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A comparison of micro-structured flat-plate and cross-cut heat sinks for thermoelectric generation application

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ABSTRACT

Heat sink configuration has strong impact on net power output from thermoelectric generators (TEGs). A weak cooling strategy can even cause negative net power output from the thermoelectric device. However, the net power output can be significantly improved by optimal design of the heat sink. In this study, a micro-structured plate-fin heat sink is compared to a modified design of cross-cut heat sink applied to TEGs over a range of temperatures and thermal conductivities. The particular focus of this study is to explore the net power output from the TEG module. The three-dimensional governing equations for the flow and heat transfer are solved using computational fluid dynamics (CFD) in conjunction with the thermoelectric characteristics of the TEG over a wide range of flow inlet velocities. The results show that at small flow inlet velocity, the maximum net power output in TEG with plate-fin heat sink is higher, while the TEG with cross-cut heat sink has higher maximum net power output at high flow inlet velocity. The maximum net power output is equal in the TEGs with plate-fin heat sink and cross-cut heat sink.

1. Introduction

Micro-scale single-phase heat transfer has been widely used in industrial and scientific applications [1]. Using micro-structured heat sinks provides low weight and compact energy system, compared to the conventional types of heat sinks and increases modularity of the power system. This type of heat sink has been interest of researchers for configuration optimization. To decrease the peak temperature and thermal conductance in a microchannel heat sink, Adewumi et al. [2] presented a three-dimensional numerical study of an integrated design with micro pin fin inserts.

Leng et al. [3], improved design of double-layered microchannel heat sink with a proposed truncated top channel. They investigated effect of total pumping power on the performance of the proposed design, where they showed that the maximum temperature difference on the bottom wall is reduced by 37.5% compared to the original design of double-layered microchannel heat sinks for the same pumping power. Chai et al. [4] proposed a newly microchannel heat sink with periodic expansion–constriction cross section that can enhance the average Nusselt number and reduce thermal resistance of the heat sink. Bifurcation of the channels also enhances thermal performance in microchannel heat sinks [5]. However, more bifurcations cause higher pressure drop and higher required pumping power. Therefore, there is an optimal number bifurcation for improving the overall thermal performance, including the pumping power, of the heat sink [6]. One technique to reduce the pressure drop in the microchannels is to use transversal-wavy design. Although the heat transfer coefficient decreases in transversal-wavy microchannels, it enhances the overall thermal performance compared to straight-rectangular microchannels [7].

Wang et al. [8–10] developed numerical methods to study the flow and heat transfer for optimal structures of microchannel heat sinks. They illustrated that the optimal geometric structure is different as pressure drop, flow rate and pumping power varies in the heat sink [9]. At low pumping power range, the cooling performance enhances of the heat sink when the pumping power increases [8]. However, increasing the pumping power does not always make a cost-effective heat sink design, as the effectiveness of the design can drop significantly under high pumping power conditions [10]. Pressure drop in the microchannels is lower at low Reynolds numbers compared to that in the flat plate microchannels. Beside thermal resistance consideration, pressure drop is an important factor for optimization of the micro-structured heat sink design, where the performance of the system depends on the required cooling power [11,12]. The results of a study by Shafeie et al. [13] indicate that for the same required

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Nomenclature

A	footprint area, m^2
$D_{h,fr}$	hydraulic diameter of heat sink frontal area, m
c	specific heat capacity, J/kg K
H	length, m
k	thermal conductivity, W/m K
$\dot{m}$	mass flow rate, kg/s
n	number of uni-couples
Nu	Nusselt number
P	power, W
p	pressure, Pa
Q	absorbed heat, W
q	heat flux across TEG, W/m^2
R	internal electrical resistance, Ω
Re	Reynolds number
T	temperature, K
ΔT	temperature difference, K
$\vec{V}$	velocity vector, m/s
v	velocity, m/s
W	volumetric flow rate, m^3/s
w	width, m
x	distance from channel inlet, m

Greek symbols

μ	dynamic viscosity, N s/m^2
ρ	fluid density, kg/m^3
σ	electrical conductivity, S/m

Subscripts

c	cold junction, channel
cc	cross-cut
f	coolant fluid
h	hot junction
i	inlet
n	n-type thermoelement
net	net
max	maximum
o	outlet
p	p-type thermoelement
pump	pump
teg	thermoelectric generator
w	wall

cooling power, the heat removal of the microchannel heat sink is higher than that in pin finned heat sink at high and medium range of required cooling power (P_{pump} > 0.5 W). However under low required cooling power condition, the pin finned heat sink performs slightly better.

