International Journal of Heat and Mass Transfer 69 (2014) 92–105

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Manifold microchannel heat sink design using optimization under uncertainty

Suchismita Sarangi [a], Karthik K. Bodla [a], Suresh V. Garimella [a,*], Jayathi Y. Murthy [b]

[a] School of Mechanical Engineering and Birck Nanotechnology Center, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, USA
[b] Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX 78712, USA

ARTICLE INFO

Article history:
Received 10 July 2013
Received in revised form 25 September 2013
Accepted 26 September 2013
Available online 29 October 2013

Keywords:
Manifold
Microchannel
Uncertainty quantification
Optimization under uncertainty
DAKOTA
Generalized polynomial chaos
Sensitivity analysis

ABSTRACT

A three-dimensional numerical model is developed and validated to study the effect of geometric parameters such as microchannel depth and width, manifold depth, and manifold inlet and outlet lengths on the performance of a manifold microchannel (MMC) heat sink. The manifold arrangement used to distribute the flow through alternating inlet and outlet pairs greatly reduces the pressure drop incurred in conventional fluid supply arrangements due to its shorter flow paths, while simultaneously enhancing the heat transfer coefficient by limiting the growth of thermal boundary layers. The computational analysis is performed on a simple unit-cell model to obtain an optimized design for uniform thermal boundary conditions, as well as on a porous-medium model to obtain a complete system-level analysis of multiple microchannels across one manifold. The porous-medium approach can be further modified to analyze the performance under asymmetrical heating conditions. Along with conventional deterministic optimization, a probabilistic optimization study is performed to identify the optimal geometric design parameters that maximize heat transfer coefficient while minimizing pressure drop for an MMC heat sink. In the presence of uncertainties in the geometric and operating parameters of the system, this probabilistic optimization approach yields a design that is robust and reliable, in addition to being optimal. Such an optimization analysis provides a quantitative estimate of the allowable uncertainty in input parameters for acceptable uncertainties in the relevant output parameters. The approach also yields information such as the local and global sensitivities which are used to identify microchannel width and manifold inlet length as the critical input parameters to which the outputs are most sensitive. The deterministic analysis shows that the heat transfer performance of the MMC heat sink is optimal at a manifold inlet to outlet length ratio of 3. A comparison between the deterministic and probabilistic optimization approaches is presented for the unit-cell model. A probabilistic optimization study is performed for the porous-medium model and the results thus obtained are compared with those of the unit-cell model for a uniform heat flux distribution.

1. Introduction

Conventional microchannel heat sinks are characterized by long microchannels that run parallel to the base of the heat sink, as proposed by Tuckerman and Pease [1]. These microchannel heat sinks have been successfully investigated for use in electronics cooling applications [2]. Several analytical and numerical models for predicting pressure drop and heat transfer through such heat sinks have been proposed in the literature [3–5]. Although conventional microchannels provide substantial heat transfer augmentation, they are also associated with very high pressure drops. Microchannel heat sinks with various modified configurations have been previously studied for improved performance over conventional single-layered rectangular microchannels. Deterministic optimization studies have been performed on microchannel heat sinks with double-layered channels [6] and tapered channels [7] to obtain optimum geometric parameters. An alternative configuration that has been proposed to lower the incurred pressure drop while simultaneously increasing the heat transfer is the manifold microchannel (MMC) heat sink. An MMC heat sink consists of a manifold system which distributes the coolant via multiple inlet–outlet pairs, thereby reducing the flow length of the coolant through the microchannels, as shown in Fig. 1(a). Such an arrangement results in a significant reduction in the pressure drop, while also reducing the thermal resistance by interrupting the growth of thermal boundary layers. This design was originally proposed by Harpole and Eninger [8], who demonstrated a significant reduction in thermal resistance relative to conventional microchannel heat sinks at a constant pumping power. Their MMC system consisted

---

* Corresponding author. Tel.: +1 765 494 5621.
E-mail address: sureshg@purdue.edu (S.V. Garimella).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.09.067

Nomenclature

a_i	coefficients in the gPC response function
B_i	polynomials in the gPC response function
C_p	specific heat, J/kg K
D_c	depth of microchannel
D_h	hydraulic diameter of microchannel
D_m	depth of manifold
D_{sub}	depth of substrate
f	friction factor
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	total length of coolant flow path, μm
L_{in}	length of inlet path, μm
L_m	length of manifold, μm
L_{out}	length of outlet path, μm
Nu	Nusselt number
OF	objective function
P	pressure, Pa
ΔP	pressure drop, Pa
q''	heat flux input, W/m^2
r	manifold ratio
R	response function
Re	Reynolds number
T	temperature, K
u	velocity, m/s
w_1, w_2	weight functions
W_c	width of microchannel

