged electrical resistivity (Ω m)
$\rho n,avg$	electrical resistivity of n type TEG leg (Ω m)
$\rho p,avg$	electrical resistivity of P type TEG leg (Ω m)
σ	Stefan-Boltzmann constant, $5.6697 \times 10^{-8}\,W\,m^{-2}\,K^{-4}$

connected to heat exchangers have been investigated by both theoretical [8] and experimental analysis. Chen et al. considered the analytical equation for the TE devices, which includes irreversible energy balance equation inside the device [9]. Pramanick et al. conducted analysis of a TEG based on the assumption that the device is isolated without heat leaks at the legs [10]. Some prior numerical models of TEGs were developed without including another important factor in TE device design, which is thermal loss [11]. Temperature dependent material properties and radiative heat loss in the TEG usually are not considered for analytical models due to their nonlinearity, although they vary with temperature and the loss is not negligible with large temperature range [12–17]. From a practical standpoint, consideration of temperature dependence and heat loss is essential for more accurate performance modeling. While most of the analytical models use average values for the material properties, Yamashita et al. and Wee et al. have used temperature dependent material properties for analytical modeling in order to identify the effect of nonlinear component in the model [18,19]. In order to investigate the influence of Thomson effect as well as the nonlinear material properties, analytical expressions were obtained for temperature distribution including the nonlinear effects [19,20]. Numerical methods such as finite difference methods were used for TEG comprising of lead telluride or half-Heusler materials in order to calculate nonlinear effects and provide wider comparison [21,22]. Heat losses have been included in some of the numerical models for TEGs. For example, Muto et al. developed a one-dimensional TEG model with radiative heat loss [23].

The model and the analysis presented here incorporate not only temperature dependent properties and Thomson effect but also thermal losses and interfacial resistance inside the device. The comprehensive modeling approach for thermoelectric devices captures the contributions from thermal losses, Thomson effect, interfacial resistance, and temperature dependent material properties. These effects are shown to be essential in accurately predicting TE performance—since maximum TE performance (either maximum power or maximum efficiency) requires a thorough optimization, accurate performance models are essential. The model demonstrates effectiveness in quantifying the performance of a $(30\,mm)^2$, 127-couple thermoelectric generator and is validated by comparing with Finite Element Modeling (FEM) results. The output power and efficiency variation with thermal losses are investigated. If the thermal losses, and contact and interconnect electrical resistance are low, the internal loss can be reduced resulting in higher power density and smaller device dimensions, which is desired for a portable TEG. A small magnitude of thermal loss or changes in the geometry can significantly affect the performance of a TEG due to its small power, low conversion efficiency and limited size. The modeling and optimization approach is discussed subsequently, followed by the quantification of the performance considering effective properties of the TEG to understand the effect of various thermal losses and structural design variables. Furthermore, the method is applied to the different material properties and the results are compared to verify the feasibility and applicability of the effective properties to various designs so that engineers designing TEG can take advantage of this approach for design optimization with a variety of materials.