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Technical and economic analysis of thermoelectric modules with macroporous thermoelectric elements

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ABSTRACT

Limited heat transfer between thermoelectric modules and external heat reservoirs reduces the temperature difference imposed on thermoelectric materials, which reduces the power output of thermoelectric generators. In this study, the addition of macroscopic pores into thermoelectric materials is proposed as one way for resolving the issue. A semi-empirical model that relates the conductivities to the level of porosity is used for modeling the effect of porosity. The maximum power and other relevant parameters are compared between the generators with and without porosity at a realistic condition. An analytic model for evaluating economic performance is utilized to study the economic benefits of the implementation of porosity in thermoelectric elements. We demonstrate that the use of macroporous thermoelectric elements can effectively decrease the thermal conductance of the thermoelectric module, resulting in improved performance. The amount of raw materials needed to produce thermoeletric modules can be reduced simultaneously, resulting in economic benefits.

1. Introduction

Direct energy conversion from heat to electricity using solid thermoelectric materials is an attractive alternative option to the use of conventional heat engines for electricity generation. Such themoelectric generators (TEGs) can be incredibly useful as compact waste heat recovery systems or in generic power supplies at remote, isolated locations. Typically, the conversion efficiency of thermoelectric energy conversion is expressed in terms of the temperature of each heat reservoir and the thermoelectric figure of merit $ZT = \alpha^2 T/(\rho k)$. Here, α is the Seebeck coefficient, ρ is the electric resistivity, k is the thermal conductivity, and T is the temperature. As ZT is one of the most important control parameters for the efficiency of thermoelectric energy conversion, significant efforts have been exerted on creating materials with high ZT values [1–11].

On the other hand, studies to resolve issues regarding the design and optimization of thermoelectric devices have been also conducted. Advanced designs, including segmented elements [12,13], exotic configurations [14–16], hybrid generation schemes [17–22], and even internalized heat sources [23,24], have been discussed. Despite continued efforts, contemporary thermoelectric generators do not possess optimal geometric features for achieving large power densities. A thermoelectric module is typically attached to contact pads and/or a heat sink, where heat is transferred between a thermoelectric module and heat reservoirs, which results in significant thermal resistance between them. Limited heat transfer between the module and the external heat reservoirs reduces the available temperature difference imposed on thermoelectric materials inside the module, resulting in a low electromotive force due to the Seebeck effect, which eventually reduces the power output of the generator. Since the problem is caused by the mismatch between the external thermal resistance between the module and the heat reservoirs as well as the internal thermal resistance of the module itself, this problem can be fixed either by reducing the external thermal resistance or by increasing the internal thermal resistance. The reduction of the external thermal resistance may require use of an extremely large heat sink, a forced convection heat transfer assisted by a fan, and/or a liquid-based cooling system [25], penalizing the net performance of the TEG and increasing the cost. The other path, i.e. increasing the internal thermal resistance of the module itself, was also pursued by increasing the length of the thermoelectric legs inside the module [25]; however, the optimum leg length is typically unrealistically large and hence difficult to achieve in practical situations.

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Nomenclature

A	ceramic plate area, m^2
A_{TE}	thermoelectric material cross sectional area, m^2
C	capital cost, \$
C_B	material cost, \$/kg
C_{HX}	heat exchangers and ceramic plates cost, \$/(W/K)
$C_{M,A}$	areal manufacturing cost, \$/m^2
$C_{M,B}$	bulk manufacturing cost, \$/kg
F	fill factor, –
F_{opt}	fill factor for the optimum G cost, –
G	cost-performance metric, \$/W
I	electrical current generated, A
k	material thermal conductivity, W/m K
K	thermoelectric thermal conductance, W/K
L	thermoelectric leg length, m
m	resistance ratio, –
N	number of thermoelectric couples, –
P_{gen}	output electrical power, W
P_{max}	maximum power generated, W
Q_1	heat absorbed by the hot side, W
Q_2	heat rejected in the cold side, W
R	electrical resistance of the thermoelectric module, Ω
R_{ct}	electrical contact resistance, Ωm^2
R_L	electrical load resistance, Ω
S	module Seebeck coefficient, V/K
T	temperature, K
T_1	hot junction temperature, K
T_2	cold junction temperature, K
T_{ave}, $\bar{T}$	temperature average, K
T_C	thermal reservoir temperature (cold-side), K
T_H	thermal reservoir temperature (hot-side), K
U	heat transfer coefficient of the heat exchanger, W/m^{2}K
V	voltage generated, V
Z, ZT	figure of merit, –
C'''	the volumetric cost, \$/m^3
ΔT	temperature difference, K
$\alpha_{p/n}$	individual Seebeck coefficient, V/K
α_{p-n}, α	absolute Seebeck coefficient, V/K
η	conversion efficiency, –
η_{max}	maximum conversion efficiency, –
ρ	electrical resistivity of the material, Ωm
$\rho_{density}$	density of the material, kg/m^3
σ	electrical conductivity of the material, S/m
σ^{eff}	relative effective conductivity, –
Φ	porosity, –
Ψ	thermal resistance, K/W

