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A numerical study of laminar convective heat transfer in microchannel with non-circular cross-section ☆

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Abstract

Three-dimensional numerical simulations of the laminar flow and heat transfer of water in silicon microchannels with non-circular cross-sections (trapezoidal and triangular) were performed. The finite volume method was used to discretize the governing equations. Numerical results were compared with experimental data available in the literature, and good agreements were achieved. The effects of the geometric parameters of the microchannels were investigated, and the variations of Nusselt number with Reynolds number were discussed from the field synergy principle. The simulation results indicate that when the Reynolds numbers are less than 100, the synergy between velocity and temperature gradient is much better than the case with Reynolds number larger than 100. There is an abrupt change in the intersection angle between velocity and temperature gradient around $Re = 100$. In the low Reynolds number region the Nusselt number is almost proportional to the Reynolds number, while in the high Reynolds number region, the increasing trend of Nusselt number with Reynolds number is much more mildly, which showed the applicability of the field synergy principle. In addition, for the cases studied the fully developed Nusselt number for the microchannels simulated increases with the increasing Reynolds number, rather than a constant.

Keywords: Numerical simulation; Laminar flow; Heat transfer; Microchannel; Field synergy principle

1. Introduction

Due to the rapid growth of technology applications which require heat transfer at high rates in relatively small spaces and volumes, the ability to remove heat from the high heat flux region becomes an important factor in designing reliable microsystems. Microchannel has the attributes of high surface area to volume ratio, large convective heat transfer coefficient, small mass and volume, etc. All of the attributes make it possible to cool such devices by micro-heat sinks, to produce micro-biochips and mini-compact heat exchangers developed in recent years. Because of the limited heat transfer ability of air-cooling technique, researchers show more interest in microchannel liquid-cooling technique. In the early 1980s, Tuckermann and Pease [1] introduced the heat sink concept of microchannel. To develop an optimization design scheme of such microsystem it is essential to have an accurate description of the transport processes. Since it is very difficult to get an analytical solution, developing a numerical method becomes necessary. Weisberg et al. [2] numerically analyzed a two-dimensional conjugate heat transfer problem in microchannel. Fedorov et al. [3] studied the three-dimensional conjugate heat transfer in the microchannel heat sink for electronic packaging. In these papers, the incompressible laminar Navier–Stokes equations of fluid motion were employed and the governing conservation equations were numerically solved using the generalized single equation framework for solving conjugated problems. Toh et al. [4] reported numerical results based on the experimental conditions of Tuckermann [5]. Fedorov and Viskanta [6] reported numerical results based on the experiments of Kawano et al. [7]. Using the FVM, they predicted the friction and thermal resistance which agreed well with the results of [7].

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Nomenclature

D	hydraulic diameter of microchannel	μm
BH	height of silicon-wafer	μm
H	height of microchannel	μm
L	length of microchannel	μm
W	width of computation domain	μm
W_b	bottom width of microchannel	μm
W_t	top width of microchannel	μm
h	heat transfer coefficient	$\mathrm{W\,m^{-2}\,K^{-1}}$
k	conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$
c_p	specific heat at constant pressure	$\mathrm{J\,kg^{-1}\,K^{-1}}$
P	pressure	Pa
T	temperature	K
T_{in}	inlet temperature	K
$\vec{U}$	vector of velocity	$\mathrm{m\,s^{-1}}$
U	velocity	$\mathrm{m\,s^{-1}}$
u, v, w	velocity in x, y, z directions	$\mathrm{m\,s^{-1}}$
w_{in}	inlet velocity	$\mathrm{m\,s^{-1}}$
q	heat flux	$\mathrm{W\,m^{-2}}$
m	mass flow rate	$\mathrm{kg\,s^{-1}}$
Re	Reynolds number	
Pr	Prandtl number	
Nu	Nusselt number	
N	number of grid	
f	friction factor	

Greek symbols

ρ	density	$\mathrm{g\,m^{-3}}$
μ	dynamic viscosity	Pa s
θ	microchannel angle	°
β	angle between U and ∇T	°
δ_t	thermal boundary layer thickness	m
Γ	interface between solid and liquid	
Φ	heat source	$\mathrm{W\,m^{-3}}$

Subscripts

b	bottom of microchannel
l	liquid
in	at inlet of microchannel
s	solid
t	top of microchannel
w	value on the wall surface
∞	value at great distance from a body
th	thermal entrance
x	based on width
z	based on length

Wu and Cheng [8] conducted the experimental study of convective heat transfer in silicon microchannel with different surface conditions. It is found that the values of Nusselt number and apparent friction coefficient depend greatly on different geometric parameters. The laminar Nusselt number and apparent friction coefficient increase with the increase of surface roughness and surface hydrophilic property. The experimental results show that the Nusselt number increases almost linearly with the Reynolds number at low Reynolds number ($Re < 100$), While if the Reynolds number is greater than 100 the increasing rate of Nu with Re gradually decreases. The channels used in their experiment are integrated in silicon-base, which is a common practice for MEMS. Thus a better understanding of the fluid flow and heat transfer characteristics for such case is crucial for the development of compact, efficient, and reliable microsystems.

In this paper, a detailed numerical study was conducted based on the experimental conditions of Wu and Cheng [8]. The FVM (finite-volume-method) was used to solve the discretized governing equations for water flow and heat transfer in the microchannels. The thermal properties of water are assumed to be constants except the viscosity varying with temperature. The predicted thermal resistances are compared with their experimental data and quite good agreements are obtained. A detailed description of the heat sink temperature distribution, heat transfer coefficients in the developing region and fully developed region are presented and discussed. Furthermore, by using the field synergy principle the experimental results are discussed.

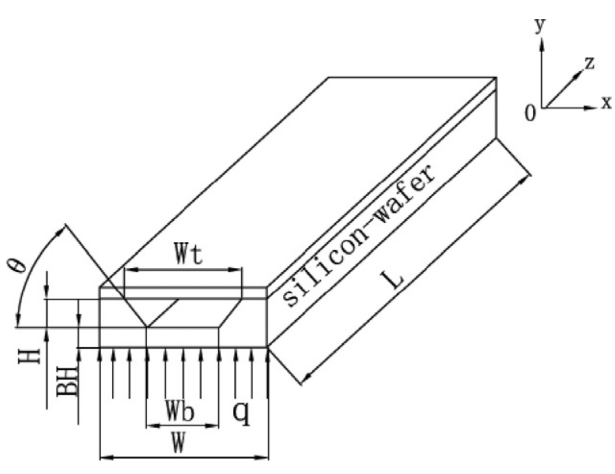

Fig. 1. Schematic of physical arrangement and the coordinate system.

2. Numerical analysis

2.1. Assumptions of physical model

In this paper, the fluid flow and heat transfer in a three-dimensional symmetric microchannel (Fig. 1) is simulated. The geometry dimensions were copied from the experimental work by Wu and Cheng [8]. The channels were heated from their bottom as shown in Fig. 2. The entire rectangular section is taken as the computational region (shown by the dash-lines in Fig. 2) with conjugated method [9]. Two sets of geometric parameters of microchannels were adopted (Table 1). The simulations were performed based on the following assumptions: