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Experimental and numerical study of fluid flow and heat transfer characteristics in microchannel heat sink with complex structure

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ABSTRACT

Thermal management has become crucial to ensure the performance and reliability of high power chips and micro-cooling systems. The forced convective heat transfer of microchannel heat sink is a very promising method. In this paper, experiment is used to perform temperature and pressure drops and numerical simulation is used to understand and interpret the complex thermal behavior by presenting the flow field in the current complex corrugation microchannel heat sink. The comprehensive performance is evaluated by total thermal resistance and thermal enhancement factor. Compared with the equivalent rectangle microchannel heat sink, the average temperature and maximum temperature is reduced obviously and temperature distribution is more uniform albeit with higher pressure penalty for flow rates larger than 100 ml/min. It is observed that the vortex becomes bigger and moves to the middle of channel with increasing of flow rate. The enhance heat transfer mechanisms can be contributed to the heat transfer area enlarged, thermal boundary interrupted and redeveloped, chaotic advection, hot and cooling fluid better mixed by vortex formed in the reentrant cavity. The pumping power is reduced 18.99% when total thermal resistance equals to 0.446 K/W, compared with rectangle microchannel heat sink. The thermal enhancement factor can reach 1.24 for Reynolds number of 611. Therefore, complex corrugation microchannel heat sink is more economical for chip cooling system.

1. Introduction

Over the last few decades, with the rapid development of Micro-Electro-Mechanical-Systems, microchannels single-phase liquid cooling has been identified to be one of the most promising and effective cooling methods in the fields of microelectronics, laser, image processing, aerospace, etc. Microchannel heat sink (MCHS), proposed firstly by Tuckerman and Pease in the early 1980s [1], features a higher heat transfer performance, smaller geometric size, lower coolant requirement than conventional heat sinks.

Many scientific and engineering programmers have been conducted to develop more effective and sophisticated MCHS. Focusing on heat transfer enhancement based on microchannels, Chai et al. [2] investigated the heat transfer performance of microchannel heat sink with periodic expansion–constriction cross-section. The results showed that the thermal entrance effect weakened and the wave motion of local Nusselt number reduced, compared with rectangular channel. Zhai et al. [3] presented the heat transfer performance of microchannels with reentrant cavities and ribs. They found the performance of channel with trapezoidal ribs was best for *Re* less than 300, but the circular ribs is best for *Re* larger 300. And heat transfer enhancement was contributed to the better synergy between velocity vector and temperature gradient. The entropy minimization method was applied to optimize the heat sink with staggered arrays of pin fin and tip clearance by Shi et al. [4]. It was found that the effects of tip clearance was more pronounced for conductive at the high aspect ratio, compared with convective, while the convective effect dominated at low ratio. The heat transfer performance of heat sinks with converging channels was studied by Dehghan et al. [5]. The results showed the pumping power decreased and Nusselt number increased with increasing of tapering under the given pressure drop. The width-tapered ratio of 0.5 was the most promising.

The working mediums of heat sink also were investigated. Bigham et al. [6] presented the effects of rarefactions and geometry on thermally and hydrodynamically in constricted microchannels, and viscous dissipation also was considered in literature [7]. The results showed that viscous dissipation enhanced the heat transfer, but effected slightly for hydrodynamic. The $C_f Re$ and Nusselt number decreased with increasing of Knudsen number that had a

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Nomenclature

a_c	aspect ratio of channel
A_c	contact area between fluid and silicon (mm^2)
Λ	mean free path of fluid (m)
c_p	special heat capacity (kJ/(kg K))
D_h	hydrodynamic diameter (mm)
f	friction factor
h	heat transfer coefficient ($W/(m^2 K)$)
H_{ch}	depth of channel (mm)
K	Hagenbach's factor
Kn	Knudsen number
L	length of channel (mm)
L'	characteristic dimension of channel
L_h	hydrodynamic developing length (mm)
L_t	thermal entry length (mm)
Nu	Nusselt number
P	power (W)
ΔP	pressure drop (Pa)
P_p	pumping power (W)
Q_v	flow rate (ml/min)
R	total thermal resistance (K/W)
Re	Reynolds number
T	temperature (K)
ΔT	temperature different (K)
v	mean velocity (m/s)
W_{ch}	thickness of channel (mm)
x	non-dimensional flow length for the flow boundary layer development
x^*	non-dimensional flow length for the flow boundary layer development
x, y, z	three coordinates

