International Communications in Heat and Mass Transfer 66 (2015) 47–57

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Optimum thermal design of triangular, trapezoidal and rectangular grooved microchannel heat sinks☆

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ARTICLE INFO

Available online 15 May 2015

Keywords:
Optimization
Thermal design
Grooved microchannel
Heat sink
Numerical simulation

ABSTRACT

A three-dimensional numerical simulation is conducted to investigate the effect of geometrical parameters on laminar water flow and forced convection heat transfer characteristics in grooved microchannel heat sink (GMCHS). Four geometry variables which are; the depth, tip length, pitch and orientation of the cavities are taken into account in order to optimize the aluminum heat sink design. These geometric parameters could change the cavity shape from triangular to trapezoidal and then to rectangular shape. The governing and energy equations are solved using the finite volume method (FVM). The performance of GMCHS is evaluated in terms of Nusselt number ratio, thermal/hydraulic performance (*JF*) and isotherm and streamlines contours. The results showed that the trapezoidal groove with groove tip length ratio of $\delta = 0.5$, groove depth ratio $\beta = 0.4$, groove pitch ratio of $\psi = 3.334$, grooves orientation ratio of $\zeta = 0.00$ and $Re = 100$ is the optimum thermal design for GMCHS with Nusselt number enhancement of 51.59% and friction factor improvement of 2.35%.

1. Introduction

With the fast sophistication of nano-technologies and the high heat dissipation requirement in a small area of electronic devices such as processers, the application of microchannel heat sink (MCHS) had more attention from researchers to design more compact and efficient heat sink to transfer the heat from a power source to a cold fluid. Microchannel heat sink contains of many parallel microchannels (fins) having less than 1000 μm hydraulic diameter and a single-phase fluid is forced to pass through these fins to carry heat away from the power source. The MCHS is used in wide engineering applications such as: electronic cooling devices, laser process equipment and computers processers. The high pressure drop in MCHS due to its small cross-section area restricts researchers to implement it for high velocities applications. Therefore, the low fluid velocity is the essential challenge that the limited ability of fluid to absorb heat from the heated wall. In addition, the traditional straight MCHS became inadequate to absorb the great heat generated by micro-scale chip devices that restricts the micro-fabrication processes unless action is taken in account to optimize the thermal/hydraulic performance of MCHS. To overcome this challenge, new channel configurations can be considered in order to enlarge the heat absorption capacity of heat sink while maintaining the size of heat sink substrate.

The research on micro-scale rectangular channels and circular tubes started from 1980s when Tuckerman and Pease [1] and Tuckerman [2] examined a 1 × 1 cm^2 silicon wafer MCHS. They were the first who stated that reducing the heat sink size to micron scale increases the heat transfer rate. From that time, lot of studies has been carried out to enhance the thermal performance of MCHS using various techniques.

Adams et al. [3] stated that a large amount of heat transfer could be transferred from microchannels built-in a chip substrate with a small temperature difference between the liquid–solid interfaces. While Rahman [4] measured experimentally the heat transfer and pressure drop in MCHS with water. He found that the average Nusselt number was larger than those predicted for macro-channels using parallel channels (I-shape) and series channels (U-shape).

Xia et al. [5] investigated numerically the effect of geometrical parameters of MCHS having triangular reentrant cavities on heat transfer and fluid flow. They revealed that the triangular reentrant cavities enhance the heat transfer by interrupting the thermal and hydraulic boundary layer compared to the plane channel. They obtained an optimum design by varying the geometrical parameters of cavities. While, the same previous research group, Chai et al. [6], examined numerically and experimentally the heat transfer augmentation of

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☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.05.009
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Nomenclature

a	groove depth length, m
A	cross-sectional area, m^2
AR	aspect ratio
b	tip length of the groove, m
D_h	hydraulic diameter, m
f	friction factor
GMCHS	grooved microchannel heat sink
h	convective heat transfer coefficient, $W/m^2 \cdot K$
h_c	height of the groove, m
H_s	total microchannel height, m
j	Colburn factor
JF	Performance evaluation criterion
k	thermal conductivity, $W/m \cdot K$
L_g	length of the groove, m
L_s	total length of the microchannel (m)
Nu	Nusselt number
ΔP	differential pressure (pa)
P	perimeter, m
p_g	pitch length of the groove, m
r	distance of the groove beginning point of one side to opposite side, m
Re	Reynolds number
u_m	mean velocity, m/s
u, v, w	velocity components in x, y, z direction, m/s
U, V, W	dimensionless velocity components in x, y, z direction, respectively
W_c	microchannel width, m
W_s	total microchannel width plus lateral wall, m
Z	dimensionless axial distance, m
X, Y, Z	dimensionless Cartesian coordinates
Greek symbols	
β	groove depth ratio
δ	tip length ratio of the groove
μ	dynamic viscosity, $kg/m \cdot s$
ρ	Density, kg/m^3
ϑ	kinematic viscosity, m^2/s
ψ	pitch length ratio of the groove
ζ	orientation ratio of the groove
Subscripts	
avg	average
c	microchannel
m	mean
o	initial
out	outlet
s	substrate
*	modified case

