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A new coupling method for slip-flow and conjugate heat transfer in a parallel plate micro heat sink

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ABSTRACT

The present study investigates the effect of temperature jump boundary condition on conjugate heat transfer in parallel plate micro channel heat sink. A new method for coupling equations between fluid and solid domains with temperature jump boundary condition is proposed and implemented in the open-source computational fluid dynamics package, OpenFOAM. The method and the code have been hydro-dynamically and thermally validated with data from previous studies. Both constant wall temperature and constant heat flux boundary conditions are considered. Impacts of effective parameters including Knudsen number and conductivity ratio on overall heat transfer characteristics of the heat sink have been discussed in detail. Results show that temperature jump has a significant effect on temperature field and heat transfer in heat sink.

1. Introduction

Today's electronic components are required to perform tasks at faster rates; high-speed circuits, consequently, are expected to generate more heat which accounts for these devices to exceed their allowable temperature. Overcoming this problem, micro-channel heat sinks were introduced in 1981 by Tuckerman and Pease [1] and have been interesting to many researchers in the field of fluid mechanic and heat transfer for many years.

As the channel size gets smaller, some of conventional theories for fluid, energy and mass transport need to be revisited for validation. Deviation from the continuum assumption for gas flow and increase in influence of some additional forces, such as electro-kinetic forces, are some of these discrepancies from conventional channels [2].

In microfluidics, theoretical knowledge for gas flows is currently more advanced than that for liquid flow [3]. Concerning gases, the issues are actually clearly identified: the main micro-effect that results from shrinking down the devices size is rarefaction. It is convenient to differentiate the flow regimes in function of Knudsen number, Kn, and following classification is usually accepted:

For $Kn < 0.001$, the flow is continuum and it is actually modeled by the compressible Navier–Stokes equations with classical no-slip boundary condition; while for $0.001 < Kn < 0.1$, the flow is known as slip flow and Navier–Stokes equations remain applicable, provided that velocity slip and temperature jump are taken into account at the wall. These new boundary conditions point out that rarefaction effects become sensitive at the walls. Next, for $0.1 < Kn < 10$, the flow regime is transition and the continuum approach of Navier–Stokes equations is no longer valid and finally for $Kn > 10$, the flow is a free molecular flow and the occurrence of intermolecular collisions is negligible compared with collisions between the gas molecules and the walls [2].

Slip flow and heat transfer in micro-channel with negligible wall effect have been investigated during recent years [4,5]. Conjugate heat transfer is another important issue in heat transfer in micro scale. In macro scale, the effect of conjugate heat transfer can be neglected due to small thickness of channels compared to the hydraulic diameter [6], but in micro scale, wall thickness of channel is comparable with channel hydraulic diameter and consequently effects of conduction in the channel should be considered. Tiselj et al. [7] studied experimentally and numerically the effects of axial heat conduction in micro heat sink. They found significant changes in both flow and wall temperature gradient. It is also observed that the sign of channel temperature gradient is inverted near the outlet of channel. Comprehensive comparison between experimental, theoretical and numerical studies on the effect of axial heat flux due

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Nomenclature

c_p	specific heat at constant pressure, J/kg K
D_h	hydraulic diameter, m
E	ratio of thickness of solid layer to the half channel height, Δ/h
Ec	Eckert number, $u^2/c_p\Delta T$
h	half height of the channel, m
K	thermal conductivity ratio, k_s/k_f
Kn	Knudsen number, λ/D_h
k_f	thermal conductivity of fluid, w/m K
k_s	thermal conductivity of solid, w/m K
l	length of the channel, m
L	l/h
n	normal direction
$n_{i,f}$	normal vector in fluid interface
$n_{i,s}$	normal vector in fluid interface
p	pressure, Pa
Pr	Prandtl number, ν/α
q''	heat flux, W/m^2
Re	Reynolds Number, $\rho u D_h/\mu$
refVal	reference value
$S_{i,f}$	location vector in fluid
$S_{i,s}$	location vector in solid
T	temperature, K
T_{avg}	average temperature, K
T_{in}	inlet temperature, K
T_{int}	inlet temperature, K
T_w	wall temperature, K
u	velocity, m/s
u_{in}	inlet(average) velocity, m/s
U	non-dimensional velocity, u/u_{in}
vf	value fraction
X	non-dimensional axis, x/D_h
X^*	X/RePr
Y	non-dimensional axial coordinate, y/D_h
Greek symbols	
β	$(\gamma + 1/2\gamma)$Pr
γ	specific heat ration, c_p/c_v
ε	residual
θ	non-dimensional temperature, $(T - T_{\text{in}})/(T_w - T_{\text{in}})$, $(T - T_{\text{in}})\cdot k_f/(D_h \cdot q'')$
$\theta_{\text{int},f}$	non-dimensional temperature of fluid interface
$\theta_{\text{int},s}$	non-dimensional temperature of solid interface
$\theta_{m,s}$	non-dimensional average temperature of solid
$\theta_{m,f}$	non-dimensional average temperature of fluid
θ_f	non-dimensional fluid temperature
θ_s	non-dimensional solid temperature
μ	dynamic viscosity, kg/m s
ρ	density, kg/m^3
σ_v	tangential momentum accommodation coefficient
σ_T	thermal accommodation coefficient
φ	non-dimensional variables

