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Numerical investigation of heat transfer in extended surface microchannels

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ABSTRACT

Microchannel heat sinks (MCHS's) are currently projected as twenty first century cooling solution. In the present numerical study, heat transfer enhancement in microchannel using extended surface has been carried out. Rectangular microchannel and cylindrical microfins are used in current study. Three different configurations of extended surface microchannel; Case I (upstream finned microchannel), Case II (downstream finned microchannel) and Case III (complete finned microchannel) are compared with plain rectangular microchannel. It is found that heat transfer performance of Case I is better than Case II. Case I even performs better than Case III at low Reynolds number. Average surface temperature is also significantly reduced in case of extended surface microchannels. Optimization of extended surface microchannel has also been successively carried out following univariate search method for number of fins, pitch, diameter and height of fins. Average heat transfer enhancement in optimized case is around 160% with acceptable pressure drop penalty.

1. Introduction

Breakthrough in diversified fields is largely dependent on the ability to safely dissipate large amount of heat from extremely small surface area. This urgency has thrown challenge to design compact size efficient heat sink especially for applications; where conventional heat sink cannot be used either due to space constraint or due to high heat flux duty requirement i.e. high speed component [1], laser process equipments [2], fusion related [3] and defense related equipments [4]. Effective thermal management in these applications not only increases their reliability but also helps in achieving next level of miniaturization. With the objective of efficient cooling system for high speed Very Large Scale Integrated (VLSI) circuits, Tuckerman and Pease [5] for the first time fabricated MCHS (w,h) (50 μm, 320 μm), which was capable of removing heat flux up to the rate of 700 W/cm^2. Since then MCHS's have been used as one of the prominent solution for the problems, where electronic devices fail due to excessive heating [6–9]. Major advantages MCHS offer over conventional heat sink are larger surface area to volume ratio, high heat transfer coefficient and very small coolant inventory requirement. MCHS's are generally fabricated with copper [4,10] or silicon [5,6,11–13] as base material. Copper is an excellent conductor of heat and silicon has maintained its popularity as good semiconductor in electronic industry. Due to excellent heat removal capability of MCHS's, understanding the associated fluid flow and heat transfer characteristics have been topics of intense research in the last decade [14–17].

Surprisingly, the limit to define microchannel has not been unanimously accepted. Different researchers had proposed different criteria for it. Kandlikar and Grande [18,19] suggested the range as ($10\ \mu m < d_h \leqslant 200\ \mu m$), whereas Mehendale et al. [20] projected the range as ($1\ \mu m \leqslant d_h \leqslant 100\ \mu m$) to distinguish between micro and macrochannel. Cornwell and Kew [21] and Kew and Cornwell [22] advised that macro to micro scale transition criteria should be based on confinement number ($Co \geqslant 0.5$). Recently, Harirchian and Garimella [23] suggested new transition criteria ($Bo^{0.5}Re < 160$) for distinguishing between micro and macro channels. Exclusive literature review of microchannel is presented by Kadam and Kumar [24], Kandlikar [25–27] and Kandlikar et al. [28]. Lots of work has been carried out on single phase and two phase heat transfer and pressure drop characteristics of microchannel. Due to superior heat transfer characteristic of boiling process major efforts are concentrated on two phase flow studies. However, various associated instabilities such as parallel channel instability [29], pressure fluctuation [12], vapor blocking [30] and flow reversal [31–33], turn two phase flow in microchannel more susceptible against stable performance. Performance fluctuation causes overheating, which induces malfunctioning of the

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Nomenclature

A_B	base area of unit cell (m^2)
A_c	cross-sectional area of channel (m^2)
A_{sur}	surface area (m^2)
Bo	Bond number
c_p	specific heat (J/kg K)
Co	confinement number
d_h	hydraulic diameter (μm)
d_f	diameter of fin (mm)
g	gravity (m/s^2)
h	height of microchannel (μm)
h_f	height of fin (mm)
k	thermal conductivity (W/m K)
L	length of microchannel (mm)
L_{in}	distance of first fin from inlet (mm)
N	number of fins
Nu	Nusselt number
p	fin pitch (mm)
P	pressure
ΔP	pressure drop (bar)
q''	heat flux (W/cm^2)
Re	Reynolds number
T	temperature (°C)
U	velocity (m/s)
$\vec{V}$	velocity vector
v_x	velocity component in x direction
v_y	velocity component in y direction
v_z	velocity component in z direction
w	microchannel width (μm)
x	Cartesian coordinate
y	Cartesian coordinate
z	Cartesian coordinate

Greek

ρ	density (kg/m^3)
μ	viscosity (Pa-s)
Γ	interface
η	thermal performance factor

Subscripts

avg	average
cr	critical
eff	effective
f	fluid
in	inlet
s	solid
m	mean
o	plain channel

system or may even lead to permanent damage of the system. Hence, single phase studies are equally important. Peng and Wang [34] in their experimental study on rectangular microchannel observed that single phase heat transfer coefficient was affected by liquid subcooling and flow velocity. Peng and Peterson [35] concluded that heat transfer performance of laminar flow can be augmented by increasing the ratio of hydraulic diameter to centre to centre distance of microchannel. They further showed that increasing aspect ratio also facilitated the performance of MCHS. Harms et al. [11] suggested transition criteria from laminar to turbulent flow in microchannel as Re_{cr} = 1500. Low Reynolds number transition in case of microchannel was attributed to sharp inlet, long entrance region and surface roughness. Qu and Mudawar [10] verified that Navier-Stoke and energy equation were capable of predicting heat transfer behavior of the single phase flow in microchannel. They also observed that at constant Reynolds number pressure drop reduced with increase in heat flux, which they attributed to decrease in viscosity of water with increase in temperature. Ergu et al. [36] concluded that single phase pressure drop behavior of rectangular microchannel follows macrochannel theory for laminar flow region. However, Koyuncuoglu et al. [37] found that predicted single phase friction factor by conventional theory was lower than experimental values in case of rectangular microchannel. Wang et al. [38] optimized design parameters of a MCHS using inverse problem approach integrating simplified conjugate-gradient scheme with three dimensional heat transfer and flow model. They found that increasing pumping power is not always cost effective approach for practical heat sink designs.

In search of finding suitable heat transfer augmentation technique for single phase flow, researcher have also worked on by choosing among from conventionally proven methods e.g. modification in channel geometry [39–50] and through nanofluids [51–55]. Gong et al. [39] used wavy microchannel in their numerical study and observed that redevelopment of thermal boundary layer helped in heat transfer enhancement. Sui et al. [40] experimentally verified heat transfer enhancement provided by wavy microchannel as compared to straight microchannel. They accredited it in favor of secondary flow inside the curves of wavy microchannel. Xu et al. [41,42] carried out experimental and numerical study for understanding the effect of combining parallel longitudinal microchannel and transverse microchamber. They observed that presence of microchamber promoted redevelopment of the thermal boundary layer, which augmented heat transfer performance. Yong and Teo [43] numerically investigated heat transfer and pressure drop characteristics of the conversing–diverging microchannel. They observed that heat transfer performance of conversing diverging microchannel was superior to that of straight channel with acceptable pressure drop penalty. Xie et al. [44] proposed double-layer wavy MCHS for improving the heat transfer performance of single layer wavy MCHS. They found lesser pressure drop in case of double-layer wavy MCHS. Xie et al. [45] compared numerically the performance of counter and parallel-flow double-layer plain and wavy MCHS. For better heat dissipation performance, they suggested parallel-flow arrangement for low flow applications and counter-flow arrangement for high flow applications. Overall thermal performance of doubled layer plain MCHS was found to be better than wavy double layer wavy MCHS. Xie et al. [46] suggested partial bifurcation (using straight plates) of exit flow field for improving the performance of straight MCHS. They found increase in heat transfer performance with increase in number of bifurcations. Li et al. [47] numerically compared laminar flow heat transfer characteristics of rectangular straight MCHS and MCHS's with vertical Y-shaped bifurcation plates with arm angle of 60°, 90°, 120° and 180°. The MCHS with 90° arm angle has highest heat transfer performance. Zhang et al. [48] compared numerically performance of straight and three configurations of entrance region multiple (single and two-stage) bifurcated MCHS. They suggested two-stage bifurcated microchannel with shorter plate at the back of each sub-channel for the best performance. Leng et al. [49] suggested truncation of top channel for improving the performance of double-layer counter-flow MCHS. Optimal truncated length of top channel was found when the coolant temperature in the top channel is approximately equal to the bottom coolant temperature. Leng et al. [50] optimized the design parameters of