Applied Thermal Engineering 111 (2017) 855–862

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Transient conjugate heat transfer in a circular microchannel involving rarefaction, viscous dissipation and axial conduction effects

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HIGHLIGHTS

- Transient conjugated heat transfer in circular microchannel flow is analysed.
- Hydrodynamically developed flow is considered with slip-flow boundary conditions.
- A parametric study is done to analyse on heat transfer characteristics.
- For microchannel flows the rarefaction effects for the fluids in gaseous phase must certainly be included in the analysis.

ARTICLE INFO

Article history:
Received 24 March 2016
Revised 11 August 2016
Accepted 2 October 2016
Available online 4 October 2016

Keywords:
Conjugate heat transfer
Microchannel
Slip flow
Rarefaction effect
Viscous dissipation
Axial conduction

ABSTRACT

Transient conjugate heat transfer of a hydrodynamically developed and thermally developing laminar flow in a circular microchannel is investigated considering the effects of rarefaction, viscous dissipation and axial conduction. The problem is solved numerically by a finite difference method based on Patankar's (1980) control volume approach. Momentum and energy equations are solved with the boundary conditions of the first degree velocity slip and temperature jump. The problem depends on four parameters. These are the Peclet number (*Pe*), the Knudsen number (*Kn*), the Brinkman number (*Br*) and the wall thickness ratio (d'). The results obtained showed that heat transfer characteristics are significantly affected by these parameters and that in micro channel flows, the fluid's rarefaction effects, viscous dissipation and axial conduction should not be ignored.

1. Introduction

Recently, micro scale electro-mechanic systems have been used in different areas such as automotive, defense, aviation and spacecraft industry, and also in bio-medical and nuclear energy sectors. The heat generated per unit area or volume is increasing in these progressively advancing systems and leads to serious problems as a result of higher temperatures. In order to solve the overheating problem, thermal systems utilizing various fluids in microchannels and microtubes have recently been developed.

Heat transfer problems of micro-scale devices have a crucial role in engineering applications. The heat transfer mechanism in devices having micro sizes is analysed in a different way as compared to that in macro sizes and hence leading to a peculiar problem. In this aspect, investigation of flow characteristics at micro and nano scales has been an important research area in recent years.

It is also necessary to investigate axial conduction and viscous effects which are important in various flow analyses in circular microchannel flows. In microchannels, the wall thickness may be comparable to channel height and depending on the Reynolds number (*Re*) and the temperature distribution within the flow, fluid axial conduction may be very important. Axial conduction is particularly effective at low Peclet number flows [2–4].

Theoretical analysis performed on flow and heat transfer mechanisms in microchannels have become extremely useful, regardless of the fact that the difficulties in carrying out empirical studies on micro scale basis make researchers prefer theoretical studies. Several works for gas flow in various-shaped microchannels on slip flow and convective heat transfer are studied extensively in the past decades [5–7]. Some of the studies in the literature dealing with mini and micro tube conjugate heat transfer and gas flow can be summarized as follows:

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http://dx.doi.org/10.1016/j.applthermaleng.2016.10.005
1359-4311/

Nomenclature

a	constant of discretization equation (Eqs. (9a)–(9h))
b	source term
Br	Brinkman number $\left[=\frac{\mu_f u_m^2}{k(T_1-T_0)}\right]$
c_p	specific heat at constant pressure (J/kg K)
d	pipe wall thickness (m)
D	hydraulic diameter (m)
k	thermal conductivity (W/m K)
Kn	Knudsen number [=λ/D]
Nu	Nusselt number $\left[=\frac{2q'_{wi}}{T'_{wi}-T'_b}\right]$
Pe	Peclet number $\left[=RePr=\frac{2r_{wi}u_m\rho_f c_{p_f}}{k_f}\right]$
Pr	Prandtl number [=$\mu c_p/k$]
Po	Poiseuille number
q	heat flux (W/m^2)
R	radial coordinate (m)
Re	Reynolds number [=$u_m D/\nu$]
t	time (s)
T	temperature (K)
T_0	initial temperature of the system (K)
T_s	fluid temperature at the inner wall surface (K)
T_1	outer wall temperature at the downstream region (K)
u	axial velocity (m/s)
u_s	slip velocity (m/s)
v	radial velocity (m/s)
x	axial coordinate (m)