Greek symbols

ρ	density (kg/m^3)
λ	thermal conductivity (W/(m K))
μ	dynamic viscosity ($kg/(m\ s^2)$)
η	thermal enhancement factor

Subscripts

av	average
b	bend
ch	channel
c	contraction
exp	experiment
e	expansion
f	fluid
fd	fully developed
in	inlet
l	linear
max	maximum
o	rectangle channel
out	outlet
s	solid
$sink$	heat sink

declining effects. The heat transfer characteristics of nanofluid in a natural circulation with a mini-channel heat sink and heat source were investigated by Ho et al. [8]. It was found the average heat transfer effectiveness was enhanced 3.5–22% and 9.5–62% for the heating and cooling sections by Al_2O_3–water nanofluid.

Tortuous channels presented great potential to provide heat transfer performance, for generating secondary flows in the channel bends [9]. Ghaedamini et al. [10] numerically studied the effects of geometrical parameter on fluid flow and heat transfer of wavy microchannels. It was found that the counter rotating vortices deteriorated the heat transfer and chaotic advection was controlled by the expansion factor and Reynolds number. The chaotic advection happened at smaller expansion factors with increasing of Reynolds number, which enlarged the heat transfer rates albeit with higher pressure penalty. Ghaedamini et al. [11] revealed that the chaotic advection enhanced heat transfer for better fluid mixing. The channels with walls modulated highly could culminate in a strong chaotic advection, which resulted in significant heat transfer enhancement but with a considerable pressure drops. The suitable frequency pulsate flow could reduce the pressure drops penalty. Xie et al. [12] numerically investigated the effects of wave amplitude on thermal resistance in single-layer and double-layer wavy microchannels. It was found that no recirculation and secondary flow existed for low Dean Number and heat transfer enhanced mainly due to the thinning of the hydrodynamic and thermal boundary layers, especially in crest regions. Khoshvaght-Aliabadi [13] numerically investigated the effects of sinusoidal-corrugated channel parameters on fluid flow and heat transfer characteristics and found that the channel height and wave amplitude had great influences on Nusselt number and friction factor. Dai et al. [14] experimentally investigated the hydrodynamic and heat transfer characteristics of tortuous microchannels. It indicated that the flow recirculation and secondary flow structures would help to increase heat transfer rates and zigzag channel configuration provided highly heat transfer intensification.

While the thermo-hydraulics in microchannels has been studied extensively, entire microchannel heat sink studies are very limited. The uniformity of substrate temperature is an important factor in the design of MCHS. This could be achieved by better distribution of coolant, distribution of heat flux and better transport properties of coolants. Under given coolants and circumstances, the better distribution of coolant is an availability method to maintain substrate temperature.

Mohammed et al. [15] numerically investigated the effects of wavy amplitude on hydrodynamic and heat transfer characteristics in MCHS. It was found that the high temperature region appeared at the edge of heat sinks since there was no fluid convection heat transfer and low-temperature region occurred in the near center region of heat sink. It indicated the heat transfer became better with increasing of wavy amplitude under the small amplitude, but it was deteriorated for wavy amplitude of 0.25 due to poor fluid mixing. However, they ignored the non-uniformity of fluid distribution and assumed to fluid evenly distributed to each channel. Leela et al. [16] computationally studied the effects of inlet and outlet arrangements on fluid flow and heat transfer for rectangle microchannel heat sink (RMCHS) with four compartments and separate inlet and outlet for every compartment. It was indicated that the lower temperature gradients could be attributed to a better distribution of coolant and recirculation. Lu et al. [17] studied the effects of inlet location on the fluid and temperature distributions in parallel-channel cold-plate. It was found the heat transfer performance of I-type was better because of impingement and Z-type was worse due to dramatic recirculation and mal-distribution. Xia et al. [18] found the fluid distribution was more uniform in heat sink with I-type and rectangular header.