Chemical Engineering Journal 155 (2009) 326–332

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

Rise of Taylor bubbles through narrow rectangular channels

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ARTICLE INFO

Article history:
Received 28 January 2009
Received in revised form 25 June 2009
Accepted 4 July 2009

Keywords:
Taylor bubble
Rise velocity
Two-phase flow
Rectangular narrow channel
Inclination
Orientation

ABSTRACT

Experiments have been performed to investigate the rise of Taylor bubbles in narrow rectangular channels (0.0051 m × 0.0027 m × 0.8 m and 0.01 m × 0.0027 m × 0.8 m). The studies conducted for both stationary and moving liquid have revealed definite influence of channel orientation, dimension and inclination on the propagation velocity of Taylor bubbles. The rise velocity first increases and then decreases as the channel is moved from the horizontal to the vertical position with its broad face always lying in a vertical plane. This is in agreement to the results reported in literature for circular as well as non-circular geometries. On the other hand, the rise velocity increases continuously with inclination when the channel is oriented with its broad face in a horizontal plane. The explanation for this difference in behavior has been obtained through visualization and photographic recording. It has also been noted that the bubble rise velocity in the vertical orientation could not be predicted by any of the existing correlations proposed for non-circular channels.

1. Introduction

The recent trend of miniaturization has opened up ample opportunities to use micro-reactor technology for several applications. Miniature reactor offers a number of advantages over the conventional design. They are compact, easily controllable and require less fluid inventory as well as less reaction time. Further, the requirement of scale-up may be absent or at the best minimum in case of these new generation reactors. With this motivation, the last decade has witnessed a number of studies on gas–liquid two-phase flow through mini and micro-channel of circular as well as non-circular cross-section. Almost all the researches have noted the existence of slug flow pattern over a wide range of flow conditions. In a wide tube ($D > 10$ mm), this regime is usually characterized by the periodic appearance of axisymmetric bullet shaped Taylor Bubbles and aerated liquid slugs. In narrow passages, slug flow comprises of a train of axisymmetric elongated Taylor bubbles separated by liquid slugs. This has been termed as “pure slug flow” by Nakoryakov et al. [1].

Since the hydrodynamics of Taylor bubble governs the slug flow pattern, several works both experimental (Dumitrescu [2], Davies and Taylor [3], Zukoski [4], Benediksen [5], Das et al. [6]) and theoretical (Dumitrescu [2], Davies and Taylor [3], Wallis [7], Bretherton [8], Carew et al. [9]) have been reported on the rise of Taylor bubbles through stationary and moving liquid columns. However, the majority of the studies are confined to larger tube diameters and only a few works have been reported on small diameter conduits of circular cross-section. Barnea et al. [10] have observed elongated air bubbles in a vertical tube of 4 mm diameter and mentioned it as a limiting case of slug flow. Mishima and Hibiki [11] have studied the slug velocity and other flow characteristics for 1–4 mm diameter vertical tube. They have estimated the rise velocity of slug bubbles using the drift flux model and found the approximate value of distribution parameter to be 1.1. Cheng and Lin [12] have reported slug flow to be the dominant flow regime for gas–liquid flow through tubes of 2–8 mm diameter and noted higher slug rise velocity in inclined tube as compared to the vertical or horizontal configuration. They have also reported the shape of gas slugs to change with inclination, tube diameter and gas superficial velocity. Liu et al. [13] have studied the effect of geometry and fluid properties on Taylor bubble rise velocity in vertical capillaries with air as the gas phase and water, ethanol or oil mixture as the liquid phase.

In non-circular passages, one of the earliest studies dates back to Maneri and Zuber [14]. They investigated the effect of inclination and fluid properties on the rise of bubbles in a two dimensional tank and reported the influence of fluid properties on the bubble rise to be more pronounced at the inclined plane. Sadatomi et al. [15] reported the pressure drop and rise of large air bubbles through water in rectangular, triangular and annular passages and expressed the rise velocity of slug bubbles in still water as:

$$u_\mathrm{b} = 0.35\sqrt{gD_\mathrm{e}} \tag{1}$$

where D_e is the equi-periphery diameter of the non-circular cross-section.

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doi:10.1016/j.cej.2009.07.006

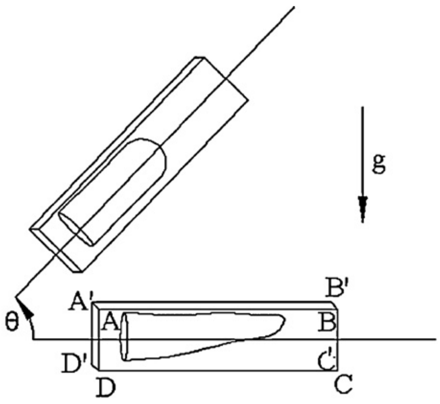
They have further reported Eq. (1) to be valid for Eotvos number greater than 70. Mishima et al. [16] have estimated slug rise velocity, pressure drop and flow regimes for three narrow rectangular channels of nominal gap 1 mm, 2.4 mm and 5 mm, width and length of each being 40 mm and 2000 mm. The rise velocity was correlated by drift flux model and the distribution parameter was reported to be in the range of 1–1.2. They have also noted significant wall effect on the rise as well as shape of the bubbles in narrow channels. Bi and Zhao [17] have studied the motion of Taylor bubbles in non-circular (triangular, square and rectangular) as well as circular channels and noted slug flow to cease for tube diameter less than 2.9 mm. Subsequently, Liao and Zhao [18] performed a theoretical investigation on the motion of Taylor bubbles through triangular and square passages. They accounted for the effects of gravity, capillary and viscous forces in their model and reported that the drift velocity in a triangular passage is higher than that of a square passage of same hydraulic diameter. Clanet et al. [19] studied the bubble dynamics in a rectangular cross-section and obtained the following analytical expression for rise velocity of air bubbles in vertical tubes of arbitrary cross-section for Reynolds number greater than 1:

