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Multi-objective design optimization of a micro heat sink for Concentrating Photovoltaic/Thermal (CPVT) systems using a genetic algorithm

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HIGHLIGHTS

► Overall performance of fixed- and variable-channel-width heat sink is evaluated.
► Multi-objective optimization for geometric parameters and CFD model are applied.
► Introduction of stepwise channel-width variation enhances overall performance.
► Thermal entry length is negligibly small for the fixed-width configuration.
► The combined methodology proven valid in predicting the overall performance.

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ABSTRACT

An optimization methodology for a microchannel, plate-fin heat sink suitable for the cooling of a linear parabolic trough Concentrating Photovoltaic/Thermal (CPVT) system is applied in this study. Two different microchannel configurations are considered, Fixed (FWμ) and stepwise Variable-Width (VWμ) microchannels respectively. The performance evaluation criteria comprise the thermal resistance of the heat sink and the cooling medium pressure drop through the heat sink. Initially, the effect of the geometric parameters on the heat sink thermal and hydrodynamic performance is investigated using a thermal resistance model and analytical correlations, in order to save computational time. The results of the 1-D model enable the construction of surrogate functions for the thermal resistance and the pressure drop of the heat sink, which are considered as the objective functions for the multi-objective optimization through a genetic algorithm that leads to the optimal geometric parameters. In a second step, a 3-D numerical model of fluid flow and conjugate heat transfer for the optimized FWμ heat sink is developed in order to investigate in detail the flow and thermal processes. The overall analysis demonstrates that microchannel heat sinks achieve very low values of thermal resistance and that the use of variable-width channels can significantly reduce the pressure drop of the cooling fluid. Furthermore, it is proven that the 1-D model is capable of providing a good estimate of the behavior of the heat sink.

1. Introduction

Microchannel heat sinks constitute an innovative cooling technology capable of dissipating high heat fluxes from confined areas. The implementation of microchannel heat sinks was initially necessitated for the cooling of electronic integrated circuits, as the ongoing increase in circuit density and operational speed of modern electronic components also leads to increased heat generation rates that need to be efficiently dissipated. Furthermore, advances in fabrication techniques have led to electronic chips of continuously diminishing dimensions, which, as a consequence, require compact cooling systems. Microchannel schemes meet

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Nomenclature

a	wall thickness to channel width ratio, dimensionless
A	area, m^2
AR	aspect ratio, dimensionless
Ar	Archimedes number $Ar = Gr/Re^2$, dimensionless
c_p	specific heat, J/kg K
D_h	hydraulic diameter $D_h = 2W_{ch}H_{ch}/(W_{ch} + H_{ch})$, m
f	Fanning friction factor, dimensionless
Gr	Grashof number $Gr = g\beta q'' D_h^4 / k_f \nu^2$, dimensionless
H	height, m
h	heat transfer coefficient $h(z) = q''(z)/(T_w(z) - T_m(z))$, W/$m^2$ K
k	thermal conductivity, W/m K
L	length, m
m	fin parameter $m = \sqrt{2h/k_s W_w}$, m^{-1}
N	number, dimensionless
Nu	Nusselt number, dimensionless
P	channel perimeter, m
p	pressure, Pa
P_{pump}	pumping power, W
Pr	Prandtl number, dimensionless
Q	thermal power, W
q''	heat flux, W/m^2
R_{th}	thermal resistance, K/W
Re	Reynolds number $Re = u_m D_h/\nu$, dimensionless
T	temperature, K
t_s	substrate thickness
u	flow velocity, m/s
$\dot{V}$	volumetric flow rate, m^3/s
W	width, m
X^*	non-dimensional spanwise coordinate $X^* = (x - (W_w/2))/W_{ch}$
Y^*	non-dimensional height-wise coordinate $Y^* = (y - t_s)/H_{ch}$
Z^*	non-dimensional streamwise coordinate $Z^* = z/RePrD_h$
z_{th}	thermal entry length, m

Greek symbols

β	volumetric thermal expansion coefficient, K^{-1}
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3

Subscript

ave	average
c	contraction
cs	cross-section
cal	caloric
conv	convective
cond	conductive
ch	channel
cs	cross section
d	developing
e	exit
f	fluid
fd	fully developed
hs	heat sink
i	inlet
init	initial
m	mean
s	solid, section
th	thermal
tot	total
w	wall

these demands as they combine high surface-to-volume ratio and large convective heat transfer coefficient [1].

Tuckerman and Pease [2] were the first to introduce the concept of liquid cooling by utilizing microchannels. They created three different heat sink configurations by chemically etching parallel channels onto silicon chips. Their experimental evaluation showed that the thermally superior configuration was able to dissipate a flux of 790 W/cm^2. Harms et al. [3] conducted an analytical and experimental evaluation of laminar flow and forced convection inside a heat sink of total dimensions 2.5 cm × 2.5 cm incorporating deep microchannels with an aspect ratio (H_{ch}/W_{ch}) of 4.1. They pointed out that microchannels with a high aspect ratio exhibit enhanced thermal and hydrodynamic performance. Moreover, they demonstrated that the multiple-channel configuration exhibits superior thermal performance for a given pressure drop, in comparison to a single-channel heat sink designed for turbulent flow. Qu and Mudawar [1,4] numerically investigated the three dimensional laminar flow and heat transfer inside two heat sink configurations having channel widths of 57 μm and 231 μm with respective channel heights of 180 μm and 713 μm. Different heat sink materials were also selected for the two configurations, namely silicon and copper respectively. In both cases a periodic unit cell consisting of a single microchannel and the surrounding material was selected as the computational domain, due to the existent symmetry. The numerical analysis demonstrated that the average temperature rise along the flow direction, in both the fluid and solid part of the heat sink can be considered as linear. The numerical procedure was validated against the experimental evaluation that was also conducted for the second heat sink configuration, as close agreement was found between the predicted values and the experimental data for the heat sink temperature distribution and pressure drop. The authors came to the conclusion that the conventional Navier–Stokes and energy equations can accurately predict the flow and heat transfer conditions inside a microchannel heat sink. In general, the open literature is quite extensive on the subject of microchannel cooling and additional references concerning the flow and heat transfer inside microchannels can be found in review papers on high heat flux cooling technologies such as those by Agostini et al. [5] and Kandlikar & Bapat [6].

A critical stage in the heat sink design procedure is the determination of the optimal geometric parameters that maximize overall performance. A number of researchers [3,7–11] have utilized analytical methods in order to highlight the effect of the microchannels main dimensions, such as channel width, aspect ratio and vertical wall thickness, on the heat sink thermal and hydrodynamic performance.

Multi-objective optimization techniques in combination with genetic algorithms have also been proven to be suitable solution methods for problems where multiple criteria must be satisfied, as they result to concurrent optimization of all the objectives [12]. Copiello and Fabbri [12] coupled a simplified numerical procedure with a multi-objective optimization technique in order to determine the optimal geometry of a wavy finned heat sink. They stated that the use of a detailed three-dimensional numerical model would lead to excessively time consuming computations. Husain and Kim [13] used a full three-dimensional numerical model of a parallel microchannel heat sink, in order to produce an initial number of objective function values required for the multi-