Greek symbols

α_i	coefficients in the response function
ξ_i	random variable
μ	dynamic viscosity, Ns/m^2
ρ	density, kg/m^3
σ	standard deviation
ψ_i	polynomials in the gPC response function

Subscripts

det	deterministic mean value from outer loop
f	fluid
in	inlet
int	interface
out	outlet
s	solid
w	bottom wall

of 10 to 30 manifolds spanning the entire flow length. Kermani [9] and Kermani et al. [10] performed experiments to demonstrate the use of MMC heat sinks to cool concentrated solar cells, and reported a significant increase in heat transfer coefficient as compared to conventional microchannel heat sinks of similar dimensions. Experimental investigations were also reported by Copeland et al. [11] who observed the thermal resistance to be inversely proportional to the volume flow rate of the coolant. Kim et al. [12] demonstrated a 35% reduction in thermal resistance relative to a conventional arrangement for forced air cooling. Copeland et al. [13] conducted a simplified 1D analysis to predict the pressure drop and thermal resistance of MMC heat sinks based on correlations for a straight rectangular channel. This analytical model was reasonably accurate at high flow rates, but was found to be inadequate for the geometry under consideration at low flow rates. The thermal resistance obtained using the analytical model was found to be about 50–70% lower than that predicted using a simplified 3-D isothermal numerical model. Ryu et al. [14] performed a detailed 3-D numerical analysis for quantifying the thermal performance of an MMC heat sink configuration, and included a consideration of the manifold depth and the bottom solid wall which were previously excluded from analysis [13]. Further, an optimization study was also performed using the steepest-descent method for arriving at the optimal design that would yield the minimum thermal resistance at different pumping powers. It was observed that the optimal geometric parameters as well as the optimal thermal resistance had a power-law dependence on the pumping power.

Microchannel-based heat sinks involve uncertainties in a number of parameters, such as those due to inherent limitations of the fabrication technique, and in the operating conditions such as the inlet flow rate and the input heat fluxes. In the presence of such

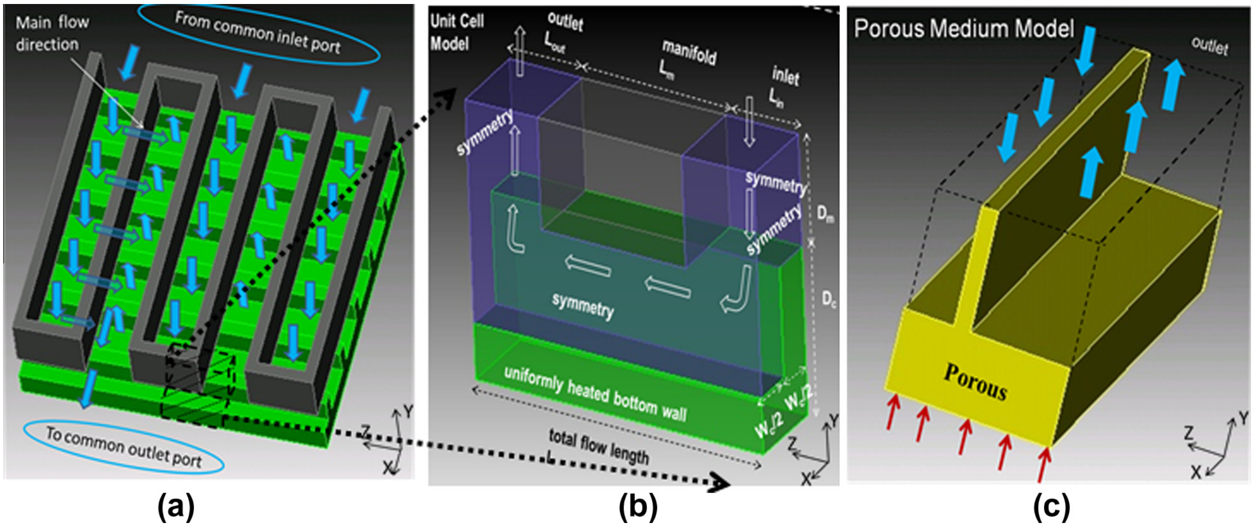

Fig. 1. Computational domains for the MMC heat sink: (a) complete heat sink with coolant path, (b) unit-cell model used for direct simulation, showing geometric parameters and boundary conditions and (c) computational domain for the porous-medium model along with boundary conditions.