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Heat transfer and pressure drop characteristics of gas–liquid Taylor flow in mini ducts of square and rectangular cross-sections

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ABSTRACT

The thermal and flow characteristics of gas–liquid Taylor flow in vertical mini square and rectangular ducts were studied numerically for water and ethylene glycol as the liquid phase and nitrogen as the gas phase. The effects of fluid properties, flow parameters, and aspect ratio on the bubble shape, recirculation time, friction factor, and Nusselt number are discussed. The results indicate that the gas phase is confined by the tube wall in square and rectangular tubes leading to an asymmetrical Taylor bubble at low Capillary numbers, while an axisymmetric bubble is formed at high Capillary numbers. The liquid film thicknesses in the square and rectangular ducts are not uniform with a thicker liquid film formed at the tube corner. The recirculation region decreases and the dimensionless recirculation time increases with increasing Capillary number, which means that the intensity of recirculation decreases with increasing Capillary number. The friction factor decreases with increasing two-phase mixing velocity and aspect ratio and increases in gas void fraction, while the reverse is true for the two-phase Nusselt number. Compared with the ethylene glycol/nitrogen cases, the addition of Taylor bubble plays a more significant role on the pressure drop increase and heat transfer enhancement for the water/nitrogen cases because of the larger recirculation volume and smaller dimensionless recirculation time. Two empirical correlations are developed to predict the apparent slug Nusselt number and the film-to-slug Nusselt number for gas–liquid Taylor flow in square and rectangular ducts.

1. Introduction

With the development of microreactors, compact heat exchangers, and micro heat sinks, more attention has been paid to the heat and mass transfer and frictional characteristics in mini/micro channels. The heat and mass transfer characteristics of mini/micro channels are similar to those of conventional ones for single-phase flow, while the surface tension effect gradually dominates the two-phase flow with decreasing channel hydraulic diameter. Compared with single-phase flow, the two-phase flow has more potential to reach the increasing demand for high-flux thermal management solutions by taking advantage of the latent heat in phase-change flows like condensation and boiling, or internal recirculations for gas–liquid and liquid–liquid Taylor flow. Taylor flow is more stable and controllable than flows with phase change and has a relatively higher heat transfer coefficient compared with single-phase flow.

Numerous experimental studies have been conducted on the flow and thermal characteristics of Taylor flow in circular and square channels in terms of Taylor bubble shapes [1,2], bubble velocities [3], slug lengths [1,4], liquid film thickness [5,6], flow fields [7–8], pressure drops [9,10], and heat transfer characteristics [1,11–14]. Exhaustive reviews about these have been performed by Angeli and Gavriilidis [15], Gupta et al. [16], Eain et al. [17], and Bandara et al. [18].

Taylor flow is characterized by periodic capsular bubbles separated by liquid slugs with bubble and slug lengths larger than the channel hydraulic diameter [1]. Akbar and Ghiaasiaan [19], Laborie et al. [20], and Liu et al. [21] developed various correlations, which included the gas and liquid superficial velocities and properties, to predict the liquid and bubble lengths. However, the inlet distribution also plays a significant role on the liquid and gas lengths as shown in Leung et al. [12] and Shao et al. [22]. Though Kreutzer et al. [23] developed a correlation to predict slug lengths in multiphase monoliths using measured pressure drops, this method only showed good prediction for short slugs (shorter than seven times of the channel diameter) for which the pressure drop was sensitive to slug length variations.

A thin liquid film is formed between the Taylor bubble and the channel wall, which plays an important role in heat and mass

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Nomenclature

AR	aspect ratio, h/w
c_p	specific heat capacity, J/kg K
Ca	Capillary number, $\mu_L v_{tp}/\sigma$
d	hydraulic diameter, $2w\ h/(w+h)$, m
h	duct height, m
H	enthalpy, J/kg
f_s	friction factor in the liquid slug, $\Delta P\ d/(2\rho_L\ v_{tp}^2\ L_s)$
F	surface tension force, N/m^3
g	gravity acceleration, 9.81 m/s^2
k	thermal conductivity, W/m K
L_c	length of the computational domain, m
L_s	length of the liquid slug, m
L_s^*	dimensionless slug length, $L_s/(Pr_L\ Re_{tp}\ d)$
Nu	Nusselt number
Nu_{lo}	Nusselt number for the fully-developed single-phase flow
P	pressure, Pa
q_w	wall heat flux, W/m^2
Q	flow rate, m^3/s
Re	two-phase Reynolds number, $v_{tp}\ \rho_L\ d/\mu_L$
t	time, s
T	temperature, K
v	velocity, m/s
v_{rel}	dimensionless slip velocity, $1 - v_{tp}/v_b$
V	volume, m^3
w	duct width, m

Greek letters

α	volume fraction
κ	interface curvature, 1/m
μ	dynamic viscosity, N/m
ε	gas volume fraction in a unit cell
ρ	density, kg/m^3
σ	surface tension coefficient, N/m
τ	dimensionless recirculation time

Subscripts

b,in	liquid bulk value for velocity inlet
b,out	liquid bulk value for pressure outlet
corner	tube corner
G	gas phase
L	liquid phase
tp	two phase, average value for a computational domain
w	wall

transfer [1,11]. The liquid film thickness is mainly determined by the Capillary number (Ca) as indicated in the correlations developed for circular channels by Irandoust and Andersson [24], Aussillous and Quéré [25], and Han and Shikazono [5]. However, Taylor bubbles are confined by the tube wall in square and rectangular ducts, and a thicker liquid film is formed at the corners [26]. Thulasidas et al. [27–28] studied Taylor flow in square channels and pointed out that the transition from a non-axisymmetric to an axisymmetric bubble occurs at $Ca \approx 0.04$.

A recirculating flow, which could efficiently enhance the heat and mass transfer in the continuous phase, is induced by two-phase interfaces. The visualization of this recirculating flow has been conducted by Devoria et al. [7] and Meyer et al. [8] using micro-PIV technology. The pressure drop also increases with the addition of a second incompressible phase. Kreutzer et al. [10], Abiev [29], and Warnier et al. [9] proposed empirical models for the frictional pressure drops of Taylor flow. However, these correlations assumed an axisymmetric Taylor bubble with a uniform thickness liquid film. Compared with the flow characteristics, limited work has been done on the heat transfer characteristics of Taylor flow. Though the experimental studies in circular tubes [1,11,12,14] and square and rectangular channels [30] all show significant enhancement of heat transfer compared with their single-phase counterparts, the values of this enhancement varied in different studies. As pointed out in Bandara et al. [18], there was little agreement in the heat transfer coefficient correlations proposed by Kreutzer et al. [31], Walsh et al. [14] and Leung et al. [1,12].

Numerical simulation can serve as a complementary method to investigate the flow and heat and mass transfer characteristics of Taylor flow with less expense. Most of the numerical studies about Taylor flow are performed in two-dimensional channels using a fixed reference frame [32–34] or a moving frame [35–38]. A brief review of the numerical work on Taylor flow has been conducted by Talimi et al. [39]. According to Gupta et al. [34], the near wall mesh must be sufficiently fine, at least five mesh elements across the film, to capture the thin liquid film present in Taylor flow. However, the two-dimensional simulation cannot consider the flow and heat and mass transfer characteristics in channels with non-circular cross-sections. For the three-dimensional numerical work, the moving reference frame is mostly adopted to save computational time. Taha and Cui [40,41] studied the bubble shapes and streamlines of gas–liquid Taylor flow in square channels. Liu and Wang [21] investigated the hydrodynamics of Taylor flow in square and triangular capillaries. Falconi et al. [42] studied numerically and experimentally local flow phenomena in co-current upward laminar Taylor flow through a small square channel. A local backflow region in the rear part of the liquid film was observed. Abadie et al. [43] analyzed the mixing and recirculation characteristics of gas–liquid Taylor flow in square and rectangular ducts. The numerical results indicate that the recirculation volume decreases and the recirculation times increase with increasing aspect ratio. Abiev [44] pointed out that recirculation times were depended on slug lengths and that circulation occurred even in very short liquid slugs (about 0.17 times of the tube diameter). The three-dimensional numerical work about heat transfer characteristics in non-circular channels is limited. Talimi et al. [45] studied numerically the heat transfer characteristics of Taylor flow in square microchannels under constant heat flux boundaries. The liquid film and the gas phase were neglected, and the bubble shapes were determined by the contact angles. However, the liquid films at the duct corners exist even at lower Capillary number for the case of square channels. As a consequence, the numerical Nusselt number was higher than that of the experimental work of Betz and Attinger [30]. As stated in Dai et al. [11], the thermal resistance contribution of the liquid film is important for the heat transfer performance of Taylor flow. Neglecting this part will lead to a higher heat transfer enhancement compared with the single-phase flow, especially at higher Ca. Che et al. [46] conducted three-dimensional simulations in square and rectangular channels under constant temperature boundary conditions taking the thin liquid film into account. The effects of droplet length, aspect ratio, and Péclet number on the heat transfer process in liquid–liquid Taylor flow were analyzed.