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The effect of geometrical parameters on heat transfer characteristics of microchannels heat sink with different shapes ☆

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A R T I C L E I N F O

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A B S T R A C T

The effect of geometrical parameters on water flow and heat transfer characteristics in microchannels is numerically investigated for Reynolds number range of 100–1000. The three-dimensional steady, laminar flow and heat transfer governing equations are solved using finite volume method. The computational domain is taken as the entire heat sink including the inlet/outlet ports, wall plenums, and microchannels. Three different shapes of microchannel heat sinks are investigated in this study which are rectangular, trapezoidal, and triangular. The water flow field and heat transfer phenomena inside each shape of heated microchannels are examined with three different geometrical dimensions. Using the averaged fluid temperature and heat transfer coefficient in each shape of the heat sink to quantify the fluid flow and temperature distributions, it is found that better uniformities in heat transfer coefficient and temperature can be obtained in heat sinks having the smallest hydraulic diameter. It is also inferred that the heat sink having the smallest hydraulic diameter has better performance in terms of pressure drop and friction factor among other heat sinks studied.

1. Introduction

The amount of literature of heat transfer effects on fluid flow in MEMS or in microchannels is vast and growing. Most of the previous works on heat transfer characteristics of fluid flows are using air as a working fluid to cool the chips. However, when dealing with components that contain billions of transistors working at high frequency, the temperature can reach a critical level where standard cooling methods are not sufficient.

In 1981, Tuckerman and Pease [1] pointed out that decreasing liquid cooling channel dimensions to the micron scale will lead to increase the heat transfer rates. They have also experimentally demonstrated that a forty-fold improvement in heat-sinking capability in Si-based microchannels anodically bonded to Pyrex cover plates.

Qu et al. [2,3] conducted experiments to investigate flow characteristics of water through trapezoidal silicon microchannels with a hydraulic diameter ranging from 51 μm to 169 μm. Their results indicate that the pressure gradient and flow friction in microchannels are higher than those given by the conventional laminar flow theory due to the effect of surface roughness of the microchannels. So, they proposed a roughness–viscosity model to interpret the experimental data. Yu et al. [4] studied the fluid flow and heat transfer characteristics of dry nitrogen gas and water in microtubes with diameter of 19, 52 and 102 μm. Pfahler [5] investigated experimentally the apparent viscosity of isopropanol alcohol and silicon oil in microchannels.

Steinke and Kandlikar [6] presented a comprehensive review of friction factor data in microchannels with liquid flows. They indicated that entrance and exit losses need to be accounted for while presenting overall friction factors losses in microchannels. Most of the data that accounted for friction factor loss show good agreement with the conventional theory. They also provided a new procedure for correcting measured pressure drop to account for inlet and outlet exit losses. Furthermore, three-dimensional fluid flow and heat transfer phenomena inside heated microchannels were investigated by Toh et al. [7]. They solved the steady laminar flow and heat transfer equations using a finite-volume method. The numerical procedure was validated by comparing the predicted local thermal resistances and friction factor with the available experimental data. They have found that the heat input lowers the frictional losses and viscosity leading to an increase in the temperature of the water, particularly at lower Reynolds numbers.

Tiselj et al. [8] performed experimental and numerical analysis of the effect of axial conduction on the heat transfer in microchannel heat sink with triangular microchannels. They pointed out that the bulk water and heated wall temperatures did not change linearly along the channel. In the study of Lee et al. [9], experiments were conducted to explore the validity of classical correlations based on conventional sized channels for predicting the thermal behavior in

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Nomenclature

A	channel flow area, m^2
a	channel width of trapezoidal and triangular, μm
b	bottom channel width of trapezoidal, μm
c_p	specific heat, J/kg.K
D_h	hydraulic diameter, μm
f	friction factor
fRe	Poiseuille number
h	convective heat transfer, W/m^2 K
h_c	channel height of trapezoidal and triangular, μm
H_c	channel height of rectangular, μm
κ	thermal conductivity, W/m.K
κ_s	solid thermal conductivity, W/m.K
L_c	channel length, μm
Nu	Nusselt number
n	direction normal to the wall
P	channel wet perimeter, μm
Pr	Prandtl number
P	pressure, Pa
p_{in}	inlet pressure, Pa
p_{out}	outlet pressure, Pa
q	heat transfer rate, W
q_w	heat flux at microchannel heat sink top plate, W/m^2
Re	Reynolds number
S	distance between two microchannels, μm
t	substrate thickness, μm
T	fluid phase temperature,
T_{in}	fluid inlet temperature, K
T_s	microchannel heat sink solid temperature, K
u	fluid velocity, m/s
u_{in}	inlet fluid velocity, m/s
W_c	channel width of rectangular, μm
x,y,z	cartesian coordinates