Subscripts

(p)	refers to a porous model or a porous material
C	cold side
H	hot side
n	n-type semiconductor
p	p-type semiconductor

In this article, another way of increasing the internal thermal resistance is proposed. The main idea is to add macroscopic pores into thermoelectric materials. By adding pores into the material without changing the geometry of the TEGs, it is possible for us to increase the thermal resistance of the module itself.

Several studies on porous thermoelectric materials have been published. Most of these previous studies consider the addition of microscopic or even nano-scale pores as a method to improve material properties, especially the power factor. Thermoelectric porous silicon with improved thermoelectric properties has been studied by various researchers [26–29]. Other nano- and microporous materials have also been investigated with various degrees of success in improving material properties [30–36]. Systems with porous thermoelectric materials were also considered to make the thermoelectric elements directly exchange heat with working fluids [37–39]. On the other hand, our proposed approach, i.e. the addition of macroscopic pores as a way to increase the thermal resistance of the module, has mostly been ignored by the research community so far.[1] One notable exception was a study carried out by Goldsmid [40], where it was clearly pointed out that the porosity might be an advantage in conventional thermoelectric modules operating at a relatively high thermal flux density, due to the limitation in heat transfer processes. However, the study mostly investigated the effects of thermal leakage by the conduction through the pores only. A thorough study on the effects of increased thermal resistance due to the implementation of porous thermoelectric elements on the system performance of thermoelectric generators was not the topic of his previous study.

The present paper aims to fill the existing gap in previous research efforts on the matter. First, the technical performance of a thermoelectric generator is analyzed in Section 2. The effects of

Table 1
Thermoelectric module properties of the studied model.

Property	Symbol	Value
Fill factor	F	0.246
Leg length	L	1.6×10^{-3} m
Module area	A	9.0×10^{-4} m^2
Figure of merit	Z	2.55×10^{-3} 1/K
Number of pairs	N	127
Thermal resistivity	k	1.82 W/m K
Electrical resistivity	ρ	7.23×10^{-6} Ωm
Thermoelectric area	A_{TE}	8.7×10^{-7} m^2
Electrical internal resistance	R	3.576 Ω
Absolute Seebeck coefficient	α_{p-n}	3.66×10^{-4} V/K
Individual Seebeck coefficient	α_p or α_n	1.83×10^{-4} V/K
Thermoelectric thermal conductance	K	0.251 W/K

Table 2
Reservoir conditions of the studied model.

Property	Symbol	Value
Thermal reservoir temperature (hot-side)	T_H	354 K
Thermal reservoir temperature (cold-side)	T_C	300 K
Hot-side thermal resistance		
Between the thermoelectric legs and the hot-side thermal reservoir	Ψ_H	1.0 K/W
Cold-side thermal resistance		
Between the thermoelectric legs and the hot-side thermal reservoir	Ψ_C	40.0 K/W
Electrical contact resistance	R_{ct}	3.41×10^{-10} Ωm^2

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[1] One previous study [38] partially addressed the issue by introducing the effect of porosity on the electrical and thermal conductivities, but the system of interest in that study was not a conventional thermoelectric module as in this study but rather a specialized generator that has hot gas flow through the pores.