Energy Conversion and Management 105 (2015) 986–994

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Fine-tuning width and aspect ratio of an improved microchannel heat sink for energy-efficient thermal management

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A R T I C L E I N F O

Article history:
Received 27 May 2015
Accepted 26 August 2015

Keywords:
Microchannel heat sink
Aspect ratio
Microchannel width
Nusselt number
Heat transfer coefficient per unit pumping power
Energy-efficient thermal management

A B S T R A C T

Computational experiments were performed to study the influence of microchannel width and aspect ratio on performance of a four-compartment, microchannel heat sink with dedicated coolant inlet and outlet for each compartment. Wide range of coolant velocity (0.25–2 m/s) & aspect ratio (2–10) and a reasonable range of microchannel width (100–200 μm) have been simulated. The appropriate microchannel width and aspect ratio were found to be 200 μm and 6, as evidenced from lowest total thermal resistance and lowest non-uniformity of substrate temperature at comparable power consumption among different microchannel widths and aspect ratios simulated. A new parameter '**ω**' has been proposed for representation of substrate temperature gradient considering maximum, average and minimum substrate temperatures. Correlations have been developed for prediction of dimensionless pumping power, Nusselt number and dimensionless total thermal resistance. Hence, the four compartment heat sink with 200 μm wide channels of aspect ratio 6 can be used for energy-efficient thermal management.

1. Introduction

Thermal management plays an important role in the functioning of membrane fuel cells and electronic components. Microchannel heat sinks (MCHS) form an integral part of thermal management of electronic chips, fuel cell and high density data storage systems through single-phase or two-phase cooling [1–6]. While introducing the concept of liquid cooled microchannel heat sink, Tuckerman and Pease [7] demonstrated a dissipation flux of 790 W/cm^2 on a silicon MCHS. The fluid flow and heat transfer in microchannels are influenced by MCHS configuration, geometry and aspect ratio of microchannels [8]. The use of double layer heat sinks [9,10], modified inlet and outlet manifolds [11], perforated fins [12], distributed heat flux [13] and high aspect ratio microchannels [14–16] improve the performance of MCHS. Total thermal resistance and substrate temperature gradient are used as performance indicators for MCHS. The total thermal resistance of MCHS is the sum of conduction, convection and bulk fluid resistances [17,18]. A reduction in channel width often leads to reduction in convection resistance and increase in bulk fluid resistance [19]. While higher aspect ratio microchannels are considered to be generally advantageous [20], considerable difficulty exists in their fabrication and heat transfer at the fin tip is poor [17]. One of the issues with microchannel heat sinks employing single-phase liquid coolant is the increase in coolant temperature along the channel. The portion of substrate in contact with relatively hot coolant is under-cooled leading to hot spots and subsequently higher substrate temperature gradient. The presence of hot spots leads to thermal stresses apart from device malfunctioning. However, this aspect has not been generally considered during microchannel heat sink design except in few reports [21]. Considering the effect of thermal stresses on mechanical properties, it is desirable to have lower maximum substrate temperature and lower difference between average substrate temperature and substrate minimum temperature. Hence, MCHS dimensions must be appropriately chosen to reduce substrate temperature gradient along with considerations of power required to pump the coolant.

In our earlier work [22], we had proposed a new configuration of a four compartment MCHS containing individual coolant inlet and outlet (Fig. 1), with each compartment containing microchannels with two 'L' sections in each channel. However the effect of microchannel width and aspect ratio on the performance of such a heat sink was not carried out. This work is first-of-its-kind attempt to study the influence of microchannel width and aspect ratio on performance of such a MCHS (Table 1). The study assumes importance due to the fact that most of the reported works on influence of aspect ratio were performed on channels without such 'L' sections where intense fluid mixing occur. With the understanding of the influence of width of the channel (W_c) and aspect

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http://dx.doi.org/10.1016/j.enconman.2015.08.068
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Nomenclature

$\vec{V}$	fluid velocity, m/s
A	area, m^2
C_p	specific heat, J/kg K
D_h	hydraulic diameter, μm
h	heat transfer coefficient, W/m^2 K
H	height, μm
k	thermal conductivity, W/m K
Kn	Knudsen number
$\dot{\mathbf{m}}$	mass flow rate, kg/s
N	Number of channels
Nu	Nusselt number
p	Pressure, Pa
P	Pumping power, W
Q	Volumetric flow rate, m^3/s
q	heat flux at microchannel heat sink bottom plate, W/m^2
Re	Reynolds number
R_{th}	total thermal resistance, K/W
T	temperature, K
$T_{f,avg}$	volume averaged temperature of the fluid, K
$T_{w,avg}$	surface averaged temperature at the fluid solid interface, K
W	width, μm

