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Research paper

Optimal rectangular microchannel design, using simulated annealing, unified particle swarm and spiral algorithms, in the presence of spreading resistance

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HIGHLIGHTS

- Rectangular microchannels were modelled considering EGM and thermal spreading.
- The designs were optimized using the SA, UPSO, and SO algorithms.
- All optimization methods yielded good designs but UPSO was more precise.
- We compared combinations of three bulk materials and two working fluids.
- We determined that an aluminum heat sink with ammonia gas was the best design.

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ABSTRACT

This article focuses on the solution of the mathematical model of a rectangular microchannel through three algorithms: SA (Simulated Annealing), UPSO (Unified Particle Swarm Optimization) and SO (spiral Optimization). The criterion of minimum entropy generation was used for constructing the model, which includes the effect of the thermal spreading resistance. This type of thermal resistance occurs whenever a smaller heat source (e.g. the chip) comes in contact with the base of a larger heat transfer element (e.g. the heat sink). This simulation work was split into two stages. The first one considered different scenarios for a silicon heat sink using air as a working fluid. In this case, volume flow rates between 4.0 and 4.5×10^{-3} m^3/s exhibited lower values of entropy generation rate. The second stage considered three materials (silicon, aluminum, and copper) and two working fluids (air and ammonia gas). We found, for this particular set of conditions, that entropy generation becomes minimum, for a given material and working fluid, as long as a volume flow rate of 4.5×10^{-3} m^3/s is used. Even so, the best practical configuration found was an aluminum heat sink with ammonia gas. For all the simulations, a marked effect due to the spreading resistance was found, typically ignored in real life applications.

1. Introduction

Almost since the beginning of modern electronics, the problem of heat transfer has been a major issue. Although there has been a huge number of experimental and simulation reports suggesting very clever solutions, it seems there is not a universal one, [1–3]. Among all the proposals, one of them has received special attention, and relates to the use of heat sinks attached to the surface of the electronic element [4–9]. The design of these heat sinks is based on traditional dissipating structures (e.g. pin-fins, plate-fins and microchannels), and the aim is to enhance the thermal efficiency of the heat being transferred from the chip, to the surrounding media [10–14]. Gururatana et al., simulated a 2D pin-fin heat sink under mechanical vibrations. Their results show how the heat transfer rate increased when the frequency was below 500 Hz. In contrast, the pressure drop raised markedly with frequency [12].

After several decades of development, there is now solid knowledge that comes from an approach based on modeling and simulation, as well as, from experimentation [15–17]. Although most of the reported research work deals with hollow channels,

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Nomenclature

A	area (m^2)
A_{ef}	effective area to convective heat transfer
Bi	Biot number
c	dimensionless factor of SA method
c_p	average specific heat (J/kg K)
D_h	hydraulic diameter $\equiv 4H_c w_c/(H_c + 2w_c)$ (m)
D_{tu}	inner diameter of the supply tubes (m)
E_i	energetic state at i iteration
f	Darcy friction factor
G	volume flow rate (m^3/s)
G_p	global velocity component of a particle
$\overline{h}$	average convection coefficient (W/m^2 K)
H_c	channel height (m)
$\mathbf{I}_{\mathscr{n}}$	identity matrix for $\mathscr{n}$ dimensions
k	Thermal conductivity of solid (W/m K)
k_B	Boltzmann constant
k_f	thermal conductivity of fluid (W/m K)
L	length (m)
$\mathbf{L}_p$	local velocity component of a particle
$\mathscr{n}$	dimensions or number of design parameters
N_c	total number of microchannels
Nu_{D_h}	Nusselt number base on hydraulic diameter $\equiv D_h h_{avg}/k_f$
p	actual cycle
P	pressure (Pa)
Pe_{D_h}	Peclet number base on hydraulic diameter $\equiv D_h U_{av}/\alpha_{th}$
$\mathbf{P}_g$	best position of the swarm
$\mathbf{P}_{g_p}$	best position found by each neighborhood
$\mathbf{P}_p$	best solution found by each particle
Pr	Prandtl number $\equiv c_p\mu/k_f$
$\dot{q}$	uniform heat flux (W/m^2)
$\dot{Q}$	total heat transfer rate (W)
r	convergence rate between a point and the origin
r	random number uniformly distributed between zero and one
R	thermal resistance (K/W)
$\mathscr{R}^{(n)}(\theta)$	rotation matrix
Re_{D_h}	Reynolds number base on hydraulic diameter $\equiv D_h U_{av}/\nu$
R_i'	grease thermal resistance times unit area (m^2 K/W)
R_o	external thermal resistance (K/W)
SA	Simulated Annealing
$\dot{S}_{gen}$	total entropy generation rate (W/K)
$\dot{S}_{gen,\Delta P}$	Entropy generation rate due to mass flow (W/K)
$\dot{S}_{gen,\Delta T}$	Entropy generation rate due to heat transfer (W/K)
$\mathscr{S}n$	Stable matrix $\equiv r\mathscr{R}^{(n)}(\theta)$
SO	Spiral Optimization
t	actual iteration or step
t_b	lower plate thickness (m)
T	average temperature (K)
u	unification factor
UPSO	Unified Particle Swarm Optimization
$\overline{V}_f$	average velocity of the fluid through the channels (m/s)
$\mathbf{V}_p$	total velocity of a particle
w_c	half of the channel width (m)
w_p	half of the fin thickness (m)
W	width (m)
x	design variable
$\mathbf{X}_p$	position of a particle

Greek symbols

α_c	channel aspect ratio $\equiv 2w_c/H_c$
β	channel-wall ratio $\equiv w_c/w_p$
ΔP	pressure drop across microchannel (Pa)
ΔT	finite temperature difference (K)
ε	dimensionless value of the heat source
η_p	efficiency of the wall
θ	rotation angle around the origin
λ	mean free path (m)
λ_b	dimensionless parameter
μ	dynamic viscosity of fluid (Pa s)
ν	kinematic viscosity of fluid (m^2/s)
ρ	average density (kg/m^3)
τ	dimensionless value of the base plate thickness
ϕ_1	own trust factor
ϕ_2	swarm trust factor
Φ_b	dimensionless parameter
Φ	total pump power
χ	constriction factor
Ψ	search agents population

Subscripts

a	surrounding or ambient
b	base plate
c	channel
conv	convection
CV	Control volume
d	heat sink
eq	equivalent
f	fluid
i	interface
p	wall or fin
tu	supply pipes of fluid flow

Solmuş proposed to fill them with a block of graphite foam. This material seems to be more attractive than metal foams for heat removal due to its high thermal conductivity, low density and high specific surface area [16]. His numerical results showed that graphite foam heat sink has a better heat transfer performance when it is compared with aluminum foam heat sink. Though, the later has a lesser pressure drop.

From the simulation point of view, literature reports several strategies for modeling this type of heat transfer problem, such as the thermal resistance model, fin model, two fin-fluid coupled models, and porous medium model, principally. On the other hand, several researches have recently started to explore different alternatives not only to construct and to solve the mathematical model, but also to design an optimal heat sink that maximizes the heat transfer process. Among those approaches, the Entropy Generation Minimization (EGM) criterion has received much attention because it is based on the second law of thermodynamics, and it incorporates a tradeoff between heat transfer and fluid flow phenomena. Through the EGM criterion, a designer can consider the entropy generation of each component in a given system, as well as phenomena related to the operation of the heat sink regarding the irreversibility of real processes (e.g. pressure drop and finite temperature difference). In this way, it is possible to build an objective function that represents the sum of all components, so appropriate