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Numerical study on the effect of initial flow velocity on liquid film thickness of accelerated slug flow in a micro tube

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ABSTRACT

Numerical simulation of air–water slug flows accelerated from steady states with different initial velocities in a micro tube is conducted. It is shown that the liquid film formed between the gas bubble and the wall in an accelerated flow is significantly thinner than that in a steady flow at the same instantaneous capillary number. Specifically, the liquid film thickness is kept almost unchanged just after the onset of acceleration, and then gradually increases and eventually converges to that of an accelerated flow from zero initial velocity. Due to the flow acceleration, the Stokes layer is generated from the wall, and the instant velocity profile can be given by superposition of the Stokes layer and the initial parabolic velocity profile of a steady flow. It is found that the velocity profile inside a liquid slug away from the bubble can be well predicted by the analytical solution of a single-phase flow with acceleration. The change of the velocity profile in an accelerated flow changes the balance between the inertia, surface tension and viscous forces around the meniscus region, and thus the resultant liquid film thickness. By introducing the displacement thickness, the existing correlation for liquid film thickness in a steady flow (Han and Shikazono, 2009) is extended so that it can be applied to a flow with acceleration from an arbitrary initial velocity. It is demonstrated that the proposed correlation can predict liquid film thickness at $Re < 4600$ within the range of ±10% accuracy.

1. Introduction

Two-phase slug flows in micro tubes are encountered in many thermal and chemical engineering applications. In a slug flow, elongated gas bubbles are separated by liquid slugs and liquid film is formed between the confined gas bubble and the tube wall. Several models for predicting heat transfer in a two-phase slug flow have been proposed. He (2008) proposed a heat transfer model of a slug flow considering that the major mechanisms are the liquid film evaporation and the enhanced convection with circulation in the liquid slug region. Thome et al. (2004) proposed a three-zone model for flow boiling heat transfer in a micro channel slug flow. In their model, a flow is divided into three zones, i.e. liquid slug, elongated bubble and dry zone. Heat transfer is significantly enhanced in the elongated bubble zone because of the thin liquid film evaporation. Assuming that liquid film is thin and thermal diffusivity is large, the local evaporation heat transfer coefficient h can be estimated by considering one-dimensional steady heat conduction inside a liquid film as:

$$h^* \approx \frac{k^*}{\delta^*}, \tag{1}$$

where k is the thermal conductivity of the liquid and δ is the liquid film thickness. An asterisk represents quantities with dimensions. Thus, liquid film thickness is one of the most important parameters to determine the heat transfer coefficient of flow boiling in a micro tube (Kenning et al., 2006; Qu and Mudawar, 2004). Accurate prediction of the liquid film thickness is crucial for developing a precise heat transfer model of micro two-phase slug flow.

A huge amount of studies on the liquid film thickness in a steady slug flow have been conducted for years. Taylor (1961) experimentally obtained mean liquid film thickness by measuring the difference between a bubble velocity and a mean velocity. It was found that the velocity difference, non-dimensionalized by the bubble velocity, approaches an asymptotic value of 0.55. Bretherton (1961) developed analytical models for the liquid film thickness and an axial pressure drop across the bubble based on

