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Analysis of local pressure gradient inversion and form of bubbles in Taylor flow in microchannels

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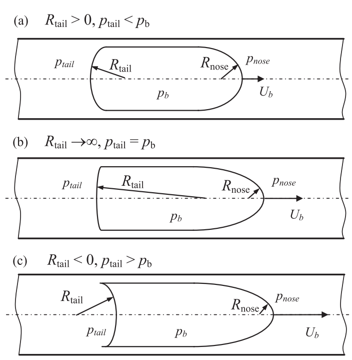
HIGHLIGHTS

- Local inversion of the pressure gradient by the gas-liquid Taylor flow is theoretically explained.
- In the film around the bubble an inverse flow of liquid exists.
- Inverse flow of fluid is caused by the inverse pressure gradient in the film.
- Pressure oscillations near the ends of the bubble reasons are explained.
- Form of Taylor bubbles is explained theoretically at qualitative level.

GRAPHICAL ABSTRACT



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ABSTRACT

Analysis of local pressure gradient inversion and pressure 'jumps' at gas-liquid Taylor flow in microchannels, which has been previously observed, but not explained by Kreutzer et al. (2005b) and Duran Martinez et al. (2015) is carried out. The new understanding originates from a mathematical model of two-phase flow developed before (Abiev (2008) for circular capillaries, Falconi et al. (2016) for micro channels with square cross-section). It is shown that the inverse flow of the fluid in the film around the bubble is caused by the inverse pressure gradient in the film.

The key factors determining the Taylor bubble surface deformation near its ends are found. The deformation occurring at the nose and tail ellipsoidal surfaces and on the cylindrical surface near the tail of the bubble is caused by the balance of pressure in the liquid film along the bubble, the pressure level in the bubble and capillary pressure.

It was shown that pressure difference in the liquid film along the bubble caused by peculiar properties of Taylor flow in micro channels is the prime cause of non-hemispherical form of the bubble ends, not vice versa. The obtained results are applicable to micro channels both with circular and square cross-section (in the latter case to the so-called axisymmetric form of the bubble or close to it).

The wavy form of the bubble near its tail observed by Kreutzer et al. (2005b), Abadie et al. (2013), Hayashi et al. (2014), and Falconi et al. (2016) is shown herein to be governed by the balance between the capillary forces at the interface and wave-like pressure field near the ends of the bubble.

The performed analysis provides a quite simple understanding of previously unexplored features of Taylor flow hydrodynamics (pressure oscillations near the ends of the bubble found by Kreutzer et al. (2005a, 2005b)) and allows a characterization of the shape of the bubble ends in general (concave or almost planar, convex, elongated convex). The results obtained will allow a more accurate modeling of developing gas-liquid slug flow and a calculation of the surface area of the bubbles in the description of mass transfer processes. Besides, the results of this paper are important for better understanding of bubbles' formation process driving forces, thus giving a tool to engineers for better design of

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Nomenclature

A	cross-sectional area, m^2
A_f, A_b, A_c	areas of cross-sections of film, bubble and capillary, m^2
d	diameter, m
d_b	diameter of a bubble, m
d_c	diameter of a capillary, m
$\mathbf{F}$	vector specific of mass forces, m/s^2
g	gravity acceleration, m/s^2
$\mathbf{I}$	unity tensor
L, l	length, m
p	pressure, Pa
$p_{c.nose}$	capillary pressure in a nose part of the bubble, Pa
$p_{c.tail}$	capillary pressure in a tail of the bubble, Pa
Δp_{in}	inertial component of pressure, Pa
R	radius, the radius of curvature of bubble surface, m
r, z, φ	cylindrical coordinates
t	time, s
U_b, U_f, U_s	radius averaged velocity of gas in the bubble, liquid in film and liquid in the slug
$\mathbf{u}$	velocity vector, m/s
u_s	local velocity in the liquid slug, m/s
z_b	axial coordinate, starting from the tail of the moving bubble, m
δ	thickness of the film around of the bubble, m
κ	surface curvature, 1/m
μ	dynamic viscosity, Pa s
μ_1	dynamic viscosity of continuous phase, Pa s
ρ	density, kg/m^3
ρ_1	density of continuous phase, kg/m^3
σ	interfacial tension, N/m
∇	Hamilton operator
∇^2	Laplace operator
$\mathrm{Ca} = \frac{\mu_1 U_b}{\sigma}$	capillary number
$Re = \frac{\rho_1 U_s d_c}{\mu_1}$	Reynolds number.

