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Geometric optimization of thermoelectric elements for maximum efficiency and power output

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ABSTRACT

The geometry of n- and p-type thermoelectric elements (TE) in terms of the cross-sectional area and length were optimized to yield either maximum thermal conversion efficiency $\eta_{th,max}$ or maximum power output $P_{o,max}$. The optimization process incorporated temperature-dependent material properties and independent thermal and electrical contact resistances that are a function of the contact area per TE leg. Additionally, $\eta_{th,max}$ and $P_{o,max}$ were quantified by simultaneously optimizing the TE geometry and varying the hot-side fluid temperature, cold- and hot-side heat exchanger effective area and heat transfer coefficients using a complete one-dimensional thermal resistance network model. Optimized compared to non-optimized geometries, excluding contact resistances, achieve a maximum 10.4% increase in $P_{o,max}$ and 3.2% increase in $\eta_{th,max}$ for conditions studied. Optimized compared to non-optimized geometries, taking into account independent thermal and electrical contact resistances, exhibit a 29% increase in volumetric power density and 12% increase in volumetric efficiency in comparison to non-optimized cases.

1. Introduction

Thermoelectric devices (TEDs) are steady-state direct-energy conversion apparatus that convert a temperature difference into electrical power (Seebeck effect [1]) or use an applied voltage potential to generate a temperature difference (Peltier effect [2]). TEDs are comprised of n- and p-doped semiconductors that have a high Seebeck coefficient α, low electrical resistivity ρ and low thermal conductivity λ [3,4]. It was not until the advent of semiconductors in the 1950's, and focused attention on the production of thermoelectric devices, that modern thermoelectric theory and devices with moderate performance began to emerge [5,6]. The performance of the device depends on two factors: device design as to provide a suitable temperature difference across the p-n junction and the intrinsic thermoelectric material properties which limit both material and device performance. The thermoelectric material's performance is characterized by a dimensionless figure of merit, $Z\overline{T}$, which is expressed as the ratio of the square of the Seebeck coefficient α over the electrical and thermal conductivity, σ $(1/\rho)$ and κ, respectively, times the average temperature $\overline{T}$ [5]. The figure of merit of commercially available thermoelectric materials has remained around unity for over half a century [7], thus emphasis is placed on device design and thermoelectric material development to maximize thermal conversion efficiency and power output per application.

TEDs are scalable per application and have been implemented in a wide range of operations, in particular waste heat recovery. The benefit of using TEDs for waste recovery operations is that they operate at steady-state and when exposed to constant operating temperatures, exhibit long operational lifetimes. TEDs have been applied to waste heat recovery in automobiles [8–10]. Jang et al. investigated experimentally the incorporation of heat pipes into a system of thermoelectric generators (TEGs) to allow remote generation of electrical energy from automotive waste heat [11]. Additionally, Liu et al. investigated the implementation of a two-stage TEG in the exhaust system of an automobile with a system

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Nomenclature

A	area or cross-sectional area, m^2
H	cavity height, m
K	thermal conductance, WK^{-1}
L	TE leg height, m
m'	ratio of resistances, dimensionless
P_o	power output, W
Q	heat transfer rate, W
R	electrical or thermal resistance, Ωor KW^{-1}
Ra	Rayleigh number, dimensionless
T	temperature, K
V	volume or voltage, m^3 or *V*
W	width, m
Z	figure of merit, dimensionless
Greek symbols	
α	Seebeck coefficient, VK^{-1}
γ	ratio of area to length, m
ε	emissivity, dimensionless
η	thermoelectric conversion efficiency, dimensionless
λ	thermal conductivity, $Wm^{-1}K^{-1}$
ξ	normal surface
Π	interface material
ρ	electrical resistivity, Ωm
σ	Stefan-Boltzmann constant, $5.67 \cdot 10^{-8}$ $Wm^{-2}K^{-4}$
Subscripts	
avg	average
braze	braze
c	cold, contact
cer	ceramic
conv	convection
Cu	copper
el	electrical
g	grease
gap	gap
h	hot
hex	heat exchanger
int	interconnector
L	load
max	maximum
N	n-type semiconductor
o	output
opt	optimum
P	p-type semiconductor
‖	parallel
rad	radiation
S	surface
total	total

efficiency of 5.35% and power output of 250 W [12]. Furthermore, conventional TEGs were applied to the exhaust system of a HUMVEE, allowing for the production of 944 W maximum at ideal operating conditions [13].

Applications of TEGs do not have to be limited to automotive applications; Luo et al. numerically studied the implementation of TEGs on a cement rotary kiln, stating that such a system could recover nearly 1/3 of wasted thermal energy, yielding 211 kW of electrical power and 3.3 MW of energy savings [14]. Ma et al. studied the application of TEGs to a biomass gasifier, providing the ability to generate 6 W of electrical power from an otherwise wasted source of thermal energy [15]. Xiong et al. numerically modeled the performance of a two-stage TEG applied to the coolant water of blast furnace slag, yielding 440 W of power output for mild operating temperatures [16]. TEDs have also been applied to hybridized photovoltaic-TE systems for improved conversion efficiency [17,18]. To improve the efficiency of TEDs, effort has been made to improve material properties, improve TED design and minimize internal and external resistances.

To maximize TED performance within applications, effort has focused toward increasing material efficiency and improving device design. The efficiency of thermoelectric materials has been increased via nano-structuring, nano-fabrication and controlling the thermal conductivity via multi-length phonon-scattering [19,20]. The most efficient TE materials for low-grade waste-heat recovery are bismuth-tellurides [21,22], whereas for high-grade applications, lead-tellurides [23–25] and clathrates [26] are used. Besides increasing the material performance, the TEDs have been improved by means of increasing the temperature difference across the device via novel designs [10,27–29] and heat sink optimization [30,31].

Within the TED, leg geometries have been optimized [32–34] and likewise internal and external resistances have been minimized [31,35]. Min and Rowe [36] evaluated the performance of TEDs in terms of power output for waste heat recovery applications taking into account the electrical and thermal contact resistances and TE element leg height, but did not optimize the cross-sectional areas to maximize either power output or thermal conversion efficiency. Freunek et al. [37] proposed an analytical model to optimize the geometry of a TED, taking into account the Peltier effect and Joule heat, Thomson effect, thermal and electrical contact resistances, source and sink conditions and load resistance. The model was oversimplified to assume the cross-sectional areas of the n- and p-type TE materials were the same and therefore only the TE material length was optimized. Liang et al. [38] used a parallel resistance network to analyze the performance of a TEG taking into account thermal and electrical contact resistances. Recently, Yazawa and Shakouri [35] studied the cost-effective waste-heat recovery using the co-optimization of TEDs by considering the TE leg shape, heat sink, load and contact resistances, and heat losses. Sahin and Yilabs [34] evaluated the efficiency and power output of a TED in terms of the shape parameter of the legs. Although the effect of cross-sectional area as a function of leg height was considered, optimizing the individual leg cross-sectional areas and the effect of contact resistances were not included.

Reviewing the literature, it is evident there is a deficiency in analyzing and optimizing the TE element geometry in terms of length and cross-sectional area taking into account independent thermal and electrical contact resistances and operating conditions, as well as the cold- and hot-side convective conditions such as heat transfer coefficients and fluid temperatures. Therefore, this work addresses the multi-faceted co-optimization of TE geometry and cold- and hot-side heat exchanger area using a one-dimensional thermal resistance network. The cross-sectional area and length of the n-type bismuth-telluride material will be optimized based upon the geometry of the p-type and the temperature difference imposed across the device, as determined by the resolution of a one-dimensional thermal resistance network.