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Characteristics of laminar flow and heat transfer in microchannel heat sink with triangular cavities and rectangular ribs

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ABSTRACT

A novel microchannel heat sink with triangular cavities and rectangular ribs (TC–RR) is presented and the characteristics of fluid flow and heat transfer are studied numerically for Reynolds number (*Re*) ranging from 173 to 635. The effects of cavities and ribs on the Nusselt number and friction factor are investigated. The method of entropy generation minimization is also adopted to analysis the thermal performance of the micro heat sink and the mechanism of heat transfer enhancement. The overall performance of the new micro heat sink is assessed based on thermal enhancement factor and augmentation entropy generation number. The results show that the TC–RR microchannel obtains significant heat transfer enhancement attributed to the interruption and redevelopment of thermal boundary layer, the intensified mainstream disturbance and the chaotic mixing between the cold and hot water. In addition, the influence of relative rib width (α) and relative cavity width (β) on the flow and heat transfer performance is investigated. The thermal enhancement factor for TC–RR microchannel with $\alpha = 0.3$ and $\beta = 2.24$ achieves 1.619 at $Re = 500$. Due to more uniform temperature of bottom surface, less irreversibility and better heat transfer performance, the novel micro heat sink is more promising for microelectronic cooling system.

1. Introduction

With the rapid development of ULSIC (Ultra-Large-Scale-Integrated-Circuit) and MEMS (Micro-Electro-Mechanical-Systems), the thermal management plays an important role in both operating performance and reliability of microelectronic devices. As a promising solution for removing high heat flux from compact space, the microchannel heat sinks (MCHSs), proposed firstly by Tuckerman and Pease [1], are widely used in the fields of microelectronics, advanced energy and power system, aerospace, biochemistry, etc.

Microchannels provide high surface area-to-volume ratio, large convective heat transfer coefficient, less demand of coolant inventory, small size and light weight comparing with macrochannels. Many effort has been dedicated to the rectangular/smooth microchannels both numerically and experimentally [2–4]. Due to the small scale of microchannels, the flow in traditional rectangular/smooth channels is invariably laminar, thus resulting in an inferior thermal performance compared to turbulent flow. With the increase of the heat load and strict temperature limitation of micro-devices, the simple smooth channel is not able to meet the demand. Thus, many novel passive techniques are applied to enhance the heat transfer performance in the microchannel, such as replacing working medium, filling the microchannel with porous materials and optimizing the geometric construction. Mirzaei et al. [5] numerically investigated the heat transfer and friction factor of Al_2O_3–water nanofluid in a microchannel. The results showed that the Al_2O_3–water nanofluid had higher friction factor and heat transfer coefficient compared to pure water and the effects of properties variation of the nanofluid could not been neglected. Dehghan et al. [6–8] carried out a series of researches on the heat transfer performance for a microchannel filled with porous material in the slip-flow regime analytically and numerically. The heat transfer performance (HTP) had been applied to measure the heat transfer enhancement versus pressure drop increment for a wide range of relevant parameters.

Besides, constructal design has attracted much attention as an efficient passive heat transfer enhancement method recently [9–13]. The microchannel with periodic expansion–constriction cross-sections is one of the sophisticated microchannels, which can enhance the thermal performance of the heat sink effectively. Ghaedamini et al. [11] numerically studied the effects of geometrical configuration on heat transfer performance and fluid flow for