Indices

1, 2	numbers of surface curvature radii in Eq. (16)
1	continuous phase
b	bubble
bc	cylindrical part of the bubble
bt	zone of transition between the cylindrical and ellipsoidal part of the bubble (in cross-section)
c	capillary
c.t	capillary in transition zone
f	film
f.t	film in transition zone
nose	nose part of the bubble
r, z, φ	velocity components in cylindrical coordinates
s	liquid slug
tail	tail part of the bubble
tr	zone of transition, longitudinal section

microreactors and micro heat exchangers. The bubble's nose elongation results in a significant change in the liquid film thickness in this area, influencing thus mass transfer characteristics by the change in the gas-liquid interface and the velocity in the liquid film.

The observed form of the bubbles could also be used in experimental praxis as a detector indicating pressure drop and two-phase flow rate in the Taylor flow.

1. Introduction

In the past three decades, mini- and microscale technologies were intensively studied and implemented in the laboratory and industrial practice. The application of micro devices for carrying out processes in multiphase media, including versatile catalytic reactions, is the subject of several reviews, chapters in books and handbooks (Hessel et al., 2005, 2009; Roy et al., 2004; Kreutzer et al., 2005a; Bauer et al., 2006).

The most preferred flow type for heterogeneous reactions in the liquid-liquid and liquid-gas systems is segmented (other names are: Taylor, slug) flow (Kreutzer et al., 2005a; Bauer et al., 2006). Good mixing inside the liquid slug due to the Taylor vortices and short diffusion path through the thin liquid film between the drop (or the bubble) and the wall coated with the catalyst result in high mass transfer coefficients (Bauer et al., 2006; Abiev and Lavretsov, 2012; Abiev, 2013).

Reviews on the hydrodynamics of slug flow in mini and micro channels are presented in (Kreutzer et al., 2005a; Abiev, 2012; Howard and Walsh, 2013). The pressure loss characterizes the power consumption for movement of fluids through the apparatus, therefore this research was the subject of many studies, among which the most significant are the following: Hessel et al. (2009), Roy et al. (2004), Kreutzer et al. (2005b), Bauer et al. (2006), Abiev and Lavretsov (2012), Abiev (2013). In addition, the hydraulic resistance of capillary with gas-liquid mixture significantly affects the distribution of the phases through the channels in the monolith, whose number may reach tens of thousands. For this reason, the information about the pressure loss in the capillaries is a key question in the simulation of micro devices.

The deformation of elongated bubbles moving in the pipes was in the focus of several tens of papers. Polonsky et al. (1999) and Talvy et al. (2000) have studied experimentally the motion of elongated (Taylor) bubbles in air-water vertical flow and the influence of the separation distance between two consecutive bubbles (liquid slug length) on the behavior of the trailing bubble in vertical slug flow, respectively. Though the experiments were performed in a 25 mm inner diameter pipe, the observed forms of the nose and the tail of the bubble are similar to those for mini and micro channels: the nose is elongated convex and the tail is almost flat. For 25 mm pipe an oscillatory motion of the bubble bottom was observed by Polonsky et al. (1999). These oscillations were assessed theoretically, though the results did not coincide well with the experimental data.

In our recent paper (Abiev, 2011) a detailed analysis of the most important factors determining the pressure loss at the Taylor flow is performed, excluding wetting hysteresis. For the first time the role of wetting hysteresis to create additional pressure losses in Taylor flows in mini and micro-channels (or capillaries) was studied by Jovanović et al. (2011), where only the case of a continuous medium and a good wetting of the capillary walls of the material is considered. In a number of studies (Kawahara et al., 2002; Liu et al., 2005; Zhao and Bi, 2001; Ju Lee and Yong Lee, 2001) this kind of pressure losses is not taken into account.