Greek

β	tip angle of triangular microchannel
μ	viscosity, kg.m/s
ρ	density, kg/m^3
θ	dimensionless temperature

Subscripts

ch	channel
h	hydraulic
i	inlet
o	outlet
s	solid
w	wall

single-phase flow through rectangular microchannels. A numerical simulation was also carried out and compared with the experimental data. They have concluded that both fluid flow and heat transfer are in the developing regime and cannot be neglected in the analysis.

In the numerical simulations mentioned above, the computational domain consists of only a single channel with the corresponding slice of wall given as symmetrical boundary conditions was used. This kind of computational domain referred to as the reduced model in the study of Tiselj et al. [8]. As pointed out by Tiselj et al. [8] and Hetsroni et al. [10], complete domain including geometric configurations of the inlet/outlet, microchannel and heat sink base plate should be included in the simulation in order to obtain results that agree with the experimental data. Thus, the entire microchannel heat sink should be used as the computation domain instead of a single unit cell. In practical simulations, the fluid should be supplied to and collected from the microchannel heat sink via the inlet and outlet. There are many ways to arrange the inlet/outlet locations for the heat sink and the configurations and it is expected to affect the fluid flow and heat transfer characteristics inside the heat sink. Detailed understanding of the inlet/outlet arrangement effect on the heat sink performance was numerically analyzed by Chein and Chen [11].

Peng and Peterson [12,13] performed experimental investigations on the pressure drop and convective heat transfer for water flow in rectangular microchannels. It was found that the cross-sectional aspect ratio had a great influence on the flow friction and convective heat transfer both in laminar and turbulent flows. Mala and Li [14] measured the pressure drop and the flow rate for flow of deionized water through microscale tubes with diameters ranging from 50 to 254 μm. The measured pressure drop was much higher than the standard values. They found that the transition flow regime started at $Re = 650$. Liu et al. [15] studied convective heat transfer in a quart microtube with three different inner diameters of 242, 315, and 520 μm. They indicated that the experimental values for Nusselt number matched well with the laminar flow heat transfer correlation. They also indicated that laminar–turbulent transition Reynolds number was in the range of 1500–5500 for the microtubes.

Harms et al. [16] presented experimental data for a single-phase forced convection in deep rectangular microchannels. The channels were fabricated in a 2 mm thick silicon substrate by means of chemical etching and covered a total projected area of 2.5 cm by 2.5 cm. A thin-film heater was deposited on the back side of the silicon substrate, corresponding to the entire projected channel area. The silicon substrate measured 2.9 cm by 2.9 cm. All tests were performed with deionized water as the working fluid, where the liquid flow rate ranged from 5.47 m^3/s to 118 m^3/s. A critical Reynolds number of 1500 for laminar–turbulent transition was found for this configuration. They indicated that when Reynolds number and channel width are constant, the pressure drop is inversely proportionally to the depth of the channel.

Recently there have been several studies that focused on various aspects of microchannel geometry to enhance heat transfer. In addition to the various interfacial effects discussed above, the cross-sectional shape of the channel can have a great influence on the fluid flow and heat transfer inside noncircular microchannels was experimentally confirmed by Wu and Cheng [17]. Furthermore, it is clear from the above literature review that a very little work has been done to investigate the effect of geometrical parameters on the heat sink performance particularly for triangular microchannels. Thus, the present work attempts to full fill the existing gap by studying the effect of the geometrical parameters, the Reynolds number, and the heat flux on pressure drop and laminar convective heat transfer in microchannels with different shapes. The results from this investigation on the effect of geometrical parameters should find its use in many industrial and natural processes in which the knowledge on the heat transfer behavior is of uttermost importance.

2. Microchannel heat sink geometric configurations

In this paper, rectangular, trapezoidal, and triangular-cross section microchannels were analyzed. The physical configuration of one from each shape of the microchannels used in the present investigation is schematically shown in Fig. 1. Heat, supplied to the aluminum substrate through a top plate, is removed by flowing water through a number of microchannels. The dimensions of three different sets for each shape of microchannels are given in Tables 1–3. In this study, the effect of geometrical parameters on heat transfer characteristics of microchannels heat sink with different shapes was considered. The dimensions of microchannels can be varied by varying the channel width and depth. When the channel width is increased, the channel