MCHS with periodic expansion-constriction cross-sections. They reported that MCHS with rectangular cross-section has higher Nusselt number by about 1.8 than straight channel. Moreover, Xia et al. [7] optimized the geometrical parameters of inlet/outlet location, header shape and MCHS cross-section shape. They found that all of these variables play an important role in the design of MCHS to prolong the life of the microelectronic devices. They proposed a new design for interrupted microchannel heat sink using rectangular ribs in the transverse micro-chamber as published in their paper of [8]. As a continuation to their work, they attributed the reason of heat transfer enhancement when offset fan-shaped reentrant cavities are used in MCHS to the increase in the heat transfer surface area and periodic thermal developing flow [9]. Vinodhan and Rajan [10] examined four MCHS configurations and compared their performance with the straight MCHS. They observed that the substrate temperature gradients in new configurations were lower than that in plane MCHS due to better distribution of coolant and recirculation.

Mohammed et al. [11] pointed out that the wavy MCHS with rectangular cross-section showed better thermal performance compared to the straight channel. The increase in the pressure drop of wavy channel was smaller than the increase in the heat transfer. Continuously with their work, they found that the MCHS having zigzag channels provide better heat transfer enhancement followed by curvy and then step shapes for the same cross-section [12]. The thermal performance of the previous channel shapes was higher compared to the straight channel. Navin Raja Kuppusamy et al. [13] stated that increasing the angle and depth of the groove leads to enhance the heat transfer with optimum pitch distance. They confirmed that there was an increase in the pressure drop penalty but less than the augmentation in heat transfer rate. Alfaryjat et al. [14] concluded that the smallest hydraulic diameter of the hexagonal cross-section MCHS has the privilege to be the best channel shape for the heat transfer coefficient and pressure drop compared to circular and rhombus shapes. However, rhombus cross-section MCHS had the optimum performance in terms of temperature, friction factor, and thermal resistance.

Li and Peterson [15] revealed that the overall cooling capacity of silicon based parallel microchannel heat sink improved by more than 20% using the optimized spacing and channel dimensions. Xie et al. [16] pointed out that the thermal performance of the microchannel heat sink with multistage bifurcation flow is better than that of the corresponding straight MCHS. They suggested that proper design of the multistage bifurcations could be employed to improve the overall thermal performance of MCHS and the maximum number of stages of bifurcations was recommended to be two. While Li et al. [17] demonstrated that the thermal performance of the MCHS with Y-shaped bifurcation plates is much better compared to the corresponding straight channel. It was suggested that the Y-shaped bifurcation plates placed in water-cooled MCHS could improve the overall thermal performance when the angle between the two arms of the Y-shaped plates is designed properly.

It is obvious from the above literature review and to the best knowledge of the authors that the optimization of thermal design of MCHS using triangular, trapezoidal and rectangular grooves seems not to have been investigated before. In addition, it is clearly seen that the MCHS was studied extensively but there is a very limited data reported in open literature that involves getting three different shapes of grooves by merely varying the groove dimensions to get triangle, trapezoid and rectangle cavities. This gap motivated the present study to examine this area of research numerically in three-dimensions. The results of parameters such as Nusselt number, *JF* and streamlines and isotherm lines contours are depicted, compared with those of straight and thoroughly explained to illustrate the effect of various channel shapes on these parameters.

2. Mathematical model description

2.1. Physical model and assumptions

The schematic diagram of the assumed geometry and the flow configuration considered in this paper is shown in Fig. 1(a) and (b). The ratio of the length and width of the aluminum substrate to its height are $(L_s/H_s) = 28.571$ and $(W_s/H_s) = 0.8571$, respectively, while the substrate height is considered as taken in Ref. [5]. The width of the microchannel is $(W_c/H_s) = 0.2857$, while the height is $(h_c/H_s) = 0.5714$. The grooves are equal in size and are arranged equidistance along the flow direction. Four design parameters,