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A model to analyze the device level performance of thermoelectric generator

Yongjia Wu, Lei Zuo*, Jie Chen, Jackson A. Klein

Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, VA, 24060, USA

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ABSTRACT

The thermoelectric generator (TEG) is a distinctive solid-state heat engine with great potential in various scale energy harvesting. Device-level heat transfer coupled with energy conversion makes the accurate analysis of the system very complicate. In this paper, the thermodynamic analysis in a TEG module is carried out to study the influence of the contact layer resistance, Thompson Effect, Joule heat, and thermo-pellet gap heat leakage on the performance of the TEG. All expressions of power output, current, matching load resistant factor, and efficiency of the device are derived and compared with a commercial module. The equations for the simplified model are also given concisely in order to give a full picture of TEG modeling. The research can evaluate the combined influence of all the factors and redress some derivations in the existing models.

1. Introduction

The thermoelectric generator (TEG) is a solid-state device which converts thermal energy into electricity based on Seebeck Effect without any moving parts. When there exists a temperature difference between the hot and cold ends of TE material, the charge carriers (electrons, e^-, in n-type materials and holes, h^+, in p-type materials) at the hot side move to the cold side, producing an electrostatic potential. The Seebeck Effect was first discovered in metal in 1821 [1], when Thomas Johann Seebeck, a German scientist, found that a compass needle defected when the joint of two conductors was heated. But the effect did not arouse much attention because the Seebeck coefficient of metal was very small (typically less than 10 μV/K). With the discovery of semiconductors and its alloys with high Seebeck in 1950s [2], the new potential of thermoelectric technology refocused people's attention. The classical thermoelectric materials [3] including Bi_2Te_3 and its alloys with Bi_2Se_3/Sb_2Te_3 working in low temperature ranges, PbTe and its alloys with PbSe/SnTe in medium temperature ranges, and SiGe alloys in high temperature ranges, all have Seebeck coefficients of more than 200 μV/K, making it possible to develop generators or coolers based on thermoelectric materials. The device has many advantages over other conventional energy harvesting technologies, including quietness, small size, cleanliness, high energy density, long lifecycle, and simplicity. TEGs are currently widely used in applications ranging from power generators in space missions [4], common thermocouple sensors [5], small energy harvesters [6] for self-powered sensors [7], to automobile exhaust energy harvesting [8]. Small TEGs can be integrated directly onto key industrial components, including pipes, pump housings, heat exchangers, reactor vessels, boiler bodies, distillation columns, shielding structures, and many other components, acting as reliable energy sources to power monitoring sensors, control circuits, and communications equipment.

The technology has receiving intensive attention in recent years as the efficiency of the devices has been greatly increased thanks to the impressive progress in the nano materials [9] and thermal design technology since the 1990s [10]. According to new research, the highest ZT reported was 3.5 in Bi-doped n-type PbSeTe/PbTe quantum-dot super-lattice by Harman et al. [11], and the corresponding energy conversion efficiency is expected to reach 20%. Another work done by Venkatasubramania et al. [12] reported a thin-film Bi_2Te_3/Sb_2Te_3 super-lattice device with a ZT value as high as 2.4. All these progresses significantly extend the potential application range of the devices. There were no evidence showed that there were ZT limitation for thermoelectric material. Mahan and Sofo [13] thought that $ZT = 14$ were achievable in rare-earth compounds. An inconvenient truth about thermoelectric is that,

* Corresponding author.
E-mail address: leizuo@vt.edu (L. Zuo).

