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Thermohydraulic performance of microchannel heat sinks with triangular ribs on sidewalls – Part 1: Local fluid flow and heat transfer characteristics

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ABSTRACT

Triangular ribs are mounted on the parallel sidewalls of microchannels in order to reinitialize the thermal boundary layer and improve the mixing of cold and hot fluids. This paper presents a detailed numerical study on local laminar fluid flow and heat transfer characteristics in microchannel heat sinks with tandem triangular ribs for Reynolds number of 443. Three-dimensional conjugate heat transfer models considering entrance effect, viscous heating, as well as temperature-dependent thermophysical properties are employed. Water and silicon are respectively used as fluid and solid for the computational domain. Triangular ribs are attached in microchannels with either aligned or offset arrangement. Four non-dimensional geometry parameters relative to the width, height, converging-diverging ratio and spacing of triangular ribs are proposed to investigate the influence on local fluid flow and heat transfer characteristics. Velocity contour, pressure and temperature distributions are examined to demonstrate the basic fluid flow and heat transfer mechanism. Local pressure and temperature profiles are studied to show the influence of the triangular ribs on fluid flow and heat transfer process. Local friction factor and Nusselt number for different non-dimensional geometry variables are further investigated to comprehensively indicate the impact of triangular ribs. Results shows that the triangular ribs can significantly reduce the temperature rise of the heat sink base and efficiently prevent the drop of local heat transfer coefficient along the flow direction, but also result in higher local friction factor than the straight microchannel. For the studied operation conditions and geometry parameters of flow passage, the heat sink base temperature varies in the range of from 301.90 to 324.31 K, the computed pressure drop and heat transfer coefficient fluctuate from one triangular rib to the next and their amplitude and wavelength significantly depend on the geometry and arrangement of triangular ribs. Compared to the reference straight microchannel heat sink, a superior configuration considered in this paper can yield an improvement of up to 2.15 times higher of average Nusselt number.

1. Introduction

With the rapid development of microminiaturization technology and the urgent requirement of high heat flux dissipation, microchannel heat sink incorporating single-phase liquid flow has been widely applied in a variety of applications, such as the cooling of electronic device, laser process equipment and aerospace technology. Firstly proposed by Tuckerman and Pease [1] in the early 1980s, it has many advantages, such as compactness, light weight and higher heat transfer surface area to fluid volume ratio compared with other macroscale heat exchangers. And extensive studies have been conducted on the fluid flow and heat transfer characteristics in microchannel heat sinks. Furthermore, the highly-integrated electronic circuit has increased the heat flux in electronic chips up to 1 kW/cm^2, pushing the traditional straight microchannel heat sink to its thermal limit [2,3]. Recently, many significant works, based on passive techniques for heat transfer augmentation, have been conducted with the potential to deliver more high heat flux for microelectronic applications [4].

For the interrupted microchannel heat sink, Xu et al. [5,6] demonstrated a heat sink consisted of a set of separated zones adjoining shortened parallel microchannels and transverse microchambers. Results showed that the hydraulic and thermal

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Nomenclature

A	area, m^2
c_p	specific heat, $J\cdot kg^{-1}\cdot K^{-1}$
D_h	hydraulic diameter, m
f	friction factor
$\bar{f}$	average friction factor
h	heat transfer coefficient, $W\cdot m^{-2}\cdot K^{-1}$
$\bar{h}$	average heat transfer coefficient, $W\cdot m^{-2}\cdot K^{-1}$
H	height, m
k	thermal conductivity, $W\cdot m^{-1}\cdot K^{-1}$
L	length, m
Nu	Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure, Pa
q	heat flux, $W\cdot m^{-2}$
Re	Reynolds number
S	spacing, m
T	temperature, K
$\overline{T}$	average temperature, K
u	velocity, $m\cdot s^{-1}$
$\bar{u}$	average velocity, $m\cdot s^{-1}$
W	width, m
x^+	non-dimensionalized length, $x^+ = x/(D_h Re)$
x^*	non-dimensionalized length, $x^* = x/(D_h Re Pr)$
x,y,z	three coordinates shown in Fig. 1a, m

