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Modeling of microchannel heat sinks for electronic cooling applications using volume averaging approach

Gagan V. Kewalramani, Amit Agrawal, Sandip K. Saha *

Department of Mechanical Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India

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ABSTRACT

In this paper, thermal and hydrodynamic characteristics in microchannel heat sinks are studied to determine the parameters required in modeling heat sinks as fluid saturated porous medium. A three-dimensional conjugate heat transfer model is developed for characterizing fluid flow and heat transfer in microchannel heat sinks. This numerical model is first validated with the results reported in literature. For effective modeling of heat sinks, two different porous medium models are studied, namely Darcy and Forchheimer flow models. Darcy flow model is used for characterizing hydrodynamically and thermally developed flow and Forchheimer model is considered for the developing flow. The regime of applicability of these models is specified in terms of non-dimensional parameter, Forchheimer number. It is found that for Forchheimer number greater than 0.008, the Forchhiemer flow model is more appropriate as compared to Darcy flow model. A generalized expression for permeability with aspect ratio of the channel is obtained. The average Nusselt number defined based on modified heat flux and modified length scale is found to remain constant for different aspect ratios and porosities of microchannel heat sink. The velocity and temperature profiles obtained from the present porous medium model, porous model reported in literature and three-dimensional microchannel heat sink are compared and a good agreement is achieved between present and three-dimensional model. The present model can be used as a reduced order model for analyzing microchannel heat sinks with entrance effects.

1. Introduction

For effective cooling of compact and high heat dissipating devices, a variety of cooling technologies, such as forced air convection, forced liquid convection, thermo-electric, and micro-refrigerators including microchannel heat sink, are available. The concept of microchannel heat sink was introduced by Tuckerman and Pease [1]. The microchannel has high area to volume ratio that results in high heat transfer coefficient, which is inversely proportional to the hydraulic diameter of the channel. Subsequently, a body of research has been reported for the microchannel heat sink, as summarized in the extensive reviews by Phillips [2] and Goodling and Knight [3]. The studies on effect shape of inlet manifold on fluid flow and heat transfer characteristics of microchannel heat sinks are reported by Ghani et al. [4], Ayyaz et al. [5].

Several studies for optimization for the design of microchannel heat sink are conducted. In these studies, different methods of analysis of microchannel heat sinks are used for the optimizations with respect with hydrothermal performance. The analytical optimization using thermal resistance was conducted by Lee [6]. Knight et al. [7] proposed the optimization criteria in terms of non-dimensional number. Numerical methods for optimization of microchannel heat sinks, like optimization with combined RSM and FVM methods [8,9], optimization using Dynamic-Q method [10] and genetic algorithm [11,12] were also developed.

Liu and Garimella [13] classified the analysis models and their optimization models of microchannel heat sinks into computational fluid dynamics (CFD) models and approximate analytical models. Further, approximate analytical models are classified into different models. Based on the increasing order of their accuracy, approximate models can be stated as one-dimensional resistance model, fin model, fin-fluid coupled approach I, fin-fluid coupled approach II, and porous medium approach. The microchannel heat sinks can be modeled as porous medium. The analysis of microchannel heat sinks as porous medium has certain advantages over other approaches. The numerical models for porous medium are computationally less expensive than three-dimensional microchannel heat sink. Extensive studies have been carried out on the three-dimensional conjugate heat transfer model for microchannels [14–17].

* Corresponding author.
E-mail address: sandip.saha@iitb.ac.in (S.K. Saha).

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Nomenclature

a	wetted area perimeter per unit volume ($\frac{w_c+2H}{WH}$), m^{-1}
A	cross sectional area of channel (w_cH), m^2
C_P	specific heat capacity, J/kg·K
Da	Darcy number ($\frac{K}{H^2}$)
F	Forchheimer constant, m^{-1}
Fo	Forchheimer number ($\frac{\rho F U_D D_h^2}{2\mu}$)
f	friction factor
h	interstitial heat transfer coefficient between solid and liquid phase, W/m^2·K
H	channel height, m
K	permeability of porous media, m^2
k	thermal conductivity, W/m K
K_I	inertial coefficient
L	length of heat sinks, m
N	number of channels
Nu	Nusselt number
P	pressure, Pa
Pr	Prandlt number
q''	heat flux, W/m^2
T	temperature, K
u	velocity, m/s
u_{mean}	mean velocity ($\frac{1}{A}\int_A u(x,y,z)dA$), m/s
U_D	mean superficial velocity in porous medium (Darcy velocity, εu_{mean}), m/s
w_c	channel width, m
w_w	fin width, m
W	width of heat sink, m
x^+	hydrodynamic entrance length, m
x^*	thermal entrance length, m
x, y, z	coordinate axes
$\langle\ \rangle_f$	volume averaged over fluid region
$\langle\ \rangle_s$	volume averaged over solid region

