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Numerical study of heat transfer enhancement using transverse microchannels in a heat sink

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ABSTRACT

In this study, the heat transfer enhancement through the use of transverse microchannels in a heat sink is investigated systematically by numerical simulations. The heat transfer in both fluid and solid regions are modeled by a three-dimensional conjugate heat transfer approach. The effects of various parameters, such as the height and density (number) of transverse microchannels and Reynolds numbers, on the pressure drop, temperature distribution and heat transfer rate inside the heat sink are investigated. The results indicate that the temperature distribution and the location of hotspots are dependent on the number and size of transverse microchannels at different Reynolds numbers. Effects of various parameters on the figure of merit for the transverse microchannels are also presented, and correlations for prediction of the friction factor and Nusselt number have been proposed within the investigated parameter ranges.

1. Introduction

Effective heat dissipation in active and passive electronic components is one of the most important criteria for the design of electronic systems. In most of the applications, the heat generated by the electronic components is not desirable and affects the performance and lifetime of different components in the systems. The idea of microchannel heat sinks and their application in thermal management was first presented by Tuckerman and Pease [1]. Thereafter parallel microchannels heat sinks using single-phase water as coolant has emerged as one of the effective and promising cooling techniques for microelectronic cooling.

Heat transfer efficiency and flow characteristic inside microchannels have been studied in many papers. Samalam [2] reported results of a theoretical study based on the experimental setup of Tuckerman [3]. They also developed a thermal resistance correlation based on their work. The cross-sectional shape of a channel is well known to have a significant effect on the fluid flow and heat transfer characteristics and performance of microchannels. For example, Qu et al. [4,5] investigated flow and heat transfer in trapezoidal silicon microchannels.

The transverse micro-channel heat sinks consist of short and usually small microchannels connecting two or more larger micro-channels laterally. In comparison with the conventional microchannels (parallel long fin-type microchannels), the transverse microchannels have higher heat transfer rate and lower pressure drop. These short passages in the microchannel heat sink divide the flow into multiple zones with disrupted boundary layer in the thermally developing region, which has a higher heat transfer coefficient. In addition, the surface areas of the heat sink per unit volume are larger in comparison with the conventional microchannel heat sinks.

On the other hand, since the transverse microchannels separate the working flow into multiple passages with larger total cross-section area the pressure drop is smaller or at least not larger than the conventional microchannels. Previous studies have been shown the above advantages of the transverse microchannels clearly [6,7]. Skidmore et al. [6] demonstrated a microchannel heat sink comprising a wet-etched Si layer and a machined glass block. The intersecting channels provided a larger heat transfer area to minimize the stagnant boundary layer of working fluid and increased the heat transfer efficiency significantly. Xu et al. [7] employed several transverse microchannels to separate the whole flow length into several independent zones. The developing flow is repeated in the independent zones hence the overall heat transfer efficiency is greatly enhanced. Wang and Ding [8] studied the effects of transverse microchannels on the heat transfer efficiency of a copper heat sink. They demonstrated that the transverse microchannels can achieve a high local heat transfer efficiency and enhance the overall heat transfer. Moreover, their design could obtain a uniform temperature distribution through the heating area. Copeland et al. [9] performed a series of analytical and experimental studies of fluid flow and heat transfer in manifold microchannels, where alternating inlet and outlet channels guide the working fluid to and from the microchannels.

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Nomenclature

A_c	Cross-sectional area (m^2)
C_p	Specific heat at constant pressure (j/kg-K)
D_h	Hydraulic diameter of microchannel (m)
F_{merit}	Figure of merit
ff	Friction factor
H	Height of transverse microchannels (m)
k	Thermal conductivity (w/m-k)
n	Normal vector
N	Number of transverse microchannels
p	Pressure (Pa)
q''	Heat flux (w/m^2)
$\dot{Q}$	Heat transfer rate (J/s)
Re	Reynolds number
T	Temperature (K)
Nu	Nusselt number
$\vec{V}$	Velocity vector (m/s)
x, y, z	Cartesian coordinates (m)

