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Elucidating modeling aspects of thermoelectric generator

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ABSTRACT

Multidimensional numerical models are useful tools for understanding the heat transfer mechanisms and performance optimization of thermoelectric generators (TEGs). In this study, two three-dimensional numerical models are developed for TEGs based on different formulations, but with similar abilities for heat and electricity transfer analysis and performance prediction. Model 1 solves the conservation equations of the Seebeck potential and the Ohmic potential separately, and the total built-in potential can be obtained based on the solved Seebeck and Ohmic potentials. Model 2 solves the conservation equation of the total built-in potential directly, and the conservation equation for the Ohmic potential is also solved. The comparison between Model 1 and Model 2 shows that Model 2 is slightly more precise for power output prediction. The detailed formulations of these two models are described, and the difference among the present and previous models is also discussed. Some important modeling aspects are elucidated for the TEG models, such as the conservation equations and boundary conditions. Parametric studies are carried out based on various thermal boundary conditions. The influence of the TEG semiconductor shape on performance is investigated in details. It is found that for the nearly same volume of semiconductor materials, changing the shape from normal cuboid (constant cross-sectional area) to hexahedrons (variable cross-sectional area) could increase the power output significantly. The reason is that the temperature gradient could be enhanced when proper variable cross-sectional areas are used.

1. Introduction

Thermoelectric generator (TEG) is an energy conversion device that converts thermal energy into electrical energy directly, and it can potentially increase the overall efficiency of some power systems (e.g. internal combustion engines) by recovering part of the waste heat [1]. TEG does not consume any fuel, and can be used without any moving part, it therefore has some outstanding features such as quiet and reliable operation and compact design. In recent years, due to the increasing demand on energy saving, TEG received considerable attention for the waste heat recovery in the major energy conversion devices, such as internal combustion engines. The application of TEG in these devices may recover some of the waste heat and produce electrical energy, leading to improved overall efficiency. In addition, if electrical energy is supplied to a TEG, it becomes a thermoelectric cooler (TEC), which transfers heat from one side to another through the Peltier effect, and can be used as portable refrigerator, chip cooler and heat pump.

A single TEG unit is mainly composed of a p-type and an n-type semiconductor. In order to produce the power required, a number of TEG units are often assembled together to form a TEG module, as shown in Fig. 1. When TEGs are used in a specific condition, it is important to choose suitable semiconductors with satisfactory performance in the temperature range of that condition. The figure of merit is a parameter commonly used to evaluate the performance of a thermoelectric material at a temperature of T (K):

$$Z = \frac{\alpha_{p,n}^2 \sigma_{p,n}}{\lambda_{p,n}} \tag{1}$$

where $\alpha_{p,n}$ ($\mathrm{V\,T^{-1}}$) is the Seebeck coefficient of a p-type or n-type material. Note that $\alpha_{p,n}$ does not refer to the difference of α_p and α_n, and it only represents the Seebeck coefficient of a p-type material or an n-type material separately. $\sigma_{p,n}$ ($\mathrm{S\,m^{-1}}$) is the corresponding electrical conductivity, and $\lambda_{p,n}$ ($\mathrm{W\,m^{-1}\,K^{-1}}$) is the thermal conductivity. In most situations, a dimensionless number, Z times T, or "ZT" is used, where T (K) is the operating temperature of p-type and n-type semiconductors [2]. For commercial thermoelectric cooling/heating modules, ZT is typically about 1.0 [3]. Common thermoelectric materials can be the alloys of antimony and bismuth tellurides with traces of other elements to dope the semiconductors, such as Bi_2Te_3 [4]. Experimental studies have been

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Nomenclature

A	contact area of heat source/sink and hot/cold side of TEG (m^2)
E	electric field intensity generated by Seebeck effect ($V\,m^{-1}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
I	electrical current (A)
J	current density in the entire TEG model ($A\,m^{-2}$)
J_v	virtual current density defined in Model 2 ($A\,m^{-2}$)
Lx	length of TEG units in x-direction (m)
Ly	length of TEG units in y-direction (m)
Lz	length of TEG units in z-direction (m)
P	output power of TEG (W)
Q	ratio of Thomson heat absorbed or released ($W\,m^{-3}$)
Q_h	heat transferred into the hot side (W)
Q_c	heat transferred out from the cold side (W)
q	heat of Peltier effect (W)
S_{sbk}	source term of Seebeck potential ($V\,m^{-2}$)
S_T	source term of energy conservation equation ($W\,m^{-3}$)
S_{total}	source term of total built-in potential ($S\,V\,m^{-3}$)
T	temperature (K)
V	potential (V)