In addition to computer chip applications [14], micro-structured heat sinks have been recently studied for thermoelectric generator (TEG) applications [15,16]. TEGs, which convert heat energy to electrical power by means of semiconductor charge carriers due to temperature difference, have been of great interest to the energy research community in recent years for waste heat recovery applications such as automotive applications [17], biomass boiler [18], micro-combustor [19] and wood stove [20]. A key factor in TEG systems is co-optimization of the TEG design with its heat sink, where a challenge is to design and develop of effective heat exchanger. The maximum power generation in a TEG can enhance by applying an effective heat sink. For instance, heat transfer coefficient on the cold junction of TEG can affect the optimal design of the thermoelements, where the maximum power generation occurs at larger ratio of the thermoelements foot print area as the heat transfer coefficient increases [21].

Performance of thermoelectric device is significantly affected by its geometry [22,23] and thermal boundary conditions [24–26]. Meng et al. [27] considered multi-parameter optimization of TEG by multiphysics modeling. Wang et al. [28] studied three-dimensional numerical modules of thermoelectric device where the temperature field is coupled with the electric potential field. Enhancement of the thermoelectric net power output must have priority to increasing of the power generation in a TEG device. Jang et al. [29] explored optimal fin height of plate-fin heat sink to maximize the net power density in TEGs. Lesage et al. [30] studied heat transfer enhancement in TEGs using flow channel inserts in the both cold and hot side heat exchangers. Although the pressure drop increases by the tabulating inserts, they showed that the net power generation enhances for a range of temperature difference. In this study, the net power generation is defined as power output by the TEG minus required cooling power in the heat sink.

Temperature distribution in the thermoelements is strongly affected by the flow and heat transfer in its heat sink [31,32]. Variation of temperature distribution in the heat exchanger causes different temperature distribution in the thermoelements [33]; so that each thermoelement shows particular electrical and thermal behavior, and produces different voltage generation compared to other thermoelements in the TEG. Higher voltage can be generated in the TEG if the temperature difference of the hot and cold junctions increases by reduction of thermal resistance in the heat sink. One way to reduce the thermal resistance is to enhance the convective heat transfer coefficient by increasing mass flow rate in the heat sink. On the other hand, for a given channel hydraulic diameter, when the mass flow rate increases, so does the required cooling power due to increase of the pressure drop. Therefore, high mass flow rate may require higher cooling power than the power generated by the TEG, causing negative net power output from the system [34]. The optimal mass flow rate can be explored at a practical limit on the available required cooling power by maximization of power generation in the TEG [15].

Pin–fin heat sinks and flat-plate heat sinks have been widely used in industrial applications due to their advantages. Kim et al. [35] found that to determine the effectivity of these heat sinks, both of the required cooling power and the length of the heat sinks should be considered. Because of the advantage of redeveloping region, the pin–fin heat sink can provide high heat transfer rate [36]. On the other hand, the advantages of plate-fin heat sink are easy fabrication and small pressure drop [37]. At high required cooling power and small length of the heat sink the pin–fin heat sink is recommended, while in small range of cooling power and at large heat sink length the plate-fin heat sink has better performance. Moreover, it is revealed that, in middle range of the required cooling power and heat sink length, the cross-cut heat sink is superior depending on its cross-cut length [38].

In this study, the effectiveness of a plate-fin heat sink and a cross-cut heat sink are compared for reduction of the required cooling power and for maximization of the net power output from TEGs. This study is part of an on-going effort to optimize the thermal performance in TEG systems, where new configurations of micro-structured plate-fin heat sink were recommended [39] to reduce the required cooling power. In contrast to the previous study, a modified design of the fins under the thermoelements is