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Numerical simulation of thermofluid characteristics of two-phase slug flow in microchannels

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ABSTRACT

A fundamental study of heat transfer characteristics of two-phase slug flow in microchannels is carried out employing the Volume-of-Fluid (VOF) method. Despite of the fact that numerical simulations of two-phase flows in microchannels have been attempted by many investigators, most efforts seem to have failed in correctly capturing the flow physics, especially those pertaining to the slug flow regime characteristics. The presence of a thin liquid film in the order of 10 μm around the bubble is a contributing factor to the above difficulty. Typically, liquid films have a significant effect on the flow field and heat transfer characteristics. In the simulations reported in this paper, the film is successfully captured and a very high local convective heat transfer coefficient is observed in the film region. A strong coupling between the conductive heat transfer in the solid wall and the convective heat transfer in the flow field is observed and characterized. Results showed that unsteady heat transfer through the solid wall in the axial direction is comparable to that in the radial direction. Results also showed that a fully developed condition could be achieved fairly quickly compared to single-phase flows. The fully developed condition is defined based on the Peclet number (*Pe*) and a dimensionless length of the liquid slug. Local and time-averaged Nusselt numbers for slug flows are reported for the first time. It was found that significant improvements in the heat transfer coefficient could be achieved by short slugs where the Nusselt number was found to be 610% higher than in single-phase flows. The study revealed new findings related to slug flow heat transfer in microchannels with constant wall heat flux.

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1. Introduction

Microchannels are commonly used in many applications. Pipes with hydraulic diameters smaller than the Laplace constant, $\sqrt{\frac{\sigma}{g(\rho_L-\rho_G)}}$ (where σ is the surface tension, g is gravitational acceleration and ρ_L and ρ_G are the liquid and gas densities, respectively) are typically classified as microchannels [1]. Characteristics of two-phase flows in microchannels are mainly governed by the surface tension force with the gravitational acceleration playing only a minor role on the flow field [1–4]. The absence of the stratified two-phase flow regime in microchannels was observed in many previous experiments [1,2]. Slug flow (sometimes called Taylor bubble flow, bubble train flow, intermediate flow or plug flow) is a typical two-phase regime that occupies a large area on the flow regime map in microchannels [2–5]. Flow circulation in the liquid slug significantly enhances radial heat transfer. Also, the presence of a gas slug between two consecutive liquid slugs reduces axial liquid mixing [6]. Due to the aforementioned facts, slug flow has applications in many technologies. Examples include electronic microchips, capillary micro-reactors, and microelectromechanical systems (MEMS).

Understanding slug hydrodynamics and its internal structure has significant engineering value. Even though slug flow appears to be a relatively simple physical phenomenon, there are still considerable unresolved questions about the physics and boundary conditions. These include the dynamics of a moving contact line among three materials (two fluids in contact with a solid boundary [7]). Also, there is uncertainty as to the applicability of the "no-slip" boundary condition at the "micro" scale [8,9]. The complexity of the flow physics increases as the geometry becomes more complicated. For example, many unsettled problems are associated with the slug flow pressure drop in a microchannel with an abrupt area change [10,11]. To date there are no slug flow studies that address all of the aforementioned problems.

Recently, discrepancies in connection with the presence of a liquid film surrounding the gas bubble in slug flows have been observed in various CFD simulations. While some researchers admitted that the thin liquid film was not captured because of the need for a finer mesh [12,13], others reported that the film simply does not exist. The latter group then had to study the effect of

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Nomenclature

k_{eff}	effective thermal conductivity
k_s	thermal conductivity of a solid surface
L_L	length of the liquid slug
L_G	length of the gas slug
Nu	Nusselt number
Pe	Peclet number
p_s	perimeter of microchannel
Pr	Prandtl number
$q''_{w,ave}$	average heat flux
$q''_{w,x}$	local heat flux
Re_D	Reynolds number
T_0	inlet temperature
T_m	mean temperature
T_w	wall temperature
u_s	liquid slug velocity
$\vec{v}$	fluid velocity
x	axial position
x^*	dimensionless position
Greek symbols	
τ_{cir}	circulation time scale
$\tau_{diff,L}$	time scale of conduction in liquid
$\tau_{diff,w}$	time scale of conduction in solid
σ	Surface tension
ρ_L	liquid density
ρ_G	gas density
ρ	density
Θ	contact angle

the three-phase contact angle on the characteristics of the slug flow [14,15]. Gupta et al. [16] reviewed the presence of wall dry-out during experimental studies and compared the observed regime with those described in numerical simulations. They showed that a finer mesh is needed as non-physical results could easily be produced if care was not exercised when modeling slug flows in microchannels. They compared five mesh resolutions and concluded that if mesh size were to be approximately ¼ of the liquid film thickness, capturing the liquid film could in fact be achieved. However, achieving this goal is computationally very costly (450,000 elements for their case).

Employing a dynamic mesh adaption method with interface tracking, the current authors [17] were able to significantly reduce the number of elements required for capturing the liquid film. With being able to reduce computational time they could investigate the effects of different capillary numbers and superficial velocities on the slug characteristics. This was achieved by employing 12 test cases, with the results being in good agreement with available experimental data.

Recently, Walsh et al. [18] performed experimental studies on heat transfer of slug flows in microchannels. One of the objectives of this paper is to attempt simulating the aforementioned experiment employing the Volume-of-Fluid (VOF) method. In the paper, heat transfer of the slug flow will be compared to that in the conventional plug and Poiseuille flows where a constant heat flux boundary condition is applied. Fig. 1 shows a schematic of such flows.

Using a simple energy balance the mean temperature, T_m, can be defined as:

$$T_m = T_0 + \frac{q''_{w,ave} P_s x}{m_L cp_L + m_G cp_G} \tag{1}$$

where T_0 is the inlet temperature, $q''_{w,ave}$ is the average heat flux, p_s is the perimeter of the microchannel, x is the axial distance from the edge of the heater, and m_L and m_G are the water and liquid mass flow rates, respectively. The dimensionless position downstream of the heated section is defined by the reciprocal of the inverse Graetz number according to the following equation:

$$X^* = \frac{x/D}{Re_D Pr} = \frac{x}{DPe} = Gr^{-1} \tag{2}$$

where D is the diameter of the microchannel, Pe, is the Peclet number, Pr, is the Prandtl number and Gr is known as the Graetz number. For a fully-developed laminar flow in a circular pipe with a constant heat flux boundary condition, Graetz et al. [19] reported an analytical solution for the temperature field. For the fluid with Prandtl number greater than one, Muzychka and Yovanovich [20] introduced a correlation for the Nusselt number which is valid in both the thermal entry and fully developed regions as follows:

$$Nu_{1\varphi} = \left[4.36^5 + \left(\frac{1.302}{X^{*1/3}}\right)^5\right]^{1/5} \tag{3}$$

For inviscid flows or very low Prandtl number fluids, a flat velocity profile (plug flow) is a reasonable assumption. For such flows, Muzychka and Yovanovich [20,21] introduced an expression for the Nusselt number that is valid for both the thermal entry and fully developed regions as follows:

$$Nu_{Plug,1\varphi} = \left[7.96^2 + \left(\frac{0.886}{X^{*1/2}}\right)^2\right]^{1/2} \tag{4}$$

Detail experimental measurements of the flow field and heat transfer characteristics in microchannels are very difficult mainly because of the sensors size limitations. In this paper, the heat transfer characteristics of slug flows in microchanels employing numerical simulations. The overall Nusselt number will be compared to the above correlations in addition to relevant experimental data. The fluctuations of the local Nusselt number, which are very

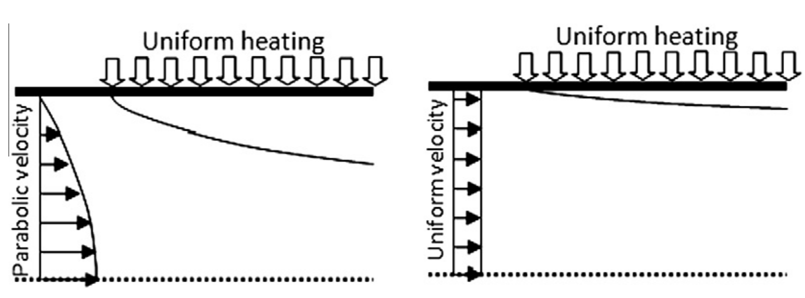

Fig. 1. Schematic of thermal boundary layer development for plug flow (left) and Poiseuille flow (right).