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Co-optimized design of microchannel heat exchangers and thermoelectric generators

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ABSTRACT

Designs of heat exchangers have mostly been disconnected to the performance of thermoelectric generator (TEG) systems. The development work, mostly focused on thermoelectric materials, required a significant amount of engineering parametric analysis. In this work, a micro plate-fin heat exchanger applied to a TEG is investigated and optimized to maximize the output power and the cost performance of generic TEG systems. The cost per performance is counted by a measure of price per power output ($/W). The channel width, channel height, fin thickness of heat exchanger, and fill factor of TEG are theoretically optimized for a wide range of pumping power. In conjunction with effective numeric tests, the model discusses the optimum size of the system components' dimensions at two area sizes of the substrate plate of heat exchanger. Results show that at every pumping power, there are particular values of channel width and fin thickness that provide maximum output power in the TEG. In addition, for producing maximum cost performance at lower pumping power, larger channel width and channel height and smaller fill factor are required. The results also illustrate that there is a unique pumping power for fixed thickness of fin and ceramic substrates that provides minimum cost per performance for the TEG systems. The theoretical results of the micro heat exchanger are in a good agreement with the experimental investigation data.

1. Introduction

Researches in thermoelectric phenomena have mostly focused on developing thermoelectric materials to improve the dimensionless figure-of-merit (ZT) of the material [1,2]. As there is no general model commonly accepted for the whole thermoelectric generator (TEG) system, most of the earlier works required a significant amount of engineering parametric analysis. Although Fukutani et al. [3] optimized thermoelectric refrigerators for integrated circuit cooling applications, there are a few important studies in the case of power generation. Mayer et al. [4] optimized the thickness of the thermoelectric element at which it is thermally matched to the heat exchangers, but this work ignored Peltier and Joule effects in heat transfer. It has been observed that in a model where electrical impedance matching was not considered [5], the maximum power output was achieved when internal thermal resistance matched the sum of external thermal resistances. In addition, in order to obtain the maximum power formula as a function of conversion efficiency, the matching of electrical load, maximum efficiency condition and thermal resistance in a thermal circuit have been considered by Snyder [6,7]. Furthermore, it is shown that the system efficiency at maximum power output is inversely proportional to the sum of heat dissipation in hot and cold thermal resistances [8].

In the power generation systems, a key factor is the optimization of the systems design together with its heat source and heat sink. Effective heat exchanger design is a limiting factor in thermal systems with high heat dissipation rate. To provide high heat flux at the surface of the structure, micro-scale single-phase heat transfer has been widely used in industrial and scientific applications [9]. As is observed, the geometric configuration of the microchannel heat exchanger has a critical effect on the convective heat transfer of laminar flow in the heat exchanger [10,11].

For decreasing the convective resistance at a given substrate area, both the convective heat transfer coefficient and the surface area of the channel walls in contact with the fluid should increase [12]. One way to increase the convective heat transfer coefficient is to reduce the hydraulic diameter of the microchannels. On the

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Nomenclature

A	area, m^2
b	fin thickness, m
C_p	specific heat of water, J/kg K
D_h	hydraulic diameter of the channel, m
d	thermoelement length, m
H	channel height, m
h	heat transfer coefficient, W/m^2 K
F	fill factor
K	contraction and expansion loss coefficient
k	thermal conductivity, W/m K
L	heat exchanger length, m
M	mass, kg
m	resistance ratio, ohm/ohm
$\dot{m}$	mass flow rate, kg/s
N	number of elements
Nu	Nusselt number
Δp	pressure drop, Pa
P	price, $
Re	Reynolds number
R_{th}	thermal resistance, K/W
Z	figure-of-merit, 1/K
T	temperature, K
t	thickness, m
u	fluid velocity, m/s
U	cost performance, W/$
W	heat exchanger width, m
w	power, W

Greek symbols

δ	channel width, m
η	efficiency
λ	normalized thickness of substrate
μ	dynamic viscosity, Ns/m^2
ρ	density, kg/m^3
Ø	spreading angle, deg

Subscripts

a	cold reservoir
b	base of microchannels
ch	channel
cr	ceramic substrate
hx	heat exchanger
f	fluid
fin	fin
in	inlet
max	maximum
o	overall
out	outlet
p	pump
pl	plenum
s	hot reservoir, substrate plate
t	total
teg	thermoelement

other hand, for a given pump power, when the hydraulic diameter decreases, the heat resistance of the heat exchanger increases due to rapid decreasing of the volumetric flow rate. The channel dimensions can be optimized at a practical limit of the available pumping power by minimizing the sum of conductive resistance, convective resistance and heat resistance of the system [13]. At a constant pumping power, when the aspect ratio of the channel becomes larger, the heat transfer area increases, but the volumetric flow rate and fin efficiency decrease. Furthermore, as an important parameter in the output power of the system, the pumping power due to friction factor in the microchannels should be carefully considered.

In order to decrease the coolant pumping power in the TEG system, an effective design of microchannel heat exchanger is proposed and implemented in a three-dimensional TEG model [14]. Nonetheless, when it comes to real-world design of thermoelectric system for direct thermal to electricity conversion, a focused discussion on the TEGs integrated to heat exchangers in micro-scale is still lacking. A consideration of the whole energy conversion system which involves thermal contacts with the hot and cold reservoirs is specifically required. In particular, an analysis of the thermal cost performance, which is a cornerstone for any energy technology, is missing in the thermoelectric field.

In the case of power generation, there are a few important studies [15] that were carried out using optimized analytic models for the parametric analysis of TEG systems. Developing analytic models suitable to predict the performance of micro heat exchangers and TEG can yield a simple approximate approach for designing a TEG system that can achieve maximum power and maximum cost performance. Based on this model, the thermal resistance of the system can be optimized to maximize the cost performance of the system. In addition, the thermal resistance of the microchannel heat exchanger can be minimized for a set of aspect ratio (the ratio of channel height to channel width) [16].

In this study, a TEG system including the system cold side micro plate-fin heat exchanger is optimized parametrically, in order to maximize the output power of the TEG and cost performance of the power system. The cost performance of the system is defined as the difference of output power and pumping power divided by the system mass. This mass includes both the TEG and the heat exchanger. On the other hand, the thermoelectric output power depends on the channel dimensions that define the heat exchanger thermal resistance. Therefore, the modified fill factor and the channel dimensions play key roles in lower material usage and higher output power. The particular focus of this study is exploring the optimum values of these parameters in a wide range of practical pumping power.

This work is based on developing a thermal equivalent network model that takes into account external finite thermal resistances keeping the TEG ceramic substrates and the micro heat exchanger at a fixed temperature difference of hot and cold reservoirs. The Peltier effect and the Joule heating effect are taken into account in the thermal circuit model. The width and height of the microchannels, the fin thickness, and the thermoelements' length that significantly influence power generation are geometrically optimized. The fill factor, which is the fractional area coverage of a thermoelement per unit TEG substrate area, is optimized to generate the maximum system cost performance. In addition, using an effective numeric test, the generated equations also discuss the optimum value of the parameters at two sizes of the heat exchanger substrate plate. Fig. 1a shows the schematic of the TEG system including the heat exchanger. Fig. 1b presents the detailed dimensions of the plate-fin heat exchanger, where water is used as the coolant fluid and the fluid path is made of parallel aluminum