CHEMICAL ENGINEERING RESEARCH AND DESIGN 88 (2010) 263–269

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Bubble lengths in the gas–liquid Taylor flow in microchannels

*Paweł Sobieszuk**, *Paweł Cygański*, *Ryszard Pohorecki*

Faculty of Chemical and Process Engineering, Warsaw University of Technology, Warynskiego 1, PL 00-645 Warsaw, Poland

ABSTRACT

Experimental results of measurements of the bubble and slug lengths in Taylor (slug) flow are presented. The experiments were carried out using 3 different straight microchannels (microreactor with square cross-section made of polydimethyloxosilane (PDMS); microreactor with circular cross-section made of glass; microreactor with rectangular cross-section made of polyethylene terephthalate modified by glycol (PETg)) and 4 different liquids (water, ethanol propanol and heptane). The results have been compared with the available literature correlations. It is concluded, that the values obtained from the correlation proposed by Laborie et al. [Laborie, S., Cabassud, C., Durant-Bourlier, L., Laine, J.M., 1999. Characterization of gas–liquid two-phase flow inside capillaries. Chem Eng Sci 54, 5723–5735] do not agree with the results of measurements, while the agreement of these results with the predictions obtained using the correlation proposed by Qian and Lawal [Qian, D., Lawal, A., 2006. Numerical study on gas and liquid slugs for Taylor flow in a T-junction microchannel. Chem Eng Sci 61, 7609–7625] is good. New, corrected values of the pre-exponential constant and the exponents in the Qian and Lawal [Qian, D., Lawal, A., 2006. Numerical study on gas and liquid slugs for Taylor flow in a T-junction microchannel. Chem Eng Sci 61, 7609–7625] correlation are proposed.

Keywords: Microreactor; Bubble length; Liquid slug length; Taylor flow

1. Introduction

Modern structured process equipment usually involves microstructures. Microstructures ensure significant intensification of mass and heat transfer owing to short diffusion/conduction paths, large concentration/temperature gradients and high surface to volume ratio. These features warrant intensification of physical, chemical and biochemical processes, especially in multiphase (gas–liquid, liquid–liquid, gas–solid, liquid–solid or gas–liquid–solid) systems.

The basic elements of microstructures are microchannels.

There are two kinds of microchannels used to contact two different phases:

- Open microchannels.
- Closed microchannels.

Open microchannels have the form of grooves in a flat plate, opened from one side to ensure contact with the other phase.

Closed microchannels are microtunnels through which both contacted phases flow simultaneously.

Closed microchannels are much more commonly used in microstructures, the flow structure in these channels is more complicated and definitely less understood than the flow structure in the open channels. Consequently, the closed channels have been chosen as the main object of investigation in our investigation program.

This paper concerns two-phase gas–liquid flow in closed microchannels. A number of different flow patterns (regimes) may be distinguished in the case of such flow. They include:

- Bubble flow.
- Slug (Taylor) flow.
- Annular flow.
- Spray flow.
- Foam flow.

and transition regimes between those listed above.

* *Corresponding author*. Tel.: +48 22 234 63 19.
E-mail address: sobieszuk@ichip.pw.edu.pl (P. Sobieszuk).
Received 12 December 2008; Received in revised form 5 July 2009; Accepted 7 July 2009
0263-8762/$ – see front matter © 2009 The Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.cherd.2009.07.007

Nomenclature

A, B, C, D, E constants
$Ca = \mu u_{TP}\sigma_L^{-1}$ capillary number
d channel (hydraulic) diameter (m)
$Eo = (\rho_L - \rho_G)d^2 g\sigma_L^{-1}$ Eotvos number
L_G bubble length (m)
L_L liquid slug length (m)
$Re = u_{TP}d\rho_L\mu_L^{-1}$ Reynolds number for two-phase flow
$Re(u_G) = u_G d\rho_L\mu_L^{-1}$ Reynolds number in Laborie et al. (1999) correlation
$Re(u_S) = u_S d\rho_L\mu_L^{-1}$ Reynolds number in Laborie et al. (1999) correlation
u superficial velocity (m s^{-1})
u_S gas bubble velocity (m s^{-1})
$u_{TP} = u_G + u_L$ superficial two-phase velocity (m s^{-1})
$We = u_{TP}^2 d\rho\sigma^{-1}$ Weber number

Greek letters
ε hold-up
μ viscosity (Pa s)
ρ density (kg m^{-3})
σ surface tension (N m^{-1})
ϕ diameter (m)

