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Effects of different geometric structures on fluid flow and heat transfer performance in microchannel heat sinks

G.D. Xia *, J. Jiang, J. Wang, Y.L. Zhai, D.D. Ma

Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Ministry of Education, College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124, China

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ABSTRACT

In the present study, fluid flow and heat transfer in microchannel heat sinks with different inlet/outlet locations (I, C and Z-type), header shapes (triangular, trapezoidal and rectangular) and microchannel cross-section shapes (the conventional rectangular microchannel, the microchannel with offset fan-shaped reentrant cavities and the microchannel with triangular reentrant cavities) are numerically studied with computational domain including the entire microchannel heat sink. Detailed three-dimensional numerical simulations are useful in identifying the optimal geometric parameters that provide better heat transfer and flow distribution in a microchannel heat sink. Results highlight that flow velocity uniformity is comparatively better for I-type and poor for Z-type. The flow distribution is found to be symmetrical for I-type. It is seen from the header shapes analysis that the rectangular header shapes provides better flow velocity uniformity than the trapezoidal and triangular headers. The fluid flow mechanism can be attributed to the interaction of the branching of fluid and the friction offered by the walls of the header. Effects of microchannel cross-section shapes emphasize that the microchannel with offset fan-shaped reentrant cavities and the microchannel with triangular reentrant cavities of the heat sinks enhance the heat transfer compared to the conventional rectangular microchannel. The heat transfer mechanism can be attributed to the jetting and throttling effect, the additional flow disturbance near the wall of the reentrant cavities and the form drag of the reentrant cavities. The heat sink C has better heat transfer characteristic for $q_v = 150$ ml/min and is able to prolong the life of the microelectronic devices.

1. Introduction

With the rapid development of ULSIC (Ultra-Large-Scale-Integrated-Circuit) and MEMS (Micro-Electro-Mechanical-Systems), the application of microchannel heat sinks has attracted much attention in the field of advanced energy and power engineering, microelectronics, military and nuclear energy, aerospace, biochemistry, etc. As one of the most promising high efficiency heat exchange technologies, the microchannel heat sinks are used in a lot of devices for cooling down the miniature systems.

According to the International Technology Roadmap for Semiconductors (ITRS), the peak power consumption of high performance desktops will rise by 96% (147 W–288 W) in 2016, and by 95% (91 W–158 W) in lower-end desktops in 2016 [1]. With the increase of the heat load and the intensity of the heat exchange systems, the traditional straight microchannel heat sink cooling systems have been unable to meet the requirements and impose limits on product design if no action is taken to propose more effective cooling methods. Since Tuckerman and Pease [2] first proposed the microchannel heat sink cooling concept for electronic cooling in the early 1980s, there have been a variety of interests in the study of fluid flow and heat transfer characteristic in microchannel. It combines two ways of heat transfer: increasing the convective heat transfer coefficient by decreasing the hydraulic diameter of the microchannel and the heat conduction through the microchannel walls. Gunnasegaran et al. [3] studied the effects of geometrical parameters on heat transfer and fluid flow in microchannel heat sink. It is found that the temperature distribution is much uniform for the smallest hydraulic diameter of the microchannel heat sinks, and pressure drop and friction factor are larger. Eun et al. [4] investigated the cooling performance of microchannel heat sinks with different geometric structures, which is straight and diverging channels under various heat flux conditions. The straight microchannels show less sensitivity of the temperature distributions on the variation of the header shape than diverging

* Corresponding author. Tel.: +86 1067392176; fax: +86 1067391983.
E-mail address: xgd@bjut.edu.cn (G.D. Xia).

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Nomenclature

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	height mm
k_f	thermal conductivity of fluid W/(m K)
k_s	thermal conductivity of solid W/(m K)
L	length mm
Nu	Nusselt number
Δp	pressure drop Pa
Po	Poiseuille number
q_v	volume flow rate m^3/s
q_w	heat flux W/m^2
Q	total heat input W
Re	Reynolds number
v	mean velocity m/s
W	width mm
x	length of header mm

Greek symbols

ρ	density kg/m^3
μ	dynamic viscosity kg/(m s)

Subscript

ave	average
in	inlet
max	maximum
min	minimum
m	mean
out	outlet

micro channels. The pressure drop in the straight channels is higher than that in the diverging microchannels.

Facing the challenge of increasing the heat load and the intensity of the heat exchange systems, a significant amount of innovative cooling techniques have the potential to remove high heat flux for some microelectronic applications.

Enhancement of microscale heat transfer can be attributed to better flow distribution. Chein and Chen [5] investigated the inlet/outlet arrangement effects on the fluid flow and heat transfer inside the heat sinks. The focus of their research is inlet/outlet arrangement effects on the flow distribution. They indicated that the low heat sink temperature takes place at the entrance zones of microchannels because high heat transfer coefficient and the highest heat sink temperature occur at the edge of the heat sink, where there is no heat dissipation by fluid convection. Kumaran et al. [6] revealed the effects of header design on flow mal-distribution in a microchannel heat sink by experiment and numerical simulation. The emphasis of their research is inlet/outlet arrangement and header design effects on flow mal-distribution. It is reported that the flow distribution is better for C-type, and the triangular inlet header and the trapezoidal outlet header provide better flow distribution. Lu and Wang [7] presented the effect of inlet location on the performance of parallel-channel cold-plate. The focus of their research is inlet location effects on velocity mal-distribution and nonuniformity of temperature. They found that the I-arrangement shows the best heat transfer performance because of the impingement configurations and the Z-arrangement gives the lowest heat transfer performance due to the dramatic flow recirculation and maldistribution. Manoj et al. [8] carried out an experimental study to investigate the effect of flow maldistribution on the thermal performance of parallel microchannel cooling systems. The emphasis of their research is inlet/outlet arrangement effects on the thermal performance. It is found that the average temperature and the peak temperature of the device trend to a considerable reduction with the decreasing of channel diameter and the heat sinks have better temperature distribution. Liu et al. [9] studied the effect of flow maldistribution on the thermal performance of parallel microchannel cooling systems. The results showed that the flow distribution of the heat sink is better for UC-type.

Enhancement of microscale heat transfer can be attributed to providing more surface area and interrupting the boundary layer formation. Hong and Cheng [10] employed a three-dimensional numerical simulation to analyze the heat transfer enhancement mechanism in offset strip-fin microchannel. Foong et al. [11] numerically studied the heat transfer and fluid flow characteristics in a square microchannel with four longitudinal internal fins. Danish et al. [12] studied and optimized the shape of the microchannel heat sink with a grooved structure. The result implied the microchannel heat sink with grooved structure is better compared to the smooth microchannel both fluid flow and heat transfer characteristics, which can improve the heat transfer performance. Chai et al. [13] revealed the effects of fluid flow and heat transfer characteristics of interrupted microchannel heat sink with rectangular ribs in the transverse microchambers. The heat transfer enhancement mechanism can be attributed to the interaction of the mainstream flow separation, recirculation, vortex and interrupted boundary layer. Xia et al. [14–17] studied and optimized the structural parameters of the microchannel with offset fan-shaped reentrant cavities, triangular reentrant cavities and aligned fan-shaped reentrant cavities by numerical simulation of flow and heat transfer mechanism. They analyzed the effect of geometric parameters on fluid flow and heat transfer characteristics and obtained the optimal geometric parameters for the heat transfer enhancement of microchannel heat sinks. The heat transfer enhancement mechanism can be attributed to the interaction of increasing the heat transfer surface area, interrupting the boundary layers, redeveloping the hydraulic and thermal boundary layers, throttling effects and slipping over the reentrant cavities. These innovative cooling techniques are sufficient for cooling requirements in some applications.

From the literature review, many researchers have investigated the fluid flow and heat transfer characteristics of the microchannel heat sinks. However, it is clear that few studies (both numerical and experimental) are investigated the effects of the inlet/outlet locations, header design (shape and size) and the shape of microchannel on heat transfer and fluid flow of the entire heat sink. Therefore, in the present study, fluid flow and heat transfer in microchannel heat sinks with different inlet/outlet locations (I, C and Z-type), header shapes (triangular, trapezoidal and rectangular) and microchannel shapes (the conventional rectangular microchannel, the microchannel with offset fan-shaped reentrant cavities and the microchannel with triangular reentrant cavities) are numerically studied with computational domain including the entire microchannel heat sink. Detailed three-dimensional numerical simulations are useful in identifying the optimal geometric parameters that provide better heat transfer and flow distribution in a microchannel heat sink.