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Effect of thermal conductivity on performance of thermoelectric systems based on Effective Medium Theory

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ABSTRACT

Currently thermoelectric (TE) systems have very low efficiency due to unfavorable TE properties (e.g., high thermal conductivity and low power factor). Figure of merit ($ZT = \alpha^2\sigma T/k$) is a measure of TE material's performance which suggests that relatively lower thermal conductivity of TE materials can improve the performance (e.g., efficiency and coefficient of performance) of TE systems. A bulk composite TE material can have low thermal conductivity which can be made-up of TE micro/nano particles and base TE materials. There are various models reported in the literature based on Effective Medium Theory (EMT) which can predict thermal conductivity of composites. In this paper, three different models based on EMT are applied to investigate the performance of thermoelectric generator (TEG) and thermoelectric cooler (TEC). These models are Maxwell model, Hasselman–Johnson model, and Minnich–Chen model. Analytical modeling and numerical simulations have been performed to evaluate TE systems' performance (e.g., COP and thermal efficiency). Thermal efficiency of thermoelectric generator (TEG) increases from 2.06% to 5.59% which is 170% rise when composite thermal conductivity decreases from 1.1 W m^{-1} K^{-1} to 0.11 W m^{-1} K^{-1} based on Minnich–Chen model with particle size of 100 nm. An increase in thermal efficiency/COP can be attributed to reduction in Fourier heat conduction contribution to total heat input which leads to increase in total heat input. Results also show that performance of TE systems significantly depends on size and volume fraction of particles.

1. Introduction

Thermoelectric (TE) systems are typically made up of multiple pairs of *p*-type and *n*-type semiconductor materials which are connected electrically in series and thermally in parallel. A TE system working as a generator based on Seebeck effect is called a thermoelectric generator (TEG). Alternatively, a TE system working as a cooler/heater based on Peltier effect is called a thermoelectric cooler (TEC). TE systems can convert one form of energy to another without any moving parts. Performance of TE materials is measured using a parameter called figure of merit ($ZT = \alpha^2\sigma T/k$). Due to low ZT of TE materials TE systems are redundant in many real world applications. If efficiency of TE systems increases then many applications in the broader areas of medical, transportation, military, power generation, and thermal management will get benefit from TE systems. Such benefit includes robustness, long service life, silent operations, and environment friendliness. Poor electrical conductivity and Seebeck coefficient and higher thermal conductivity leads to a poor ZT. Although ZT can be improved in different ways and two of the ways to improve ZT are illustrated in Fig. 1.

The first way employs increase in the Seebeck coefficient and electrical conductivity, collectively called 'power factor'. While, the second way employs decrease in thermal conductivity. Hicks and Dresselhaus [2] discussed the concept of quantum wire (one dimensional) for TE materials. ZT increases because power factor ($\alpha^2\sigma$) improves due to one dimensional structure but not significantly lowering thermal conductivity [2]. A method to increase ZT was demonstrated experimentally by Venkatasubramanian et al. [3] where ZT of *p*-type superlattice of Bi_2Te_3/Sb_2Te_3 (Bismuth–Telluride–Antimony) improved from 1 to 2.4 due to the reduction in thermal conductivity. Improvement offered by Hicks and Dresselhaus [2] and Venkatasubramanian et al. [3] were primarily for low dimensional structures such as quantum dots, wires, and superlattice structures. Such structures can be employed limitedly in real world applications due to the complicated physical/chemical vapor deposition method and cost to manufacturing [4]. There is another route to improve ZT in bulk TE materials called 'nanocomposite bulk materials' [5]. Nanocomposite bulk materials, which can also be called as 'composites' are bulk materials with nanostructured features inside it [4]. Composites are made up of base material and macro/nano particles which can be manufactured via wet-chemical and mechanical synthesis techniques

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Nomenclature

A	cross-sectional area (m^2)
C	volumetric specific heat ($MJ\ m^{-3}\ K^{-1}$)
C_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
$\mathbf{D}$	depth (m), electric flux density ($N\ m^2\ C^{-1}$)
$\mathbf{E}$	electric field intensity vector ($N\ C^{-1}$)
h	convection heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
H	height (m)
I	electric current (A)
$\mathbf{J}$	electric current density, ($A\ m^{-2}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
K	thermal boundary conductance ($W\ m^{-2}\ K^{-1}$)
L	length (m)
m_1	a parameter (see Eq. (12))
m_2	a parameter (see Eq. (12))
n	n-type material, number of particles
p	p-type material
P	power input (W)
$\mathbf{q}$	heat flux vector (W)
q	heat (W)
$\dot{q}$	heat generation ($W\ m^{-3}$)
Q	heat (W)
r	radius of sphere (m)
t	time (s)
T	temperature (K)
V	electric potential (V)
W	width (m)
ZT	figure of merit