Greek symbols

ϕ	parameter
ρ	density, kg/m^3
ν	kinematic viscosity, m^2/s
α	aspect ratio (H/w_c)
μ	dynamic viscosity, kg/m·s
ε	porosity

Subscript

bulk	mass weighted average
D	Darcy
F	fluid
htd	thermally and hydrodynamically developing
high	aspect ratio greater than 1
low	aspect ratio smaller than 1
mean	average over cross sectional area
S	solid
td	thermally developing
wall	wall
1	inlet
2	outlet
∞	thermally and hydrodynamically fully developed

As an alternative to model three-dimensional microchannel heat sink, Koh and Colony [18] suggested porous medium model based on an averaging method. In this, the microchannel heat sink was modeled as a fluid-saturated porous medium, termed as porous medium approach. Mathematically, this is equivalent to averaging the flow properties and temperature distributions in the direction perpendicular to the flow direction. This approach was applied to the microchannel heat sink by Tien and Kuo [19] and later extended by Kim and his co-workers [20–24]. The averaging direction is the direction of the shortest dimension perpendicular to the flow assuming Poiseuille flow. Kim et al. [23] used the following equation for calculating constants required for porous medium analysis, in which K and h are determined as per aspect ratio (α) as,

$$K_{high} = \frac{\varepsilon w_c^2}{12}; \quad K_{low} = \frac{\varepsilon H^2}{12}; \quad h_{high} = \frac{Nu_\infty k_f}{2w_c}; \quad h_{low} = \frac{Nu_\infty k_f}{2H}$$

where $Nu_\infty = 10$ for $\alpha > 1$; $Nu_\infty = 40/7$ for $\alpha < 1$.

Kim et al. [20–24] and Zhao and Lu [25] performed porous medium analysis for the determination of optimum parameters for microchannel heat sink. Kim et al. [20–24] used concepts of thermal resistance for the analysis of optimum parameters for microchannel heat sinks. Porous medium model uses Brinkman extended equation that corresponds to Darcy flow in porous medium Brinkman et al. [26]. Darcy flow in porous medium is valid, only when the flow inside microchannels is fully-developed. To consider the entrance effects, the porous medium model is based on the Darcy flow model with the modified porous medium constants. Entrance effects, however, cannot be approximated for short channels or for large channel dimensions using the Brinkman extended Darcy flow model. Zhao and Lu [25] carried out a parametric study to obtain optimum parameters for microchannel heat sinks.

It is noted that the assumption of Poiseuille flow along the shortest dimension is usually considered, which is not an appropriate assumption, rather the assumption of fully developed rectangular channel flow model is more realistic. Hence, in this work, permeability and heat transfer coefficient are determined without Poisseuille flow approximation in microchannel heat sinks, which is more accurate and explained later. Forchheimer constant in Brinkman extended equation with Forchhiemer term, can capture the hydrodynamic entrance effects. To consider the effects of entrance at large Reynolds number, an alternative approach of Forchheimer model in porous medium is proposed in the present study. The interstitial heat transfer coefficient for the non-equilibrium two-energy equation model for the solid and liquid phases of the porous medium is determined by analyzing the heat transfer inside the microchannel heat sinks. The average Nusselt number based on a suitable characteristic length and modified heat flux is developed considering the hydrodynamic and thermal entrance lengths.

2. Description of physical model

Fig. 1(a) shows the schematic diagram of microchannel heat sink having the channel dimensions of w_c (width) × H (height) × L (length). These channels are separated by fin of width, w_w. For microchannel heat sinks with N number of channels, there are ($N - 1$) fins considered in this study. A constant heat flux (q'') is supplied at the bottom of the microchannel heat sink with the overall dimensions of W *(width)* × L *(length)* × H *(height)*, and all other sides of the microchannel heat sink are kept insulated for conservative design. The porosity ($\varepsilon = \frac{Nw_c}{W}$) is the volume fraction of fluid in microchannel heat sink, where the total width of channel, $W = Nw_c + (N-1)w_f$. A pressure difference (ΔP) is applied across the heat sink, which results in flow of coolant in the chan-