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Analytical study of transient performance of thermoelectric coolers considering the Thomson effect

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ABSTRACT

Analytical solutions of transient temperature distributions within semiconductor elements are presented in this study. The performance of a thermoelectric cooler (TEC) under the influences of the Thomson effect, Joule heating, and combined radiation and convection cooling is investigated. The solution of the temperature distributions is obtained by solving the governing heat conduction equation using the superposition technique with the aid of a special transformation function. The closed-form transient temperature profiles for the semiconductor element sizes, applied current, cooling load, heating power, power consumption, and the system coefficient of performance (COP) of a TEC are presented. The interrelationships between the aforementioned effects are examined in detail. The analytical temperature solution presented in this study can be utilized by design engineers in the thermoelectrics industry as a convenient means to demonstrate compliance of the device heating or cooling design specification requirements.

1. Introduction

Thermal management has become an important topic in the electronics industry because of miniaturization and increasing power density [1]. Furthermore, the performance of many devices depends on the complex interplay between thermal, electronic, and optical phenomena. Thus, a thorough knowledge of how to achieve electrical and thermal stability has become an integral consideration in the design process of many types of electronic equipment, e.g., semiconductor optical devices, infrared detectors, and laser diodes.

Thermoelectric coolers (TEC) are a type of solid-state heat pump. Since the 1950s they have become a viable thermal technology for small cooling applications as the result of their favorable characteristics of size and weight, no moving parts, promising thermal and electrical stability, and scalable power consumption. This technology is particularly suitable in precise applications where temperature control must be within fractions of a degree because of a system time constant. In addition, it is commonly employed in situations where the use of refrigerants is undesirable. Consequently, TECs are ideal candidates for the cooling of small devices in electronic and aerospace thermal management applications.

A TEC performs as a solid-state heat pump between junctions of two dissimilar conductors at different temperatures. When an electrical current is applied through the junctions of the two conductors, a cooling effect is produced. As a result, the TEC transfers thermal energy through the semiconductor elements from one side of the system to the other side in a direction that depends on the element. It flows opposite to the electrical current flow in the *n*-type element, but in the same direction in the p-type element as shown in Fig. 1. It cools one side and heats the opposite side of the semiconductor elements simultaneously.

A basic overview of thermoelectric devices and their potential applications, e.g., thermal energy sensors, superconductors, aeronautics and space industries, can be found in the study by Riffat and Ma [2]. Chein and Hung [3] investigated the application of thermoelectric coolers for electronic cooling. Their study provided a detailed computational technique for the determination of the cooling capacity, junction temperature, coefficient of performance, and heat sink thermal resistance of a TEC. In particular, the study addressed the application of microchannel heat sinks to TECs in detail. Zhang et al. [4] analyzed the performance of thermoelectric coolers for high power electronic packages. The study presented two analytical solutions based on the junction temperature and cooling power for common TEC parameters. The solutions were derived for one of these two parameters while the other one was held constant. The maximum cooling power and the minimum junction temperature for the TEC system were then determined through optimization. Hodes [5] performed a one-dimensional heat conduction analysis in a thermoelectric device subjected to various type of boundary conditions. Fraisse et al. [6] performed a comparison of different modeling approaches for thermoelectric devices. Several simplified models were compared to the more

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Nomenclature

A_c	local cross-sectional area of the thermoelectric element, m^2
A_m	coefficient
B_m	coefficient
$C_1 \ldots C_6$	coefficients
c_p	heat capacity, J/kg K (=Ws/kg K)
d	element diameter, m
G	thermal conductance ($= kA_c/L$), W/K
$\mathcal{G}$	function, Eq. (7b)
h	convective heat transfer coefficient, W/m^2 K
h_r	linearized heat transfer rate ($= 4\varepsilon\sigma_B T_\infty^3 + h$), W/m^2 K
I	current ($= j_e A_c$), A
i	index (= 0, 1, 2)
j	index (= 0, 1, 2)
j_e	applied current density, A/m^2
k	thermal conductivity, W/mK
L	length of the thermoelectric element, m
m	series index
P	dimensionless thermoelectric element cooling parameter ($= P^* h_r L/G$)
P^*	thermoelectric element perimeter ($= \pi d$), m
P_o	power consumption, W
Q_c	heat load at the cold side, W
Q_h	heat sink at the hot side, W
R	electrical resistance ($= L\rho_e/A_c$), Ω ($=W/A^2$)
T	temperature, K
ΔT	temperature difference ($= T_h - T_c$), K
t	time, s
W	modified temperature variable of θ
W_{0j}	quasi steady state solution of W
W_H	homogeneous solution of W
W_j	special sub-problem solution of W
x	x-coordinate, m
Y	space-dependent variable
Z	time-dependent variable

