Applied Thermal Engineering 51 (2013) 1–9

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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

Behavior of thermoelectric generators exposed to transient heat sources

Nguyen Q. Nguyen, Kishore V. Pochiraju*

Design & Manufacturing Institute, Department of Mechanical Engineering, Stevens Institute of Technology, Castle Point on Hudson, Hoboken, NJ 07030, USA

HIGHLIGHTS

► Thermoelectric model with Peltier, Seebeck, Joule and Thomson effects.
► Thomson effects are shown to play a significant role in power generation modes.
► Optimal operating points for generating power from transient heat sources.

ARTICLE INFO

Article history:
Received 20 October 2011
Accepted 25 August 2012
Available online 12 September 2012

Keywords:
Thermoelectric generators
Direct energy conversion
Dynamic transient analysis
Thomson coefficient effect
Thermoelectric coupling physics
Characterization of thermal–electrical properties

ABSTRACT

This paper describes the power generation behavior of a thermoelectric generator (TEG) exposed to a transient heat source on the hot side and natural convection on the cold side. The simulation situation is typical in energy harvesting applications. Modeling thermoelectric generators (TEGs) under these conditions is complicated compared to thermoelectric coolers because of the non-linearities and the unknown electric currents in a closed-loop circuit. A transient thermoelectric model that includes Seebeck, Peltier, Thomson, and Joule effects is solved using finite-difference techniques and the power generated from a TEG is simulated. Using open-circuit experiments were used to establish key parameters governing the thermal behavior and thermoelectric coupling. Experiments with closed-circuits and load resistors were used to validate the model. The results show that inclusion of Thomson effect plays a significant role in accurately predicting the power generated by the device.

1. Introduction

Thermoelectric generators (TEGs), or Seebeck elements, enable conversion of thermal energy into electricity without any moving parts. The Seebeck elements can be used for temperature sensing s and power generation applications [1]. TEGs generate electric current in a closed-circuit across a load when a temperature gradient develops between the two ends of the device [2–4]. The coupling effects governing the conversion are the Seebeck, Peltier, Thomson, and Joule effects.

Understanding the transient behavior of TEG is important for optimizing energy harvesting from waste heat, when one junction is exposed to an unsteady heat source and the other junction is subjected to natural convection at ambient temperature. Several models have been developed for such configurations [5–7], but most models assume either an unlimited heat source or steady state operational scenarios. Practical applications such as parasitic energy harvesting from waste heat sources generally have unsteady heat flux and/or temperature conditions on the hot side of the TEG and pose a fully coupled thermoelectric problem [8]. Simulation of TEGs operating in transient mode is more challenging than the thermoelectric coolers (TECs) because both the temperature field and the electric currents vary with time. The problem is more simplified for TECs as a constant and known electric current is applied as input and only the temperature gradients need to be determined.

Several models for TEG modules can be found in the literature. Numerous analytical [6,9] and numerical [10–13] steady state models exist for simulation of TEGs. However, fully coupled and complete transient analyses are seldom presented. Transient analysis of TEG subjected to a load change from steady state configuration has been conducted using commercial software [14,15]. Mitrani et al. [16] considered temperature-dependent material properties and the effect of thermal and electrical contacts. Furthermore, most models exclude the Thomson effects [17,18] and their influence on apparent Seebeck coefficients. Crane [19] showed the differences in the TEG behavior at steady state and during transients using an uncoupled thermoelectric model that used a constant current value in the thermal balance equation and no Thomson effects.

* Corresponding author. Tel.: +1 201 216 8232/8053; fax: +1 201 216 8963.
E-mail addresses: nnguyen@stevens.edu (N.Q. Nguyen), kishore.pochiraju@stevens.edu (K.V. Pochiraju).

1359-4311/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2012.08.050

Nomenclature

L	Length of p–n
L_1	Thickness of ceramic hot plate
L_2	Thickness of ceramic cold plate
A	Cross-sectional area
A_s	Convection area of heat sink
k	Thermal conductivity
ρ	Material density
C	Specific heat capacity
α	Seebeck coefficient
μ	Thomson coefficient
π	Peltier coefficient
ε	Electrical resistivity
T	Temperature
T_∞	Ambient temperature
t	Time coordinate
x	Spatial coordinate
R	Internal resistance
R_0	Load resistance
I	Electric current
V	Voltage
$\dot{Q}$	Heat rate
W	Stored energy
h	Film coefficient of heat sink
Subscripts	
p	p-type material
n	n-type material
1	Material of hot plate
2	Material of cold plate

In this paper, we examined the behavior of a TEG when exposed to unknown and varying heat source representative of energy harvesting scenarios. We simulated the power generation characteristics of the TEG under specified temperature profiles that emulate varying heat flux applied to the hot side. The model parameters for a commercial TEG element were characterized by correlating the simulation results and the experimental observations. We show that the developed numerical model captures the thermal behavior and the electrical behavior of the TEG in both open and closed-circuit configurations.