Greek

μ	viscosity, kg m/s
α	aspect ratio
$\boldsymbol{\theta}$	maximum substrate temperature difference per unit flux, K/W
ρ	density, kg/m^3
$\boldsymbol{\omega}$	a measure of non-uniformity of substrate temperature, K/W

Subscript

avg	average
b	microchannel heat sink bottom plate or substrate
c	channel
Dl	dimensionless
f	fluid
hs	heat sink
i	*X*, *Y* and *Z* directions
in	inlet
out	outlet
S	solid
W	wall

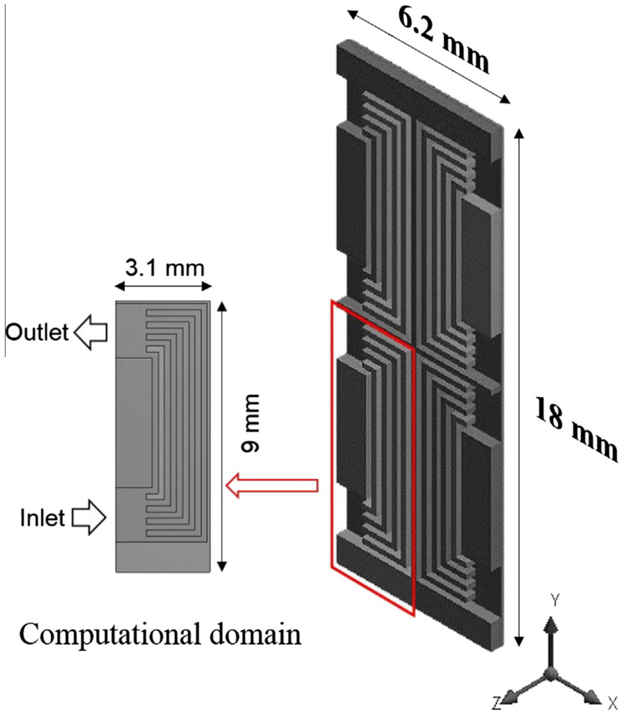

Fig. 1. Schematic representation of MCHS and the computational domain.

ratio (α) on heat transfer performance of this microchannel heat sink, the study aims to fine tune microchannel width and aspect ratio to achieve the best possible heat transfer performance in terms of total thermal resistance and substrate temperature gradient.

Three-dimensional numerical optimization, widely adopted [23–25] to identify the appropriate microchannel aspect ratio and width that lead to minimum total thermal resistance and substrate temperature gradient is used in this study. Microchannel width (100–200 μm), aspect ratio (2–10) and coolant velocity (0.25–2 m/s) have been used as independent variables. In general lower total thermal resistance is achieved with microchannels of lower width (<50 μm) and higher aspect ratio (>10), when the power consumption is greater than 0.01 W [26]. However, fabrication of microchannels of lower width and higher aspect ratio is not easy and requires higher precision. Microchannels of higher width containing ‘L’ sections can be fabricated with relative ease without exceeding the maximum permissible hydraulic diameter for microchannels [17], justifying the choice of range of microchannel width. Hence the smallest microchannel width has been fixed at 100 μm for the present work. A constant substrate thickness of 100 μm has been utilized in the present work to ensure that the changes in aspect ratio and channel width influence convective resistance while the resistance due to substrate thickness remains unchanged. Though the reduction in fin width permits incorporation of higher number of channels, too thin fins may have adverse effect on strength of the sink [19,27]. It has already been shown that lower thermal resistance and higher fin efficiency could be obtained when fin width and channel width were equal [7]. Hence fins with width as those of channels have been used in the present study. Depending upon the microchannel width, the maximum values for aspect ratio and coolant velocity were fixed in such a way that the channel height did not exceed 1000–1200 μm and Reynolds number was within the limit for laminar flow regime. A new parameter to characterize the substrate temperature gradient has been introduced that reflects both the design goals – lower maximum substrate temperature and closeness of average & minimum substrate temperatures. This would facilitate lower temperature window for fuel cell operation. Correlations have been developed for prediction of dimensionless pumping power, Nusselt number and dimensionless total thermal resistance.

2. Governing equations and numerical procedure

Steady, three-dimensional fluid flow and heat transfer has been considered in the present work. The coolant is assumed to exist in liquid phase only and hence considered incompressible. Considering the lower hydraulic diameters of microchannels and liquid