$$u_{\mathrm{b}} = 0.2\sqrt{gP} \tag{2}$$

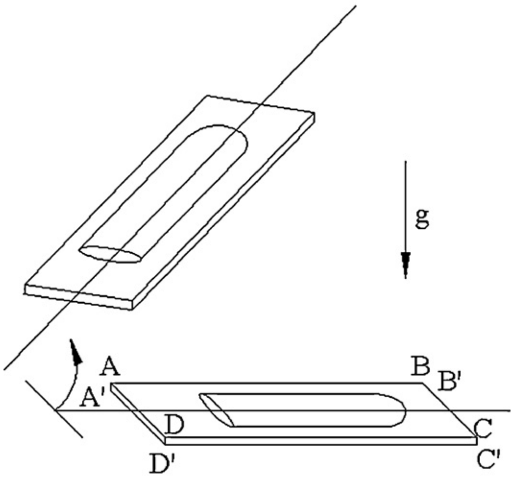
In Eq. (2) P is the wetted perimeter. In recent years Qian and Lawal [20] obtained slug lengths for various operating conditions for a T junction microchannel by using CFD software package FLUENT. Some studies on microchannels are also reported by Ide et al. [21] and Warnier et al. [22].

From the aforementioned survey, it is evident that although some studies have been reported on the rise of Taylor bubbles through mini and micro-channel of non-circular geometry, a comprehensive investigation is required for a detailed understanding. Experiments on larger channels have revealed that Taylor bubbles are influenced by the conduit shape and inclination. In a narrow channel, the additional factor of dominant wall effect is also expected to play an important role on bubble motion. With this consideration, the present study reports an experimental investigation on the rise of Taylor bubbles through rectangular channels of small width.

The rectangular channel is selected for two reasons. Firstly, non-circular passages are frequently encountered in the area of micro-fluidics. Secondly it offers an additional geometric variable to flow. In any axisymmetric channel (a circular or a square passage), the conduit dimension and inclination influences the hydrodynamics of flow while in a rectangular passage, the orientation of the conduit (Fig. 1a and b) is also an additional parameter. The bubble can rise either through orientation A or orientation B of a channel section ABCDD″A′B′C′ as shown in Fig. 1. In both the orientations the channel is rotated from the horizontal to vertical configuration as shown. In orientation A, the broad face ABCD of the channel always lies in a vertical plane. On the contrary, in orientation B, the narrow face DD′C′C lies in a vertical plane. Literature review indicates that almost nothing is known about the influence of orientation. Accordingly, the experiments are planned to investigate the rise of Taylor bubbles through stationary and moving water columns in rectangular mini channels of different dimensions, inclinations and orientation. The unique observations have further revealed the inadequacy of the existing theory in the prediction of bubble rise velocity through these channels.



(a) Orientation A



(b) Orientation B

Fig. 1. Two different orientations of rectangular channel. (a) Orientation A and (b) orientation B.

2. Experimental setup and procedure

A schematic of the experimental setup is presented in Fig. 2. It comprises of two rectangular test rigs TC1 and TC2 made of transparent acrylic resin to enable visualization and photography of flow. The dimensions of the individual channels are 0.0051 m × 0.0027 m for TC1 and 0.010 m × 0.0027 m for TC2 with the total length of each being 0.8 m. Each channel can be rotated by a clamp and connector (C) arrangement and the experiments are performed for five different inclinations ranging from 0° to 90° from the horizontal configuration. The inclination angle is measured by an axial protractor (P) attached to the connector (C) as shown in Fig. 2. In addition, the rigs are orientated along the central axis either in orientation A or in orientation B (Fig. 1a and b) and the bubble characteristics are noted for both the cases.

Water is supplied from a constant-head overhead tank (T) to either of the test sections. Two valves one in the bypass line (V1) and other in the supply line (V2) controls the flow rate of water while a three way valve (V3) directs flow to the desired test rig. Air is injected at a point (A in Fig. 2) 0.025 m above the water inlet. After passage through the test section the fluids exit from the outlet pipe (P2) located at the top of the channel. For investigating the rise of Taylor bubbles through stationary water columns, the channel is first filled with water and then air is injected at the air inlet. For the study of Taylor bubbles through moving water, the bubbles are introduced in flowing water and the water flow rate is measured by volumetric collection method. The liquid flow rate is measured several times and an average of at least 6 readings are taken to reduce the experimental error. For the measurements of flow rate, the maximum experimental error is 1.8% and that encountered for the velocity of rising bubble is ±1.5%. Each of the experiments is repeated several times and the average deviation of the data has been observed to lie within ±4%. The maximum deviation has been