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Heat and fluid flow characteristics of gases in micropipes

Orhan Aydın *, Mete Avcı

Karadeniz Technical University, Department of Mechanical Engineering, 61080 Trabzon, Turkey

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Abstract

In this study, laminar forced convective heat transfer of a Newtonian fluid in a micropipe is analyzed by taking the viscous dissipation effect, the velocity slip and the temperature jump at the wall into account. Hydrodynamically and thermally fully developed flow case is examined. Two different thermal boundary conditions are considered: the constant heat flux (CHF) and the constant wall temperature (CWT). Either wall heating (the fluid is heated) case or wall cooling (the fluid is cooled) case is examined. The Nusselt numbers are analytically determined as a function of the Brinkman number and the Knudsen number. Different definitions of the Brinkman number based on the definition of the dimensionless temperature are discussed. It is disclosed that for the cases studied here, singularities for the Brinkman number-dependence of the Nusselt number are observed and they are discussed in view of the energy balance.

Keywords: Microscale; MEMS; Flow physics; Viscous dissipation; Temperature jump; Velocity slip

1. Introduction

Microelectromechanical systems (MEMS) has gained a great deal of interest in recent years. Such small devices typically have characteristic size ranging from 1 mm down and to 1 micron, and may include sensors, actuators, motors, pumps, turbines, gears, ducts and valves. Microdevices often involve mass, momentum and energy transport. Modeling gas and liquid flows through MEMS may necessitate including slip, rarefaction, compressibility, intermolecular forces and other unconventional effects [1].

It is shown that fluid flow and heat transfer at microscale differ greatly from those at macroscale. At macroscale, classical conservation equations are successfully coupled with the corresponding wall boundary conditions, usual no-slip for the hydrodynamic boundary condition and no-temperature-jump for the thermal boundary condition. These two boundary conditions are valid only if the fluid flow adjacent to the surface is in thermal equilibrium. However, they are not valid for gas flow at microscale. For this case, the gas no longer reaches the velocity or the temperature of the surface and therefore a slip condition for the velocity and a jump condition for the temperature should be adopted.

The Knudsen number, Kn is the ratio of the gas mean free path, λ, to the characteristic dimension in the flow field, D, and, it determines the degree of rarefaction and the degree of the validity of the continuum approach. As Kn increases, rarefaction become more important, and eventually the continuum approach breaks down. The following regimes are defined based on the value of Kn [2].

(i) Continuum flow (ordinary density levels) $Kn \leqslant 0.001$.
(ii) Slip-flow regime (slightly rarefied) $0.001 \leqslant Kn \leqslant 0.1$.
(iii) Transition regime (moderately rarefied) $0.1 \leqslant Kn \leqslant 10$.
(iv) Free-molecule flow (highly rarefied) $10 \leqslant Kn \leqslant \infty$.

Viscous dissipation is another parameter that should be taken into consideration at microscale. It changes temperature distributions by playing a role like an energy source induced by the shear stress, which, in the following, affects heat transfer rates. The merit of the effect of the viscous dissipation depends on whether the pipe is being cooled or heated.

* Corresponding author. Tel.: +90 462 377 29 74; fax: +90 462 325 55 26.
E-mail address: oaydin@ktu.edu.tr (O. Aydın).

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Nomenclature

A	cross-sectional area [m^2]
Br	Brinkman number, Eq. (10)
Br_q	modified Brinkman number, Eq. (13)
c_p	specific heat at constant pressure
D	diameter of the pipe [m]
F	tangential momentum accommodation coefficient
F_t	thermal accommodation coefficient
h	convective heat transfer coefficient [W/m^2 K]
k	thermal conductivity [W/m K]
Kn	Knudsen number
Nu	Nusselt number
Pr	Prandtl number
q_w	wall heat flux [W/m^2]
R	dimensionless radial coordinate
r	radial coordinate [m]
r_0	radius of the pipe
T	temperature [K]
u	velocity [m/s]
z	axial direction [m]

Greek symbols

α	thermal diffusivity [m^2/s]
γ	specific heat ratio
λ	molecular mean free path
μ	dynamic viscosity [Pa s]
ρ	density [kg/m^3]
υ	kinematic viscosity [m^2/s]
θ	dimensionless temperature, Eq. (8)
θ_q	dimensionless temperature modified, Eq. (13)
θ^*	dimensionless temperature, Eq. (16)
θ_q^*	dimensionless temperature modified, Eq. (17)

Subscripts

c	centerline
m	mean
s	fluid properties at the wall, singularity value
w	wall

There is a scarcity of experimental data and theoretical analysis available in the existing literature, many of which are contradictory and conflicting, yielding different correlations with opposite characteristics. Therefore, the mechanisms of flow and heat transfer in microchannels are still not understood clearly.

Readers are referred to see the following recent excellent reviews related to transport phenomena in microchannels. Ho and Tai [3] summarized discrepancies between microchannel flow behavior and macroscale Stokes flow theory. Palm [4], Sobhan and Garimella [5] and Obot [6] reviewed the experimental results in the existing literature for the convective heat transfer in microchannels. Rostami et al. [7,8] presented reviews for flow and heat transfer of liquids and gases in microchannels. Gad-el-Hak [1] broadly surveyed available methodologies to model and compute transport phenomena within microdevices. Guo and Li [9,10] reviewed and discussed the size effects on microscale single-phase fluid flow and heat transfer. In a recent study, Morini [11] presents an excellent review of the experimental data for the convective heat transfer in microchannels in the existing literature. He critically analyzed and compared the results in terms of the friction factor, laminar-to-turbulent transition and the Nusselt number.

Gravesen et al. [12] explained deviations at the microscale from the macroscale in terms of wall slip and compressibility phenomena in microchannels. Gaseous flow in two-dimensional (2-D) micromachined channels with a Cartesian geometry for various Knudsen numbers was studied by Harley et al. [13]. Barron et al. [14,15] extended the Graetz problem to slip- flow and developed simplified relationships to describe the effect of slip-flow on the convection heat transfer coefficient. Ameel et al. [16] analytically treated the problem of laminar gas flow in microtubes with a constant heat flux boundary condition at the wall assuming a slip flow hydrodynamic condition and a temperature jump thermal condition at the wall. They disclosed that the fully developed Nusselt number decreased with Knudsen number. Tso and Mahulikar [17–19] studied the effect of the Brinkman number on convective heat transfer and flow transition in microchannels. Tunc and Bayazitoglu [20] studied steady laminar hydrodynamically developed flow in microtubes with uniform temperature and uniform heat flux boundary conditions using the integral technique. Toh et al. [21] numerically investigated three-dimensional fluid flow and heat transfer phenomena inside heated microchannels using a finite volume method. Xu et al. [22] theoretically analyzed and examined the effects of viscous dissipation in microchannel flows. They suggested a criterion to draw the limit of the significance of the viscous dissipation effects. Koo and Kleinstreuer [23,24] investigated the effects of viscous dissipation on the temperature field and ultimately on the friction factor using dimensional analysis and experimentally validated computer simulations. Hsieh et al. [25] presented an experimental and theoretical study of low Reynolds number flow of nitrogen in a microchannel. They concluded that using slip boundary conditions, one could well predict the mass flow rate as well as inlet/exit pressure drop and friction factor constant ratio for a three-dimensional physical system. In a recent study, Aydın [26] investigated the effect of the viscous dissipation on the heat transfer for a hydrodynamically and thermally fully developed flow in a pipe.