2. Theoretical modeling

2.1. Assumptions

The basic assumptions made include neglecting heat losses due to radiation and transverse convection. The flow of heat and current in the TEG is assumed one-dimensional. All materials are assumed homogeneous. Material property anisotropy is taken into account by selecting properties relevant along the dimension selected for the analysis. Thermal conductivities, electrical resistivity, and specific heat capacities of materials are assumed constant within the operating temperature range. While the numerical methods used did not require any of the above assumptions, these simplifications help in understanding the fundamental mechanisms. The reduction in the dimensionality of parametric space enhances the clarity during the correlation of experimental observations and model findings.

2.2. Governing equations

The schematic of a thermoelectric generator consisting of two thermoelectric elements, p- and n-type is shown in Fig. 1. The simulation dimension is divided into three local frames, namely $\{x_1, x, x_2\}$. The x-coordinate is chosen with the origin at the bottom surface of the TEG. The length of the TEG is denoted by L. x_1 and x_2 are local coordinates in the hot and cold plates at either ends of the TEG elements, respectively. The power at each junction induced by the Seebeck and Peltier effects and direction of thermal conduction through the two elements is shown in the figure. The current, $I(t)$, flowing through a load resistor indicates that the device is operating in power generation mode.

Governing equations for p- and n-thermoelectric elements are derived from the energy balance equation for an infinitesimal element, dx, as given in Eqs. (1) and (2) [17,20]:

$$A_pC_p\rho_p\frac{\partial T_p}{\partial t} = k_pA_p\frac{\partial^2 T_p}{\partial x^2} + \frac{\varepsilon_p}{A_p}I^2 - \mu_pI\frac{\partial T_p}{\partial x} \quad (1)$$

$$A_nC_n\rho_n\frac{\partial T_n}{\partial t} = k_nA_n\frac{\partial^2 T_n}{\partial x^2} + \frac{\varepsilon_n}{A_n}I^2 + \mu_nI\frac{\partial T_n}{\partial x} \quad (2)$$

where A_j, C_j, ρ_j, k_j, ε_j, μ_j and T_j are the cross-sectional area, specific heat capacity, density, thermal conductivity, electrical resistivity, Thomson coefficient and temperature of material j, respectively. I is the electric current flowing in a closed-circuit. t is the time variable and x is the spatial coordinate. Subscripts p and n denote the two TEG elements.

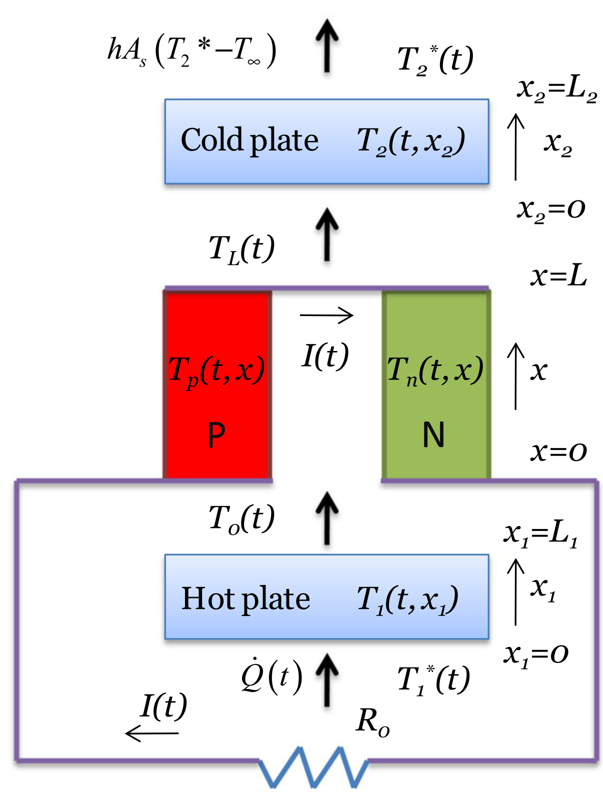

Fig. 1. Schematic of thermoelectric generators with hot and cold plates.