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Nomenclature

A_{con}	convection heat transfer area, m^2
A_{film}	heating area, m^2
A_{in}	inlet area, m^2
AR	aspect ratio
c_{p}	specific heat capacity, $J/(kg \cdot K)$
D_{h}	hydrodynamic diameter, m
f	friction factor
h	heat transfer coefficient, $W/(m^2 \cdot K)$
H	height of the microchannel, m
H_z	height of computational domain, m
Kn	Knudsen number
L	length of the microchannel, m
L_1	expansion segment length of triangular cavity, m
L_2	contraction segment length of triangular cavity, m
L_3	constant cross-section length between triangular cavities, m
L_{r}	length of rectangular rib, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number
$N_{\mathrm{s,a}}$	augmentation entropy generation number
Δp	pressure drop, Pa
Po	Poiseuille number
q	heat flux per area, W/m^2
Q	total heat input, W
Re	Reynolds number
$\dot{S}_{\mathrm{gen}}$	total entropy generation rate, W/K
$\dot{S}'''_{\mathrm{gen}}$	total volume entropy generation rate, $W/m^3 \cdot K$
$\dot{S}_{\mathrm{gen},\Delta p}$	frictional entropy generation rate, W/K
$\dot{S}'''_{\mathrm{gen},\Delta p}$	volume frictional entropy generation rate, $W/m^3 \cdot K$
$\dot{S}_{\mathrm{gen},\Delta T}$	heat transfer entropy generation rate, W/K
$\dot{S}'''_{\mathrm{gen},\Delta T}$	volume heat transfer entropy generation rate, $W/m^3 \cdot K$
T	temperature, K
ΔT	temperature difference, K
u	velocity component in the x direction, m/s
$\boldsymbol{U}$	velocity vector, m/s
v	velocity component in the y direction, m/s
V	fluid volume, m^3
w	velocity component in the z direction, m/s
W	width of rectangular channel, m
W_{c}	cavity region width, m
W_{r}	rib width, m
W_z	width of computational domain, m

Greek symbols

α	relative rib width
β	relative cavity width
η	thermal enhancement factor
λ	thermal conductivity, W/(m·K)
ʎ	mean free path of fluid molecules, m
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
Ω	fluid domain

Subscript

app	apparent
ave	average
f	fluid
gen	generation
in	inlet
m	mean
out	outlet
pp	pump power
s	solid
w	wall
0	smooth microchannel

converging–diverging microchannels. They proposed that the chaotic advection achieved at highly pronounced levels of wall curvature resulted in higher heat transfer rate at the expense of higher pressure. Khoshvaght-Aliabadi [12] carried out numerical studies of the forced convection in the sinusoidal-corrugated channel. They revealed the influence of the channel height and wave amplitude on Nusselt number and friction factor, and the correlations were proposed to predict Nusselt number and friction factor of the water and Al_2O_3–water nanofluid. Ahmed et al. [13] presented a microchannel heat sink with cavities on the sidewall and four geometry variables were taken into account to optimize the micro heat sink. The results showed that the optimum thermal design achieved a significant heat transfer enhancement.

In additional to the wavy walled channels, the heat transfer and flow characteristics in a microchannel with ribs/fins have also received much attention [14–16]. The results showed that the ribs along the wall could break the laminar viscous sub-layer. The vortex generators, fins and baffles inside the straight microchannel played an important role in fluid mixing and heat transfer. Hong et al. [14] and Liu et al. [15] found that the microchannel heat sink with offset strip-fin or longitudinal vortex generators (LVGs) could enhance heat transfer noticeably, though it was accompanied by a higher pressure drop compared with the smooth one. Wang et al. [16] demonstrated a microchannel composing of parallel longitudinal channels and rectangular ribs. It was observed that the uniform temperature distribution at the substrate of heat sink was obtained because of thermal boundary layer redevelopment caused by the presence of rectangular ribs.

The above literature review shows that the microchannel with cavity/groove or rib/fin can induce chaotic advection in a laminar flow, which is helpful to enhance heat transfer at the expense of increasing pressure drop. In order to evaluate the comprehensive performance of micro heat sink, the thermal enhancement factor η, proposed by Webb [17], is widely adopted [18–23]. Furthermore, the irreversibility of the flow and heat transfer process is essential in evaluating the overall performance of a heat sink due to the quality of thermal energy varies for different microchannel. The entropy generation mechanism was firstly proposed by Bejan [24], which can be used to evaluate the irreversibility of flow and heat transfer process. Comparing the entropy generation rate of different micro heat sinks, one can evaluate the merit of heat transfer enhancement techniques and further understand the heat transfer enhancement mechanism of the micro heat sinks from the view of the second law of thermodynamics. A number of studies focus on the effect of geometric structure on the heat transfer irreversibility in micro heat sink based on the entropy generation minimization [25–28].

As stated above, many investigations have been done to optimize the geometric structure of micro heat sink. In our previous works, the microchannel with cavities on the sidewall [29–32], the microchannel with ribs on the sidewall [22] and the microchannel with cavities and ribs on the sidewall [21,25,27] were presented. The heat transfer performance was enhanced in these microchannels due to the interruption and redevelopment of hydraulic/thermal boundary layer and the jetting and throttling effects. However, the perturbation effect on the core flow region