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Nomenclature

ΔT, T_h, T_c Temperature difference, hot and cold end temperatures of thermo-pellets (K)
T, T_H, T_C Temperature, hot and cold temperatures of TEG module (K)
Z, Z_{PN}, Z_{PN}^c Thermoelectric figure-of-merit of material
η, η_c, γ Efficiency, Carnot efficiency, and reduced efficiency
λ_P, λ_N, λ_g, λ_{CH}, λ_{CC} Thermal conductivities of P, N-type thermoelectric materials, filling gas, hot end ceramic cover and cold end ceramic covers (W/(m·K))
A_P, A_N, A_g, A_{CH}, A_{CC} Cross-section areas of P, N-type thermo-pellets, filling gas, hot and cold end ceramic covers (m^2)
L_P, L_N Leg length of P, N-type thermo-pellets (m)
K_P, K_N, K_{PN}, K_{CH}, K_{CC} Thermal conductance of P, N-type thermo-pellets, thermal conductance of a thermocouple, thermal conductance of hot and cold end ceramic covers (W/m^2 K)
ε Emissivity of the ceramic plate surface
σ Stefan-Boltzmann constant (W m^{-2} K^{-4})
ρ_P, ρ_N Electrical resistivity of P, N-type thermoelectric materials (Ω m)
R_P, R_N, R_{PN} Electrical resistance of P, N-type thermoelectric materials, electrical resistance of a thermocouple (Ω)
$\tau_P, \tau_N, \tau_{PN}$ Thompson coefficients of P, N-type thermoelectric materials, Thompson coefficient difference of P, N-type thermoelectric materials (V/K)
q, q_h, q_c Total heat flow, hot end heat absorption and cold end heat absorption (W)
α, α_P, α_N, α_{PN} Seebeck coefficient, Seebeck coefficients of P, N-type thermoelectric materials, Seebeck coefficient difference of P, N-type thermoelectric materials (V/K)
$\alpha_P^h, \alpha_P^c, \alpha_N^h, \alpha_N^c, \alpha_{PN}^h, \alpha_{PN}^c$ Seebeck coefficients of P, N-type thermoelectric materials at the hot and cold ends, Seebeck coefficient difference of P, N-type thermoelectric materials at hot and cold ends (V/K)
R_{ch}, R_{cc}, R_c Electrical contact resistance at the hot and cold ends of thermo-pellets, total electrical contact resistance (Ω)
R_G, R_L Internal resistance of TEG, load electrical resistance (Ω)
P Power output (W)
I Electrical current (A)
u, v, w, θ Non-dimensional factors
$K_P^*, K_N^*, R_P^*, R_N^*$ Reduced thermal conductance (W/m^2•K), reduced electrical resistance (Ω)
s, r_c, r_{cc}, r_{ch} Electrical load resistance factor, total contact layer electrical resistance factor, hot and cold end electrical contact resistance factors
K_H, K_C, K_{CH}, K_{CC}, K_{CCH}, K_{CCC} Thermal conductance of the hot and cold end ceramic covers, hot end and cold end ceramic cover thermal conductance, hot and cold end contact layer thermal conductance (W/m^2•K)
K_{SH}, K_{SC} Hot and cold end heat sink/exchanger thermal conductance (W/m^2•K)
f_h, f_c Hot and cold end TEG module thermal conductance factor

until now, the conversion efficiency of TEG is still far less than mechanical thermal engines [14]. For the moment, the practical and economic applications of this technology are still limited in relatively small scale, decentralized energy harvesting.

With the ever-rising demand for energy and urgency for CO_2 emission reduction, thermoelectric technology, being clean and renewable, is a potential candidate for waste-heat harvesting as well as for small scale power generation from various heat sources [15–17]. For example, more than two thirds of the heat produced in automobile is discharged into the surrounding. If ten percent of the waste energy is recovered by TEG modules, the total amount of energy saved will be huge. Moreover, nuclear plants accidents (Chernobyl, Three Mile Island, and Fukushima Daiichi) have cast a shadow on the history and future of nuclear power. The security problem in severe situation monitoring is the first consideration in industrial community. Self-powered sensing system aroused much interest these years. TEG is one of the most promising alternatives for the conventional cable power supply system for the sensing and monitoring in nuclear accidents [18].

There are many mathematical models built to analyze the performance of TEG models [16,19–21]. In most cases, people neglected the contact layer thermal and electrical resistance, Thompson Effect, and heat leakage to simplify their models [15]. However, with the development of MEMS, more subtle TEGs/TECs are requiring for small scale fabrication [12]. And more accurate, resilient device level analysis is needed to evaluate their performance. The conceptual design and optimization of TEG are still main concerns in TEG research. An accurate analysis relies on a more sophisticated mathematical model. The performance of the TEG affected by Fourier's heat conductivity, Peltier Effect and Joule heat generation rate has been analyzed by many research works [20–23]. The influence of the Thomson effect on the performance of a thermoelectric generator was also studied by some articles [23], though in most cases, the Thompson Effect will has relatively small impact on the whole performance of TEG. In real situation, heat sink and heat exchanger are fixed at the cold and hot end of TEG to maximum its efficiency and power output. Application of thermoelectric energy conversion from thermal to electricity requires careful device level analysis [21]. In addition, in the actual TEG module, there are many layers, such as a diffusion barrier between thermos-pellets and interconnectors, air or thermal insulation materials filling the gap between P, N-type thermos-pellets, and thermal grease layer between different components. Only when all these factors are taken into consideration, will we give a precise evaluation of the performance of a TEG module.

The most widely used thermodynamic model to evaluate the performance of TEG module is the ideal one-dimensional TEG model given in many books, such as [24]. This model assumes that the contact layer is ideal with no resistance; there is no heat leakage and no material properties change in the module. The model is coarse and, in most cases, will overestimate the performance of the device. Subsequently, researchers develop more accurate models to make more precise description of thermoelectric device. Min and Rowe [25] investigated the effect of thermo-pellets length on the module's coefficient of performance (COP) and heat pumping capacity. The results showed that the performance of TEG was largely deteriorated by the thermal/electrical contact resistances, particularly when the thermo-pellet length was small. As the Thompson