Greek letters

ρ	density, $kg\cdot m^{-3}$
μ	dynamic viscosity, Pa·s

Subscripts

c	channel
com	computational domain
con	contraction
exp	experimental
f	fluid
in	inlet
num	numerical
out	outlet
r	rib
s	silicon
x	flow direction
w	heat sink base

Abbreviations

ATR	aligned triangular ribs
CFD	computational fluid dynamics
LVG	longitudinal vortex generators
MCHS	microchannel heat sink
OTR	offset triangular ribs

boundary layers were redeveloped in each separated zone, and the periodic thermal developing flow resulted in significant heat transfer enhancement and similar or reduced pressure drop. The pressure drop was attributed to two effects, one was the pressure recovery effect when liquids left the upstream zone and the other was the increased head loss once liquid entered the next zone. Chai et al. [7,8,9] and Wong and Lee [10] introduced the staggered ribs into the transverse microchambers. They found that the staggered ribs not only suppressed the heat transfer deterioration in the microchamber region, but also improved the heat transfer coefficient to a much higher level in the separated microchannel zone, leading to further improved heat transfer performance due to better flow separation and mixing of hot and cold liquids. The local pressure drop and heat transfer in the microchamber were mainly influenced by Bernoulli effect, entrance and exit geometry, and the developed stagnation or recirculation zone.

For the microchannel heat sink with passive microstructures, Promvonge et al. [11] examined the laminar flow and heat transfer characteristics of a three-dimensional isothermal square channel with 45°-angled baffles mounted in tandem with both inline and staggered arrangements on the lower and upper walls. In each of the main vortex flows, a pair of stream wise twisted vortex flows was created by the baffles, which induced impinging flows on a sidewall and wall of the baffle cavity and led to drastic increase in heat transfer rate than the reference smooth channel. Liu et al. [12] and Ebrahimi et al. [13] investigated the thermohydraulic performance of a microchannel heat sink with longitudinal vortex generators (LVG). Due to the better fluid mixing, reducing the thermal boundary-layer thickness and an increase of the heat transfer area, the microchannel with LVG can enhance heat transfer while consuming larger pressure drop, compared with the smooth microchannel. Foong et al. [14] studied the fluid flow and heat transfer characteristics of a square microchannel with four longitudinal internal fins. Parametric study on thermal performance showed that for a given microchannel, there was an optimal fin height that provided the best possible heat transfer and pressure drop characteristics. Compared to a smooth microchannel, the microchannel with internal longitudinal fins had the following beneficial features: shorter length required for the development of the thermal boundary layer, better flow mixing, steeper velocity gradient at the heated surface, increase of surface area for heat transfer, and increase in surface heat transfer coefficient and Nusselt number. Xie et al. [15] investigated the thermal and fluid flow characteristics of microchannel heat sinks with internal vertical Y-shaped bifurcations and examined the effect of the length of Y-shaped bifurcation and the angles of the arms on the overall performance. The longest internal Y-shaped bifurcation microchannel resulted in the best thermal performance, and a larger arm angle led to better thermal performance but larger pressure drop.

For the microchannel heat sink with periodically varying cross-sections, Sui et al. [16,17], Mohammed et al. [18] and Lin et al. [19] studied the laminar flow and heat transfer in wavy microchannel heat sinks. When the liquid passed through the wavy microchannels, secondary flow was generated, and the quantity and the location of the vortices can change along the flow direction and result in chaotic advection, which can greatly enhance the convective mixing of the flow. The penalty of pressure drop in the wavy microchannels can be less significant than the heat transfer enhancement. And the increase of relative wavy amplitude can result in better heat transfer performance. Ghaedamini et al. [20] studied the effects of geometrical configuration (aspect ratio, waviness, and expansion factor) on heat transfer and fluid flow in a converging-diverging microchannel heat sink. For the regular advection regime, increasing the waviness resulted in better heat transfer performance, while for the chaotic advection regime, heat transfer increased drastically albeit with a higher pressure drop penalty. Furthermore, the counter rotating vortices created in the trough region were found to have an adverse effect on the performance of heat transfer. Chai et al. [21,22] and Xia et al. [23,24] investigated the fluid flow and heat transfer in microchannel heat sinks with fan-shaped or triangular reentrant cavities on sidewalls. The effects of geometry parameters, including the length, width,