to thermal conduction through the flow and channel walls is reported by Hetsroni et al. [8].

Maranzana et al. [9] studied heat transfer with conduction in the walls of mini-micro channels and found that it has a quite multi-dimensional behavior. The wall heat flux density, for small Reynolds numbers, becomes strongly non-uniform with more effective heat transfer to the fluid flow at the entrance of micro-channel. They also proposed a non-dimensional number, M, quantifying axial conduction in the walls. This parameter is defined as the ratio of axial heat conduction in the solid walls of the duct to the heat convection in the fluid. They concluded that for $M < 0.01$, the axial heat conduction in the walls can be neglected.

Impacts of axial heat conduction in the solid walls of micro-channels with circular cross-section are analyzed by Nonino et al. [6]. They investigated the effects of geometrical parameters and solid wall conductivity on heat transfer in different Reynolds numbers.

Zhang et al. [10] also studied numerically the effects of axial wall conduction on conjugate heat transfer of developing flow in circular tube with constant temperature boundary condition at the outer wall of solid.

Avci et al.[11] numerically studied conjugate heat transfer in micro-tubes with developing laminar flow with viscous dissipation. They investigated the effects of thermal conductivity ratio, diameter ratio, channel length and viscous dissipation on Nusselt number, temperature pattern in solid and fluid and heat flux distribution.

Rahimi and Mehryar [12] investigated the effects of duct wall thermal conductivity on local Nusselt number at the entrance and exit of a micro-channel with circular cross-section in a conjugate heat transfer problem. Developing laminar flow was considered and constant heat flux boundary condition was imposed on the outer wall of the channel. They found that considering conjugate heat transfer decreases the local Nusselt number at both entrance and outlet regions.

Kabar et al. [13] carried out numerical study of slip flow and conjugate heat transfer in parallel plate micro heat sink with constant heat flux boundary condition. Both thermally and hydrodynamically developing flow were considered. They found that increasing the value of solid thermal conductivity accounts for the effect of conduction to be more intensive especially in the entrance region. It is also concluded that for slip flow with temperature jump, the effect of axial conduction is negligible for any Kundsen number, thermal conductivity ratio and wall thickness.

Yang et al. [14] recently conducted a numerical and experimental investigation on nitrogen flow in micro-tubes. They found that distribution of axial bulk temperature of the gas is strongly non-linear along the tube axis. This is more intense for tubes with small inner diameters and thicker walls.

Experimental investigation of axial heat conduction effect on heat transfer in micro-channel parallel plate has been conducted recently by Huang et al. [15]. A non-linear temperature distribution in both fluid and solid was found. Compared with theoretical predictions that do not include axial heat conduction, lower Nusselt numbers in fully-developed region and higher local Nusselt number in micro-channel entrance are observed in experimental results.

Due to the lack of a comprehensive study in this area, the main purpose of this study is to investigate the effects of axial conduction of solid region on heat transfer characteristics of parallel plate micro heat sinks. Both constant temperature and heat flux boundary conditions at the outer wall of channel are considered. The effects of various parameters containing conductivity ratio and Knudsen number are examined. A new method is also introduced for coupling the heat transfer equations in fluid and solid regions. All the equations are solved with an extended solver written in