International Journal of Heat and Mass Transfer 81 (2015) 639–645

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

International Journal of HEAT and MASS TRANSFER

Multiscale modeling of Thermoelectric Generators for conversion performance enhancement

Siyi Zhou [a,*], Bahgat G. Sammakia [a], Bruce White [b], Peter Borgesen [c], Cheng Chen [a]

[a] *Department of Mechanical Engineering, Binghamton University-SUNY, Binghamton, NY 13902, USA*
[b] *Department of Physics and Astronomy, Binghamton University-SUNY, Binghamton, NY 13902, USA*
[c] *Department of System Science and Industrial Engineering, Binghamton University-SUNY, Binghamton, NY 13902, USA*

ARTICLE INFO

Article history:
Received 21 May 2014
Received in revised form 27 October 2014
Accepted 28 October 2014
Available online 18 November 2014

Keywords:
TEG
Mixing structure
Cross-sectional area
Reynolds number
Nanoparticle

ABSTRACT

The thermoelectric model developed previously is used in this study to theoretically analyze promising solutions to enhance the power generated by Thermoelectric Generators (TEGs), which incorporate water-fed heat exchangers with commercially available thermoelectric modules. The patterned topography on wall surfaces is implemented and the increased device performance can be observed by introducing stirred flows into the heat exchangers and equalizing the temperature across the channels. Referring to the analysis, an approximately 30% enhancement in power generation is captured for the base-relief TEG, indicating it is desirable to have mixing structures. In addition, varying cross-sectional area of a single channel in a conversion capability sense shows that the structured surfaces have a stronger impact on the TEGs at the micro scale, which could promote the power output by 40%. Finally, the prospect of increasing the thermal transport capability of water by loading it with nanoparticles in the TEGs with macro and micro heat exchangers is explored. It is found that the conversion performance of the nanofluid-fed TEG only performs superior to the water-fed TEG at the micro scale by 14%, where the flow rate is relatively low. As for the macro scale, no improvement can be captured.

1. Introduction

Thermoelectrics examines the direct coupling of electricity and heat within thermoelectric materials. Unlike traditional dynamics heat engines, Thermoelectric Generators (TEGs) emerge as a serious contender for waste heat recovery and present plenty of distinct advantages, such as being simple, compact and highly reliable, suited for small-scale and remote applications, and environmentally friendly. Visible in experimental studies and numerical models, however, the proposed thermoelectric systems have not generated the desired electric power output, constrained by their unfavorable conversion efficiency (typically 5–10% [1]), which is mainly caused by available thermoelectric materials in the direction of figure of merit and needs to be improved if they are to be broadly implemented, and be competitive with current energy conversion technologies. A comparatively large amount of heat is thus required to produce a given quantity of electricity and opens the door to further improve the device performance.

As a metric of measuring TEG performance, a dimensionless figure of merit $\left(ZT = \frac{\delta^2 \cdot \sigma}{\kappa} \Delta T\right)$ indicates that efficient energy conversion calls for maximizing ΔT to optimize the overall thermoelectric systems. Mixing is one of the promising solutions to promote the thermoelectric capacity. Researchers point to locate some enhanced mixing structures. Cheng [2] numerically studied the stacked two-layer microchannel heat sink with enhanced mixing passive microstructures. The geometric parameters such as the ratio of embedded structure height to microchannel height and fluid properties were studied. Compared to the smooth microchannel, the better performance of stacked microchannel with passive structures was observed. Strook et al. [3] presented a method to mix streams of steady pressure-driven flows in microchannels at low Reynolds number by using base-relief structures on the floor of the channel. The results showed that the patterned topography on surfaces such as the staggered herringbone design and obliquely oriented ridge design could be used to generate chaotic flows other than pressure-driven flows in microchannels.

Additionally, nanotechnologically produced fluids have received more and more attention in the race for the optimum efficiency of TEGs, which comprise of nanoparticles and are considered to offer important advantages over conventional heat transfer fluids such as water. Over the past decades, important theoretical

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* Corresponding author. Tel.: +1 607 348 5687.
E-mail addresses: szhou3@binghamton.edu (S. Zhou), bahgat@binghamton.edu (B.G. Sammakia), bwhite@binghamton.edu (B. White), pborgese@binghamton.edu (P. Borgesen), cchen20@binghamton.edu (C. Chen).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.10.068
0017-9310/

Nomenclature

x	axial distance along fluid flow axis, m
l	length, m
w	width, m
h	height m
P	pressure in flows, Pa
T	temperatures of fluid flow and thermoelectric layer, K
$\mathbf{u}$	velocity of flows, m/s
C_p	specific heat capacity at constant pressure, J/kg·K
W	power output, W
Greek symbols	
κ	thermal conductivity, W/K·m
σ	electric conductivity, S/m
δ	Seebeck coefficient, V/K
Subscripts	
TE	thermoelectric module
ch	channel
c	cross-sectional
H	hot stream
C	cold stream
in	inlet

and experimental research works on the convective heat transfer appeared in open literatures on the enhanced cooling performance of the forced convection heat transfer with nanofluids. Ho et al. [4] conducted experiments to investigate cooling performance of a microchannel heat sink with Al_2O_3/water nanofluid, showing that the nanofluid cooled heat sink outperforms the conventional water cooled heat sink, with a significantly higher average heat transfer coefficient, lower thermal resistance and wall temperature for high pumping power. Other researchers [5–10] presented theoretical analysis of cooling performance of a microchannel heat sink with water loaded nanoparticles having different volume fractions, and achieved good results with currently available experimental data sets.

Existing thermoelectric models are built by adapting or modifying the second law of thermodynamics. In order to fabricate ideal TEGs with optimum power performance, a more comprehensive thermoelectric model was developed and expanded to optimize selected design variables of the proposed TEGs to determine the optimal performance, including geometric properties and operation conditions [11]. In the present study, after the thermoelectric model is functioning and generates results by the use of the commercial FEA package COMSOL^{TM} [12], fully investigation is conducted to improve the device performance under a wide range of scenarios. Major promising solutions applied are structured walls and working fluids loaded with nanoparticles. This work aims to employ the experimentally verified model to implement thermoelectrics and further enhance the thermoelectric conversion efficiency.

2. Numerical Implementation

2.1. Coupled-field model

The fully Coupled-field model developed previously is used here to account for Seebeck, Peltier and Thomson effects as coupling mechanisms between thermal and electric fields. The equations governing the multidimensional temperature and electrical potential profiles in thermoelectric materials under steady-state conditions and in the absence of an applied magnetic field are shown below.

Energy conservation for the solid domain involves Joule heating can be expressed as,

$$\nabla(\kappa\cdot\nabla T)-T\cdot\mathbf{J}\cdot\left(\frac{\partial\delta}{\partial T}\right)\cdot T+\rho_{TE}\cdot\mathbf{J}=0 \tag{1}$$

In this model, the equations of heat flow Eq. (1) and of continuity of electric charge [13] Eq. (2) are coupled by a set of thermoelectric constitutive equations, Eqs. (3) and (4).

$$\nabla\cdot\mathbf{J}=0 \tag{2}$$

$$\mathbf{q}=[\Pi]\cdot\mathbf{J}-[\kappa]\cdot\nabla T \tag{3}$$

$$\mathbf{J}=[\sigma]\cdot(\mathbf{E}-[\delta]\cdot\nabla T) \tag{4}$$

where, $[\kappa]$ is the thermal conductivity matrix, $[\sigma]$ is the electrical conductivity matrix, $[\delta]$ is the Seebeck coefficient matrix, $[\Pi] = T[\delta]$ is the Peltier coefficient matrix. In the absence of time-varying magnetic fields, $\mathbf{E}$ is irrotational, and can be derived from an electric scalar potential ϕ,

$$\mathbf{E}=-\nabla\phi \tag{5}$$

Therefore, the electric power W is expressed as

$$W=\frac{V_{OC}^2}{2(R_{TE}+R_{load})} \tag{6}$$

For the maximum electrical power, $R_{load} = R_{TE}$.

2.2. Heat exchanger model

Simulating a heat exchanger while utilizing thermoelectric modules for power generation can be achieved by many approaches. The generic TEG configuration provided by Suzuki and Tanaka [14] is adopted. The panel directly touches upon a hot and cold thermal fluid. Different arrangements are possible, e.g. parallel flow, counter flow, isothermal, and mixed flow. The three-dimensional Navier–Stokes and energy equations combined with the continuity equation are solved simultaneously to determine the temperature fields of the hot and cold side of the thermoelectric modules.

Continuity equation:

$$\nabla\cdot(\rho\mathbf{u})=0 \tag{7}$$

Momentum conservation equation:

$$\rho(\mathbf{u}\cdot\nabla\mathbf{u})=-\nabla P+\nabla\cdot\varphi+\mathbf{F} \tag{8}$$

Energy equation:

$$\mathbf{u}\cdot\nabla T=\frac{\kappa}{\rho C_P}\nabla^2 T+\frac{\bar{Q}}{\rho C_P}+\frac{S}{\rho C_P} \tag{9}$$

For the liquid domain, $\bar{Q}$, the rate of internal heat generation within the solid domain, is zero. The energy equation can be rewritten as

$$\mathbf{u}\cdot\nabla T=\frac{\kappa}{\rho C_P}\nabla^2 T+\frac{S}{\rho C_P} \tag{10}$$

For the solid domain, S, the dissipation function due to the viscous force, is zero.

$$\mathbf{u}\cdot\nabla T=\frac{\kappa}{\rho C_P}\nabla^2 T+\frac{\bar{Q}}{\rho C_P} \tag{11}$$