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Nomenclature

a	bubble acceleration
A	cross sectional area
Bo	Bond number, $\rho_l^* a^* D^{*2}/\sigma^*$
Ca	instantaneous capillary number, $\eta_l^* U^*/\sigma^*$
Ca'	characteristic capillary number, $\eta_l^* U_c^*/\sigma^*$
Ca_0	initial capillary number, $\eta_l^* U_0^*/\sigma^*$
D	tube diameter
f	function
f'	function
g	function
h	heat transfer coefficient
J_0	Bessel function of the first kind of order 0
k	thermal conductivity
M	dimensionless mobility
$\vec{n}$	unit normal vector to interface
p	pressure
Pe	Phase-Field Peclet number, $U_c^* D^*/M^* \mu^*$
Q	volume flow rate
R	tube radius
Re	instantaneous Reynolds number, $\rho_l^* U^* D^*/\eta_l^*$
Re'	characteristic Reynolds number, $\rho_l^* U_c^* D^*/\eta_l^*$
r	radial direction
s	variable
S	rate of deformation tensor
t	time
t_0	initial time
u	velocity
u_m	mean flow velocity
$u_{normalized}$	normalized velocity
U	instantaneous bubble top velocity
U_0	initial bubble top velocity
U_c	characteristic bubble top velocity
U_{center}	velocity at tube center
We	instantaneous Weber number, $\rho_l^* U^{*2} D^*/\sigma^*$
We'	characteristic Weber number, $\rho_l^* U_c^{*2} D^*/\sigma^*$
x	direction normal to interface
y_n	zeros of Bessel function of the first kind of order 2
z	longitudinal direction
γ	Constant
α	modification coefficient
β	physical property
δ	liquid film thickness
δ_0	initial liquid film thickness
Δ	displacement thickness
ε	interface thickness parameter
η	viscosity
κ	curvature
λ	length of transition region
μ	dimensionless chemical potential
ν	kinematic viscosity
σ	surface tension
ϕ	Phase-Field function
Ψ	dimensionless bulk free energy
ρ	density

the lubrication theory. At a small capillary number less than 5×10^{-3}, where gravitational and inertia forces can be neglected, it was shown that the dimensionless liquid film thickness can be scaled with $Ca^{2/3}$. Aussillous and Quere (2000) extended the Bretherton's model by taking into account the effect of the liquid film thickness on the bubble top curvature, and proposed an empirical formula which fits the Taylor's experimental data up to $Ca \approx 2.0$. Klaseboer et al. (2014) also revisited the Bretherton's model, and showed that their analytical approach eventually reproduces a correlation similar to that obtained by Aussillous and Quere (2000). Han and Shikazono (2009) conducted extensive and systematic measurements on liquid film thickness of micro two-phase flows with laser focus displacement meter using three different working fluids, i.e., water, ethanol and FC-40. It was found that the inertial force effect cannot be neglected even in laminar flow. Considering the modification of the bubble top curvature with Ca and Re, an empirical correlation for the liquid film thickness based on Ca, Re and We was proposed based on scaling analysis. The correlations by Aussillous and Quere (2000) and Han and Shikazono (2009) agree well at low Ca, but the latter correlation can predict the liquid film thickness more accurately for wide range of Ca, Re and We.

Although most existing studies consider a steady flow, practical flows in engineering applications are often accompanied by rapid acceleration caused by, for example, evaporation, contraction of a conduit and so forth. Han and Shikazono (2010) modified the empirical formula for a steady flow proposed by Aussillous and Quere (2000), so that it can be applied to an accelerated flow by taking into account the change in the bubble top curvature. Unknown coefficients in the correlation are determined by fitting their experimental data. In the above study, the flow is accelerated from rest, so the initial velocity is zero. Meanwhile, in heat transfer devices such as an oscillating heat pipe, the liquid and gas bubble move with a certain constant velocity within an adiabatic section before entering the boiling or condensing sections, where the flow experiences rapid acceleration or deceleration. Recently, Youn et al. (in press) conducted an experimental study on the liquid film thickness in a flow accelerated from non-zero initial velocities. Although their data show a strong impact of the initial velocity on the resultant liquid film thickness, its detailed mechanisms are not fully understood.

In the present study, numerical simulations of adiabatic air–water slug flows in a micro tube accelerated from steady states with different initial velocities are carried out. Detailed analyses of the obtained flow field allow to discuss the mechanism of liquid film formation under acceleration and the effects of the initial velocity. Based on the above knowledge, a correlation for the liquid film thickness in an accelerated slug flow with an arbitrary initial flow velocity is first developed. The proposed model is assessed by the present numerical data.

2. Numerical conditions and mathematical formulation

2.1. Governing equations and boundary conditions

An axisymmetric two-phase laminar flow in a cylindrical micro tube is considered as shown in Fig. 1. It is assumed that both phases are incompressible and adiabatic, so the phase change does not occur. The gravity is neglected because the surface tension force is dominant in a micro-scale tube considered here. The governing equations in each phase are the following continuity and Navier–Stokes equations:

$$\nabla \cdot \vec{u}_l^* = 0, \tag{2}$$

$$\nabla \cdot \vec{u}_g^* = 0, \tag{3}$$