Greek symbols

α	Seebeck coefficient ($V\ K^{-1}$)
η	efficiency
κ	thermal barrier resistance ($W^{-1}\ m^2\ K$)
Λ	mean free path (Å)
ρ	electrical resistivity (Ω m), density (kgm^{-3})
σ	electrical conductivity ($S\ m^{-1}$)
υ	phonon group velocity (ms^{-1})
ϕ	volume fraction of particles
Φ	interface density (m^{-1})
ε	dielectric permittivity matrix
τ	Thomson coefficient ($V\ K^{-1}$)

Subscripts

1	heat source, particle sphere
2	heat sink, base sphere
a	atmospheric condition
b	base material
eff	effective property
c	composite, characteristic
d	gap distance
E	electronic contribution
h	hot temperature side
in	input
l	low temperature side
L	lattice contribution
m	material
n	n-type
out	output
p	particles, p-type
x	co-ordinate system

(e.g., solvothermal, extrusion, and high energy milling). Scoville et al. [6] reduced thermal conductivity by 40% by adding Boron Nitride and Boron Carbide particles into Silicon–Germanium composite. Bulk p-type $Bi_xSb_{2-x}Te_3$ composite prepared by hot-pressing nanopowders gave ZT of 1.4 due to low thermal conductivity [7]. In the similar manner, Bi_2Te_3 with SiC (Silica Carbide) nanoparticles [8], Co_4Sb_{12} (Skutterudites) [9], and $AgPb_xSbTe_{2+x}$ (Lead Antimony Silver Telluride) [10] reported improvement in ZT due to low thermal conductivities in composites. Bulk composites with low thermal conductivity demonstrate promise of improved ZT and, more importantly, routes to synthesize them are more cost-effective compared to low-dimensional structures [4]. Thermal conductivities of composites depend on various parameters, such as, particle size, volume fraction, particle shape, and thermal conductivities of base and particle materials. Thermal conductivities of composites can be predicted by analytical models based on the Effective Medium Theory (EMT). The EMT is a method of treating a macroscopically inhomogeneous medium in which transport properties varies in space [11]. EMT's have been applied to different situations such as, Yu et al. [12] applied EMT to calculate effective permittivity, Gong et al. [13] derived modified EMT for porous media to model thermal conductivity, Hou et al. [14] applied EMT to calculate effective thermal conductivity of porous thin films, and Chen et al. [15] developed effective thermal conductivity model for bentonites which is considered engineered barrier material for radioactive wastes. Classical work of Rayleigh [16] and Maxwell [17] can predict transport properties of a mixture which can also be applied to thermal conductivity of composite as being one of the prime transport properties. Maxwell [17] considered a heterogeneous mixture with spherical particles with thermal conductivities of base material, particles, and composite as k_b, k_p, and k_{eff}, respectively. In addition to this, ϕ is a volume fraction of particle inclusions. Eq. (1) is an expression of the effective thermal conductivity of a composite in terms of thermal conductivities of base and particle materials and volume fraction of particles.

$$k_{eff} = k_b + \frac{3\phi(k_p - k_b)}{k_p + 2k_b - \phi(k_p - k_b)} \tag{1}$$

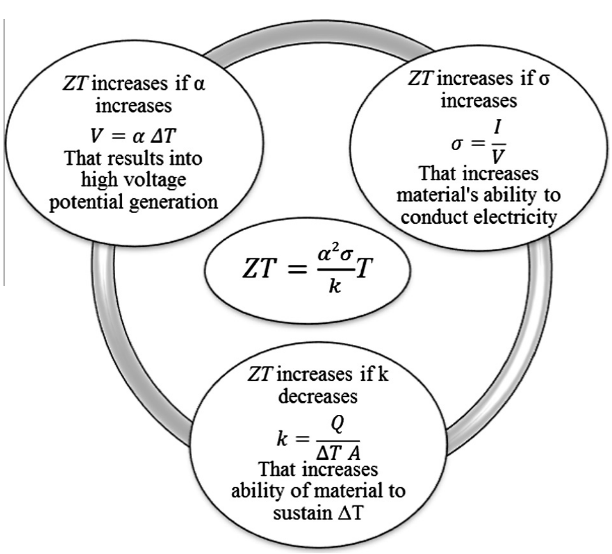

Fig. 1. Different approaches to increase ZT of TE materials [1].