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Heat transfer characteristics of plug flows with temperature-jump boundary conditions in parallel-plate channels and concentric annuli

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ABSTRACT

In this study, heat transfer characteristics of plug flows in micro/nano scale were investigated by taking rarefaction effects into account. For this, thermal analysis of plug flows in parallel-plates and concentric annuli was performed for the constant heat flux condition at the walls, which were asymmetrically heated. First-order temperature-jump boundary condition was implemented at the wall assuming a gaseous plug flow, whereas its absence would correspond to either liquid plugs or plug flows at macro scale. Closed form expressions were analytically derived for obtaining temperature distributions and Nusselt numbers as a function of key parameters such as Knudsen number, Prandtl number, wall heat flux ratio, and annulus aspect ratio. The results show that Nusselt number may increase or decrease depending on the major parameters such as rarefaction, wall heat flux ratio and annulus aspect ratio.

1. Introduction

With the miniaturization of devices involving heat and fluid flow, conventional assumptions being made in heat transfer analysis of such devices need to be modified. Micro/nano scale devices are currently widely used in many applications such as in heat exchangers, cooling systems, biomedical applications, chemical reactors, and physical particle separation applications. In order to evaluate the performance of MEMS devices in such applications, the study of heat and fluid flow in micro/nano domains is inevitable. Different heat transfer and flow characteristics for micro/nano flows compared to macro scale were reported in the literature particularly related to gas flows, for example [1–4]. For gas flows in small scale, rarefaction effects may be present, and thus, slip/jump conditions at the walls should be taken into account. Knudsen number defined as the ratio of mean free path to characteristic length is an important parameter, and its value typically varies from 10^{-3} to 10^{-1} for slip flows. In the literature about slip flows, temperature-jump and velocity-slip effects were investigated from experimental [5–8], numerical [9–13], and analytical [14–24] perspectives.

Many studies have focused on adiabatic two-phase flows in macro scale [25–29], where bubbly, slug, mist, annular, wavy or stratified flows were observed as major flow regimes. Being different from macro scale, slug/plug flow is mostly present as elongated gas bubbles occupying the entire channel cross-section in micro/nanochannels due to the small channel size. If the channel is particularly short, slug/plug flow pattern will exist along the entire channel and over the entire channel cross section [30]. Liquid plug flows could be also generated in microchannels by means of pressurization or actuation with electrical fields. Non-boiling two-phase slug flow regimes inside channels may be created by insertion of gas into a continuous liquid stream [29].

The effect of Capillary number, Ca, on the distribution of vortices inside liquid plugs was investigated [31–33], and it was found that by increasing Ca the vortex center moved from the wall towards the centerline, while a complete bypass (or no circulation) was observed at a critical Ca. It was also reported that internal circulating vortices within liquid plugs lead to the enhancement of heat transfer rate [34–37].

In experimental studies on flow boiling of water in microchannels [38–45] dry-out condition as well as other flow patterns such as elongated bubble and annular slug flows, where vapor phase mostly occupied the whole cross section along a significant portion of the channel, were observed. Thome et al. [46] and Dupont et al. [47] suggested a heat transfer model to model the evaporation process in the slug flow regime in microchannels consisting of three zones, being liquid plug, an evaporating elongated bubble, and vapor plug where dry-out condition happens at the end of the elongated bubble.

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Nomenclature

c_p	specific heat at constant pressure
D_h	hydraulic diameter
H	half height of channel
k	thermal conductivity of fluid
Kn	Knudsen number
$\dot{m}$	mass flow rate
Nu	Nusselt Number
Pr	Prandtl number
P	perimeter
q''	heat flux
R	radial coordinate
r	dimensionless radial coordinate
S	cross-section area
T	temperature
$\overline{T}$	averaged temperature
U	velocity in X direction
X, Y	spatial position in coordinate system
x, y	dimensionless spatial position in coordinate system

Greek symbols

β	heat flux ratio, q''_2/q''_1, q''_o/q''_i
γ	specific heat ratio of fluid
η	annulus aspect ratio, r_i/r_o
θ	dimensionless temperature (Equations (9) and (29))
θ^*	dimensionless temperature with temperature-jump (Equations (13) and (31))
λ	mean free path
ρ	density of fluid
μ	dynamic viscosity of fluid
ϕ	source term (here, viscous dissipation)
σ_T	thermal accommodation coefficient