Greeks

α	Seebeck coefficient, V/K (=W/A K)
α_t	thermal diffusivity ($= k/\rho c_p$), m^2/s
β	Thomson coefficient, V/K (=W/A K)
δ_{ij}	Kronecker delta
ε	emissivity
ζ	dimensionless time ($= \alpha_t t/L^2$)
η	parameter ($=\mp\Phi$)
θ	dimensionless temperature [$= (T - T_\infty)/\Delta T$]
λ_m	eigenvalue, Eq. (12i)
ξ	dimensionless spatial coordinate ($= x/L$)
ρ	material density, kg/m^3
ρ_e	electrical resistivity, Ωm ($=Wm/A^2$)
σ_B	Stefan-Boltzmann constant, W/m^2 K^4
Φ	dimensionless parameter ($= \beta j_e L/k$)
φ_j	function related to W_j
Ψ	dimensionless parameter ($= I^2R/G\Delta T$)

Subscripts

c	cold
h	hot
i	initial
n	n-type element
p	p-type element or constant pressure condition
∞	ambient

sophisticated models based on an electrical analogy using the finite element method. The study indicated that for a one-dimensional analysis, all models yield similar results, provided that a null Thomson coefficient is used under a constant Seebeck coefficient condition. An analytical solution method based on an electrical analogy devised by Fraisse et al. [7] took into account the combined Peltier, Joule, and Thomson effects.

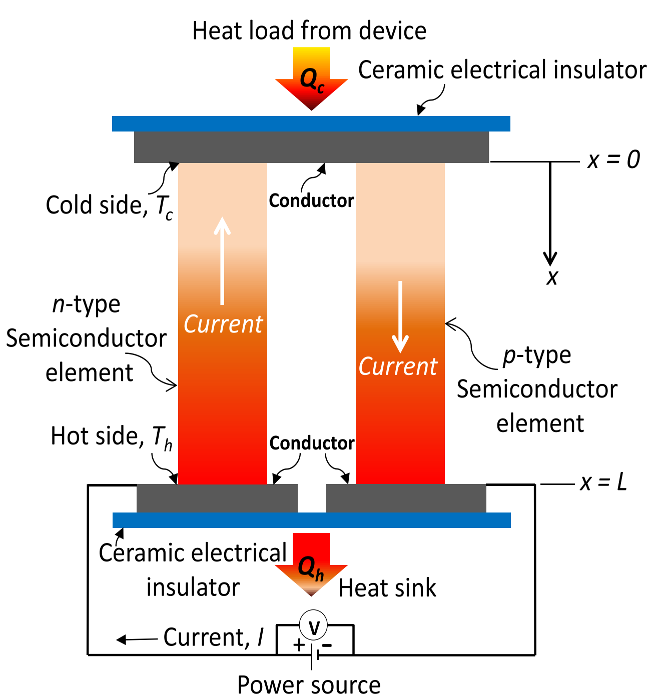

Fig. 1. Schematic cross-section of a thermoelectric cooler.

Optimization techniques were widely used in thermoelectric cooler designs. Hung et al. [8] conducted experimental tests to determine the physical properties of a thermoelectric device system. The resulting experimental performance curve was utilized as an input to the cooler thermal network system model that enabled the designer to determine an optimized heat sink or optimal cooling capacity during the thermoelectric cooler system design process. Lee [9] utilized dimensional analysis for optimum design of thermoelectric devices based on heat sink temperature requirements. The design parameters included system efficiency, power consumption, electrical current, and heat sink thermal resistance, along with geometric design information. Jeong [10] presented an approach for the study of a thermoelectric device based on a technique which optimized the current for maximum system coefficient of performance (COP) based on the cooling capacity, thermal and electrical contact resistances, properties of thermoelectric material, and the hot- and cold-end temperatures of the system. Cheng and Lin [11] performed a study to determine the optimal cooling capacity while minimizing the COP by concentrating on the geometry of a thermoelectric device that included the semiconductor element leg length, area, and number of legs. The study revealed that the cooling capacity can be increased with optimal TEC dimensions.

Most early thermoelectric cooler studies neglected the Thomson effect, but many recent studies have confirmed its importance. Two studies by Fraisse et al. [6,7] revealed that in order to improve the accuracy of the analytical results, the Thomson effect should be included in the calculations. The influence of the Thomson effect on a