Subscripts
G gas
L liquid

The flow pattern depends on the liquid and gas flow rates, on the properties of the fluids, channel geometry and its material. Several diagrams, called flow maps, have been proposed in the literature, to depict regions in which a given flow pattern occurs (e.g. Jayawardena et al., 1997; Triplett et al., 1999; Waelchli and von Rohr, 2006). An example of such a map is shown in Fig. 1. There were also numerous efforts to develop an universal flow map, valid for different microchannels and different gas–liquid systems. Although these efforts had limited success, they all confirm, that the slug (Taylor) flow occupies a large part of any flow map, and is obtainable in the most practically interesting ranges of gas and liquid flow

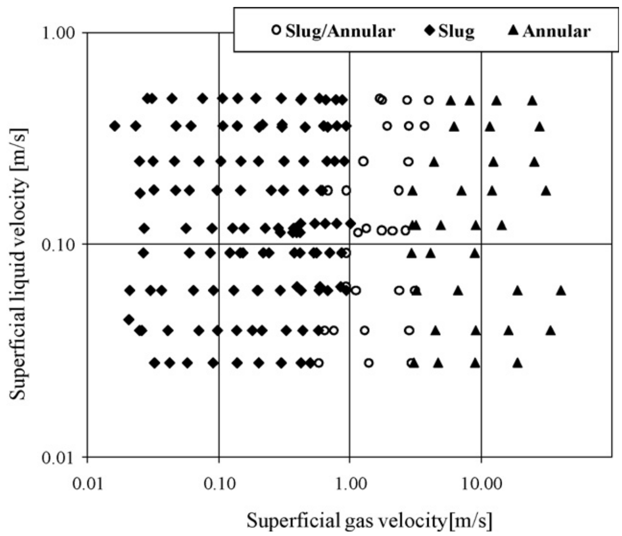

Fig. 1 – Flow map (own results obtained for glass microreactor and ethanol–nitrogen system).

rates. It also seems to be the most suitable regime to carry out the gas–liquid reactions.

To quote the opinion of Hessel et al. (2005): “Bubble and slug lengths in microchannels mainly depend on the inlet conditions, as the significance of surface tension forces means that once the Taylor bubbles form, little change to their size is expected within the channel as a result of breakup or coalescence. Although there is abundant literature on the formation of small bubbles, usually in an unconfined liquid, very little information is available on Taylor-bubble formation in microchannels”.

Indeed, only a few references describing the bubble and slug lengths have been found in the literature. Laborie et al. (1999) measured bubble and slug lengths in vertical glass capillaries of 1, 2, 3 and 4 mm inner diameter. They proposed the following correlations.

For the bubble length:

$$\frac{L_G}{d} = 0.0878\frac{[Re(u_S)]^{0.63}}{Eo^{1.26}} \quad (1)$$

where from:

$$L_G \sim d^{-0.89} \quad (2)$$

For the slug length:

$$\frac{L_L}{d} = 3451\frac{[Re(u_G)]^{-1.27}}{Eo^{1.27}} \quad (3)$$

where from:

$$L_L \sim d^{-2.81} \quad (4)$$

It follows from these correlations, that L_G should be approximately inversely proportional to d while L_L should be approximately inversely proportional to the third power of d.

In another study, Qian and Lawal (2006) performed numerical simulations of the Taylor flow, using commercial CFD package FLUENT (release 6.1.22.2003). In this package the volume of fluid (VOF) model is used to simulate two-phase fluid–fluid flows. As a result of 148 numerical simulations for channel widths ranging from 0.25 to 1 mm, they proposed the following correlations:

$$\frac{(L_G + L_L)}{d} = 1.637\varepsilon_G^{-0.893}(1-\varepsilon_G)^{-1.05}Re^{-0.075}Ca^{-0.0687} \quad (5)$$

$$\frac{L_G}{d} = 1.637\varepsilon_G^{0.107}(1-\varepsilon_G)^{-1.05}Re^{-0.075}Ca^{-0.0687} \quad (6)$$

$$\frac{L_L}{d} = 1.637\varepsilon_G^{-0.893}(1-\varepsilon_G)^{-0.05}Re^{-0.075}Ca^{-0.0687} \quad (7)$$

They also concluded, that for bigger channel diameters (2.0 and 3.0 mm) the above correlations are not applicable.

Pohorecki and Kula (2008) tried to explain the mechanism of gas bubble and liquid slug formation in Taylor flow. They proposed a simple mechanistic “switching” mechanism, which explains the form of the correlations proposed by Qian and Lawal (2006).

It should be pointed out, that bubble and slug lengths are of paramount importance for mass transfer and back mixing in Taylor flow. The existing experimental or CFD-based correlations usually relate the mass transfer coefficient to the bubble and/or slug lengths (Bercic and Pintar, 1997; Vandu et