Greek symbols

α	thermal diffusivity (m^2/s)
γ	specific heat ratio
λ	molecular mean free path (m)
δr	radial position difference (m)
δx	axial position difference (m)
K	kappa $\left[=\frac{2\gamma}{\gamma+1}\frac{1}{Pr}\right]$
Δr	radial step size (m)
Δt	time step increment (s)
Δx	axial step size (m)
ρ	density (kg/m^3)
σ_m	momentum accommodation coefficient
σ_T	thermal accommodation coefficient
μ	dynamic viscosity (Pa s)

Subscripts

b	bulk
f	fluid
i	inner wall
i,j	at nodal point i, j
m	mean
w	wall
wf	ratio of wall to fluid

Superscripts

$'$	dimensionless quantity
0	at previous time step

Çetin et al. [4] investigated the Graetz problem in a microtube under the slip flow regime and constant surface temperature boundary condition by taking into account the effects of rarefaction, viscous dissipation and axial conduction. They concluded that, fully developed Nusselt numbers and thermal entrance length increase with the effect of axial conduction. By considering viscous effects, Lelea and Cioabla [8] conducted a numerical study on the flow and conjugate heat transfer in microtubes. They analysed the effects of viscous heating on Nu and Po numbers and compared to the condition of $Br = 0$. Rahimi and Mehryar [9] numerically investigated a conjugate heat transfer problem in a circular micro channel, involving the effects of wall thermal conductivity and wall thickness on local Nusselt numbers at the inlet and exit regions of the channel. Aziz and Niedbalski [10], worked on a similar problem for microchannel gas flows with the first and second-degree slip flow boundary conditions, considering the axial conduction and viscous dissipation. They found that second-degree temperature jump boundary condition caused increases in temperatures for all the parameters. Barletta and Di Schio [3], studied a steady and laminar forced convection problem under the boundary condition of sinusoidally varying wall heat flux by taking into account the axial conduction in the fluid side. Barron et al. [11,12] used numerical methods to investigate the Graetz problem in microtube flow, for laminar and slip flow regimes. They found that thermal entrance length and Nusselt number increase with Knudsen number. A similar problem was analytically investigated by Ameel et al. [13] under a constant heat flux boundary condition, and also a temperature jump was included as a boundary condition. They showed that, Nusselt number decreases with increasing Knudsen number and explained this phenomenon with the increase in the temperature jump. Jeong and Jeong [2] conducted a numerical study on the effects of viscous dissipation and axial conduction on heat transfer in micro channel flows. They found that, viscous dissipation imposes a decreasing effect on heat transfer when fluid is heated and an increasing effect when fluid is cooled. On the other hand, they showed that axial conduction increases heat transfer for both heating and cooling cases. Renksizbulut et al. [14], numerically investigated simultaneously developing flow and heat transfer characteristics in a rectangular microchannel with constant surface temperature. They concluded that, an increase in Knudsen number is associated with significant reducing effect in Nusselt number and friction coefficient which is especially the case at the inlet region. Kabar et al. [15], investigated the effects of axial conduction and flow rarefaction in parallel plate microchannel flow. They solved the Navier-Stokes and energy equations numerically by using a finite volume method under slip and temperature jump boundary conditions and studied the effects of Knudsen number, thermal conductivity and wall thickness ratio on heat transfer. Some extended types of Graetz Problem involving fluid axial conduction and the effects of wall conjugation may be found in Bilir [16,17], Bilir and Ateş [18], Darıcı et al. [19] and Ateş et al. [20].

In this study, a transient conjugate heat transfer problem in micro channels is numerically investigated considering the effects of rarefaction and viscous dissipation. And also the effects of several parameters on heat transfer were examined. To the authors' knowledge, there is no study on conjugated heat transfer in microchannels that accounts for the simultaneous effects of rarefaction, viscous dissipation and axial conduction in transient regime. Transient conjugated heat transfer analysis is important for the micro scale electro-mechanic systems and microchannel heat exchangers during startup, shutdown and change in operating conditions.