Greek symbols

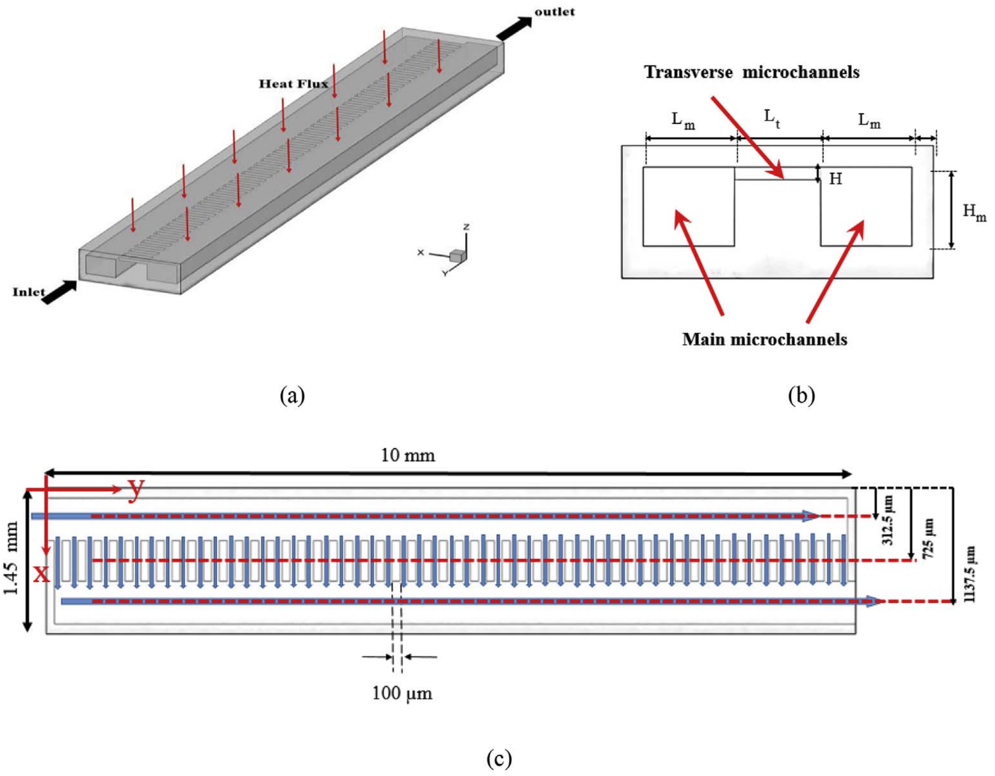
μ	Dynamic viscosity (kg/m-s)
ρ	Density (kg/m^3)

Subscripts

mean	Mean values across a cross section
f	Fluid
s	Solid
in	Inlet
out	Outlet
r	ratio
tr	Transverse part
tot	total

It was found that increasing the number of inlet/outlet channels provides lower thermal resistance and lower pressure drop.

Xu et al. [10] studied the thermal performance of interrupted microchannel heat sinks numerically. Their results showed that the repeated thermal developing boundary layer was responsible for the enhancement of heat transfer without a significant increase in pressure drop. Xu et al. [11] proposed a new silicon-based microchannel arrangement composed of transverse and longitudinal microchannels. The proposed heat sink divided the whole flow length into several thermally developing zones with higher overall heat transfer performance. Their experimental results also indicated that the microchannel heat sink with transverse microchannels can significantly reduce the pressure drops due to the shortened effective flow length. Chai et al. [12]. studied the pressure drop and heat transfer characteristics in an interrupted microchannel heat sink for various arrangements of transverse microchamber and dimensions. They used the rib length and width and the space between the ribs to optimize the geometry of the microchannel heat sink. They also suggested the inclusion of the ribs in the microchannel heat sink should be limited to Re $<$ 600. In another study, Pence [13] compared the wall temperature and pressure drop across a heat sink with fractal-like branching. The result showed that the fractal-like network in the heat sink results in up to 60% lower pressure drop and 30 °C lower wall temperature compared to the heat sinks with parallel microchannels. The better performance of heat sink with the fractal-like network was attributed to reinitiation of thermal and hydrodynamic boundary layers following each bifurcation. Chai et. al [14] investigated the heat transfer and fluid flow characteristic of a microchannel heat sink with offset fan-shaped reentrant cavities in the sidewall. Their results showed that the microchannel heat sink with fan-shaped reentrant cavities on the sidewall significantly improves that heat transfer while keeping the increase in pressure drop marginally. They also attributed the enhancement of their new microchannel to the



(a) (b) (c)

Fig. 1. Schematic and cross-section views of the microchannel heat sink with transverse microchannels.