Greek letters

α	Seebeck coefficient of p-type and n-type materials ($V\,K^{-1}$)
σ	electrical conductivity of p-type, n-type and copper materials ($S\,m^{-1}$)
k	thermal conductivity of p-type and n-type materials ($W\,K^{-1}\,m^{-1}$)
η	efficiency (%)
γ	Thomson coefficient ($W\,A^{-1}\,K^{-1}$)

Subscripts and superscripts

c	cold side of TEG
h	hot side of TEG
L	liter
n	n-type
n-top	top side of n-type
n-bottom	bottom side of n-type
ohm-hot-copper	Ohmic potential of copper-hot
ohm-hot-copper-bottom	Ohmic potential of interface of copper-hot and p-type
ohm-n	Ohmic potential of n-type
ohm-n-copper	Ohmic potential of copper-n-cold
ohm-n-copper-top	Ohmic potential of top side of copper-n-cold
ohm-n-top	Ohmic potential of top side of n-type
ohm-p	Ohmic potential of p-type
ohm-p-bottom	Ohmic potential of bottom side of p-type
ohm-p-copper	Ohmic potential of copper-p-cold
p	p-type
p-bottom	bottom side of p-type
p-top	top side of p-type
sink	heat sink
source	heat source
sbk-n	Seebeck potential of n-type
sbk-p	Seebeck potential of p-type
total	total built-in potential
total-hot-copper-bottom	total built-in potential of interface of copper-hot and p-type
total-n-top	total built-in potential of top side of n-type
total-p-bottom	total built-in potential of bottom side of p-type
v	virtual current density

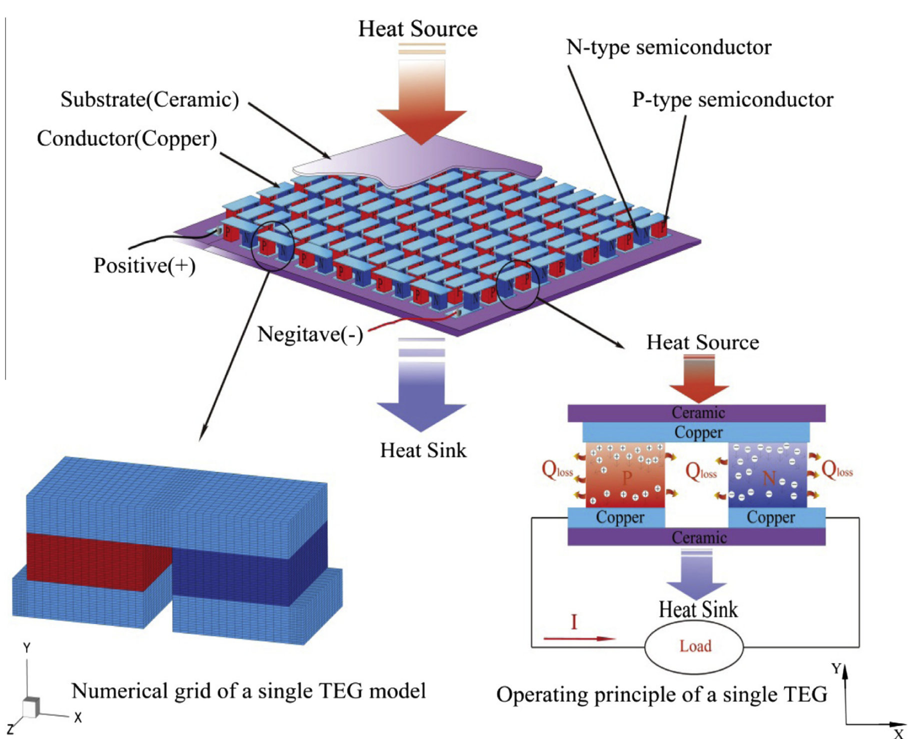

Fig. 1. Schematic of a TEG module.