Subscripts

i	inner wall
m	mean or bulk
o	outer wall
s	fluid properties at solid surface
w	wall
1	upper wall
2	lower wall

Plug flow exists in real flows and appears in several situations. For example, plug flow as a part of electro-osmotic flow has been visualized in various Refs. [48–50], and was reported in analytical calculations in the case of high value of ratio of tube radius or channel height to the Debye length [51,52], where expressions given in the literature demonstrates that the Debye length may vary typically between 1 and 1000 nm. On the other hand, dry-out region in two-phase flows as vapor plug in microchannels was visualized [53–55]. In addition, plug flows are also observed in Plug-Flow-Microreactors and segmented gas–liquid or liquid–liquid microflows with hydrophobic walls, which appear in looped and unlooped pulsating heat pipes [56].

For slug/plug flows, the velocity of the fluid could be assumed to be uniform over the entire cross-section area of the channel [57–60]. These flow conditions could be attained when the channel length is short compared to the hydrodynamic entry length or an elongated gas bubble occupies the entire cross section along the entire channel length, all of which are possible scenarios for micro/nano scale gas flows.

Muzychka et al. [35,61] analytically analyzed heat transfer of plug flows as a Graetz problem by assuming a uniform velocity distribution and presented expressions for Nusselt number values. Satapathy [62] conducted an analytical study on thermally developing gaseous slug flows inside a microtube with constant wall temperature boundary condition and the assumption of a uniform velocity profile while considering temperature-jump boundary condition. He showed that including the temperature-jump effect lead to a decrease in the value of fully-developed Nusselt number.

In this study, convective heat transfer of plug flows in concentric annuli and parallel-plate channels is investigated by the assumption of a uniform velocity distribution, while the walls are asymmetrically heated at different constant heat fluxes. The temperature-jump condition is also implemented in the wall boundary, which could be the case for plug flow in micro/nano scale, where an elongated bubble exists over the entire cross section along the entire channel and rarefaction effects are expected. Letting Kn = 0 would correspond to the liquid plug flow, macro scale plug flow or even an approximate solution for elongated bubble surrounded by a very thin liquid layer. Closed form expressions for temperature distribution and Nusselt number, which could be useful for assessing heat transfer characteristics under the above mentioned conditions, are analytically derived.

2. Analysis

The flow is considered to be a plug flow, for which the velocity distribution is uniform over the entire cross-section area including the walls. It is also assumed that the flow is thermally fully developed, steady state, incompressible and laminar. Convective heat transfer of plug flows with constant fluid thermophysical properties for parallel-plate channels and concentric annuli (Fig. 1) is analyzed. Two different heat fluxes are applied at the walls. For the parallel-plate channel case, q''_1 and q''_2 stand for the upper and lower wall heat fluxes, respectively, whereas q''_o and q''_i refer to the outer and inner wall heat fluxes, respectively, for concentric annulus case.

2.1. Parallel-plate channel case

As mentioned earlier, the velocity is considered constant and uniform. Therefore, the energy balance equation is solved together with the appropriate boundary conditions to obtain temperature distribution and Nusselt number expressions. The governing equation of interest is expressed as:

$$\rho c_p U \frac{\partial T}{\partial X} = k\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right) \quad (1)$$

where ρ is the density, T is the temperature, c_p is the specific heat at constant pressure, k is the thermal conductivity, and U is velocity in X direction.

For plug flow in the case of gaseous flows, the temperature-jump condition may exist in small scale, and must be considered in solving the energy equation. Accordingly, the temperature-jump expression for this case at the solid–fluid interface is given as [36]:

$$T_{s2} - T_{w2} = \frac{2-\sigma_T}{\sigma_T}\frac{2\gamma}{\gamma+1}\frac{\lambda}{\mathrm{Pr}}\left(\frac{\partial T}{\partial Y}\right)_{Y=-H} \text{ and } -k\left(\frac{\partial T}{\partial Y}\right)_{Y=-H} = q''_2 \quad (2)$$