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Numerical study of liquid-gas and liquid-liquid Taylor flows using a two-phase flow model based on Arbitrary-Lagrangian–Eulerian (ALE) formulation

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ABSTRACT

The liquid-gas and liquid-liquid Taylor flows in circular capillary tubes are numerically studied using a mathematical model developed in the frame of Arbitrary-Lagrangian–Eulerian (ALE), where the interface is tracked so that the important interfacial curvature and forces for Taylor flow can be accurately estimated. It is found that for liquid-gas Taylor flow, thin film thickness predicted by the present numerical model agrees very well with the benchmark experimental data both in visco-capillary and visco-inertia flow regimes. Thin film thicknesses decreases first and then increases as Reynolds number (*Re*) increases at relatively large capillary numbers (*Ca*). With the increase of *Ca*, classical pressure drop correlations become inaccurate, because of strong internal circulation inside liquid slug, the appearance of waves at rear meniscus, as well as the deviation from semi-spherical shape of head meniscus. For liquid-liquid flow, when *Ca* is small, thin film thickness correlations for liquid-gas flow can be used since the disperse phase has negligible effects, while when *Ca* is relatively large, the viscosity ratio and density ratio of continuous phase to disperse phase become two additional influencing factors. The larger are the viscosity ratio and the density ratio, the thicker is the film thickness. Different from stagnant thin film in liquid-gas flow, the flow in thin film of liquid-liquid flow is not stagnant and has a large contribution to pressure drop. The numerical model developed in this study is shown to be a powerful and accurate tool to study both the liquid-gas and liquid-liquid Taylor flows.

1. Introduction

Taylor flow is a significant two-phase flow pattern in microchannels or capillary tubes at relatively low flow rates, where surface tension normally dominates inertia or viscous force. It is relevant to diversified applications, such as in electronic cooling [1], biochemical engineering [2] and pharmacology [3]. Taylor flow is characterized by the separation of two adjacent bubbles or droplets by a liquid slug. Normally, bubbles or droplets almost fill the cross section of microchannel and are surrounded by a thin liquid film. The thin liquid film can protect chemical or biological samples from cross contamination and influence of channel wall [4]. Besides, the thickness of liquid film have a significant influence on heat and mass transfer rates [5,6]. Thus, the understanding of the influencing factors on thin film thickness is very helpful for practical applications, besides of its scientific importance.

The thin film thickness in liquid-gas Taylor flow has been studied extensively [7]. Fairbrother and Stubbs [8] measured liquid flow rates by using an indicator bubble and found that the bubble velocity is faster than the liquid, and deduced that there is a liquid film around the bubble. According to their analysis, dimensionless liquid film thickness, h/D, is proportional to $Ca^{1/2}$ when $Ca < 0.014$ (see Eq. (1) in Table 1). Taylor [9] inferred the liquid film thickness by measuring the difference between bubble velocity and mean flow velocity and extended the range of application of Eq. (1) to $Ca < 0.09$. Using lubrication theory, Bretherton [10] derived an analytical expression of liquid film thickness, which is scaled with $Ca^{2/3}$ when $Ca < 0.003$ (see Eq. (2) in Table 1). However, due to neglecting the effect of liquid film thickness on bubble curvature, the application range of this model is still limited. Aussillous and Quere [11] improved Bretherton's model and got an expression known as Taylor's Law (see Eq. (3) in Table 1), which is valid for $Ca < 1.4$, but still limited to low Reynolds numbers. They also found that the liquid film thickness predicted by Taylor's law deviated from experimental data when Reynolds number increased. They attributed this to the inertia force that contributed to liquid film thickening, and introduced the ratio of capillary number to Reynolds number, *Ca/Re*, as the transition criteria from visco-capillary flow

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Nomenclature

Ca	capillary number ($\frac{\mu U}{\sigma}$)
D	inner diameter of tube, m
h	film thickness, m
L	length, m
L_b	bubble length, m
$\boldsymbol{n}$	unit normal vector to interface
p	pressure, Pa
R	tube radius, m
R_b	interfacial radius, m
Re	Reynolds number ($\frac{\rho UD}{\mu}$)
t	time, s
$\boldsymbol{u}$	velocity, m/s
u_z	axial velocity, m/s
U	bubble velocity, m/s
U_{in}	mean inlet velocity, m/s
We	Weber number ($\frac{\rho U^2 D}{\sigma}$)

Greek symbols

μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
κ	curvature, m^{-1}
σ	surface tension coefficient, N/m
$\boldsymbol{\tau}$	Stress tensor
λ	dynamic viscosity ratio of the discontinuous phase to continuous phase
β	density ratio of discontinuous phase to continuous phase
Ω	computational domain

Subscripts

b	bubble
d	droplet
g, l	gas, liquid phase
s	surface
t	tangent direction
in	inlet boundary
$enter$	entrance zone
$exit$	exit zone

regime (where film thickness only related to Ca) to visco-inertia flow regime (where film thickness is related to Re). Based on numerical studies, Heil [12], Kreutzer et al. [13], and Ryck et al. [14] found that liquid film thickness at first decreased and then increased as Re increased for a fixed Ca. Han and Shikazono [15] measured liquid film thickness in liquid-gas Taylor flow under the variety of fluid types and capillary tube sizes by interferometer and laser focus displacement methods. Based on the analysis of scaling laws and according to their experimental data, they regressed a universal correlation (see Eq. (4) in Table 1) that can take into account of both the thinning effect through the third term in the denominator that related to Re, and the thickening effect of inertia through the fourth term in the denominator that related to Weber number, We, which is equal to $Re \cdot Ca$.

On the other hand, few studies have been conducted for the thin film thickness in liquid-liquid Taylor flow. Qiu et al. [16] realized the measurement of film thicknesses of a kerosene oil droplet/slug in a water wetted capillary tube and a water droplet/slug in a kerosene oil wetted capillary tube by improving their fringe probing optical diagnostics method for liquid-gas flow. Gupta et al. [17] used high speed photography/bright field microscopy and computational fluid dynamics (CFD) to study the hydrodynamics of vertically upward flow of Taylor droplets of water dispersed in a continuous hexadecane phase in a channel of 1.06 mm in diameter at $Ca < 0.01$. Because of the small viscosity of droplet to continuous phase (viscosity ratio = 0.3), it was found that the film thicknesses could be predicted by the Bretherton's expressions with free slip for an inviscid bubble. Eain et al. [4]. measured film thickness of liquid-liquid Taylor flow using optical microscopy. The effects of slug length and carrier phase fluidic properties were examined over a wide range of capillary numbers. The results showed that only when the liquid droplet length was greater than a certain value, a flat film with uniform thickness could be found. Their experiment also indicated the existence of visco-inertia regime at large Ca, where the film thickness was related not only to Ca but also to Re. Furthermore, the correlation equation obtained by Han and Shikazono [15] for the film thickness of liquid-gas flow could not be used to predict the film thickness of liquid-liquid Taylor flow correctly because of the non-negligible effect of viscosity of the discontinuous phase.

With the development of CFD, two-phase numerical models based on interface capturing methods have been widely adopted to simulate Taylor flows, including the volume-of-fluid (VOF) method [7,18,19], the level-set (LS) method [20], and the phase-field method [21,22,23]. Different from analytical studies based on the thin film lubrication theory, CFD methods have less restrictions and can provide detailed velocity and pressure fields, as well as the distribution of the thin film, and therefore are very useful for the deeper understanding of Taylor flow. However, these CFD methods are all based on interface capturing (or interface tracing), where two phases are modeled in a common computational domain and the interface of two phases need to be reconstructed to impose the surface tension force. This will inevitable induce unphysical velocities near the interface, known as “spurious or parasitic currents” ([24,25]). In addition, interface tracing methods cannot accurately predict the interfacial shear stress because the existence of interfacial thickness underestimates the velocity gradient.

In this study, we will simulate the Taylor flow using a numerical model based on Arbitrary-Lagrangian–Eulerian (ALE) Frame for the first time. The main idea of ALE is to introduce a third coordinate, i.e., the mesh coordinate where the partial differential equations are formulated rather than in the common material and space coordinates.

Table 1
Thin film thickness correlations from literature.

References	Correlations	Application range
Fairbrother and Stubbs [8]	$\frac{h}{D} = 0.25Ca^{1/2}$ (1)	$Ca < 0.014$, $Re = 1$
Bretherton [10]	$\frac{h}{D} = 0.67Ca^{2/3}$ (2)	$Ca < 0.003$, $Re = 1$
Aussillous and Quere [11]	$\frac{h}{D} = \frac{0.67Ca^{2/3}}{1+1.34(2.5Ca^{2/3})}$ (3)	$Ca < 1.4$, $Re = 1$
Han and Shikazono [15]	$\frac{h}{D} = \frac{0.67Ca^{2/3}}{1+3.13Ca^{2/3}+0.504Ca^{0.672}Re^{0.589}-0.352We^{0.62)}}$ (4)	$Ca < 0.4$, $Re < 2000$,