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

S. Bhusan[a], S. Ghosh[b], G. Das[b,*], P.K. Das[a]

[a] Department of Mechanical Engineering, IIT Kharagpur, Kharagpur, West Bengal 721302, India
[b] Department of Chemical Engineering, IIT Kharagpur, Kharagpur, West Bengal 721302, India

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:

$$u_b = 0.35\sqrt{gD_e} \quad (1)$$

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

* Corresponding author. Tel.: +91 03222 283952; fax: +91 03222 282250.
E-mail address: gargi@che.iitkgp.ernet.in (G. Das).

1385-8947/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
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:

$$u_{\mathrm{b}} = 0.2\sqrt{gP} \qquad (2)$$

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.

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

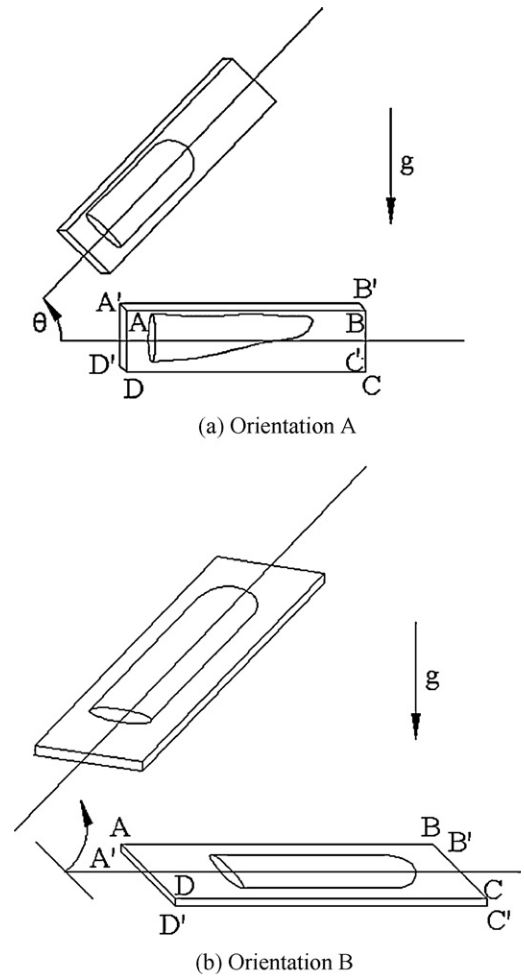

Fig. 1. Two different orientations of rectangular channel. (a) Orientation A and (b) orientation B.

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

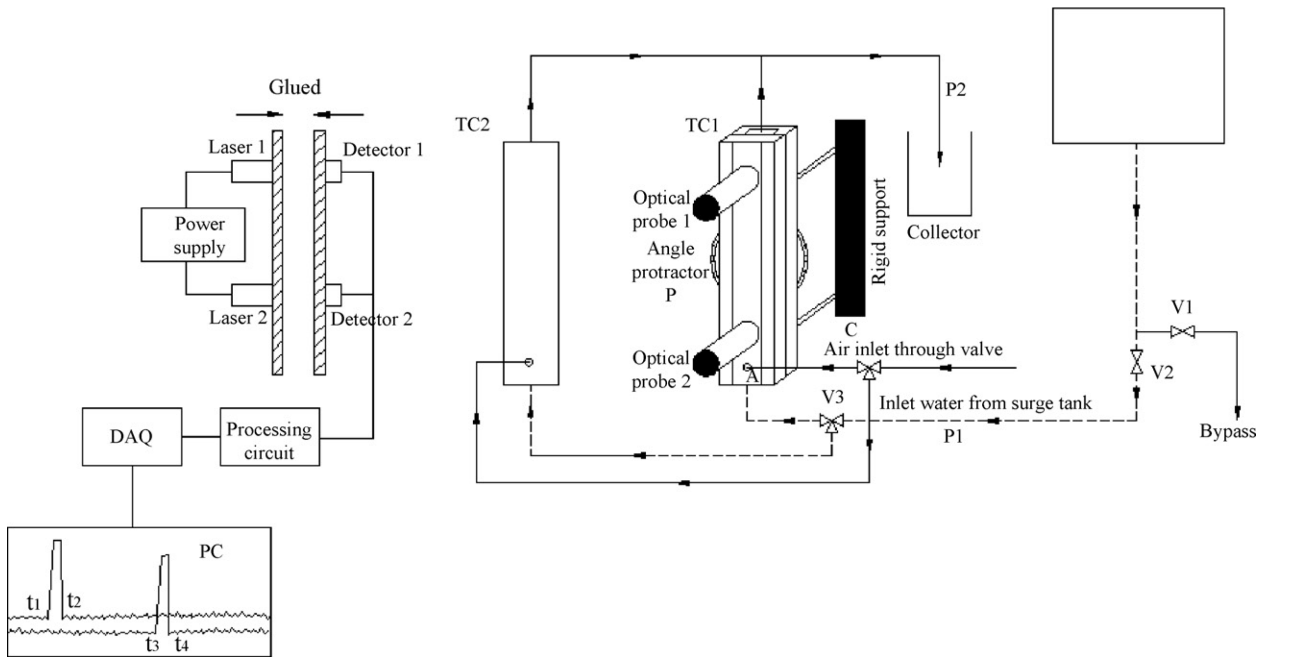

Fig. 2. A schematic of the experimental setup.

obtained as ±6%. It occurs for the larger channel (TC2) in orientation A where the bubble rise velocity is comparatively high.

The experiments are performed at a distance of 0.3 m from the entry and 0.2 m from the exit sections. These distances are decided by prior tests to ensure constant velocity of the rising bubble. The shape of the Taylor bubbles have been noted from photographs using a digital camera (DSCH9, SONY) and the rise velocity is measured by the optical probe method. The working principle and detailed design of the probe has been described elsewhere (Jana et al. [23]). Two probes are installed 0.3 m apart in the test section. The passage of the Taylor bubbles across the probe is detected by a sudden fall in the voltage signal as shown in Fig. 2. The time lag between the voltage drops as indicated by probes 1 and 2 is used to calculate the rise velocity using the following expression:

$$u_\mathrm{b} = \frac{s}{\Delta t} \tag{3}$$

where u_b is the bubble rise velocity in m/s, s is the distance between the probes (0.3 m) and Δt is the average time lag between the drop of voltage signals viz:

$$\Delta t = \frac{(t_3 - t_1) + (t_4 - t_2)}{2} \tag{4}$$

The time instants associated with the different t's in Eq. (4) are depicted in Fig. 2.

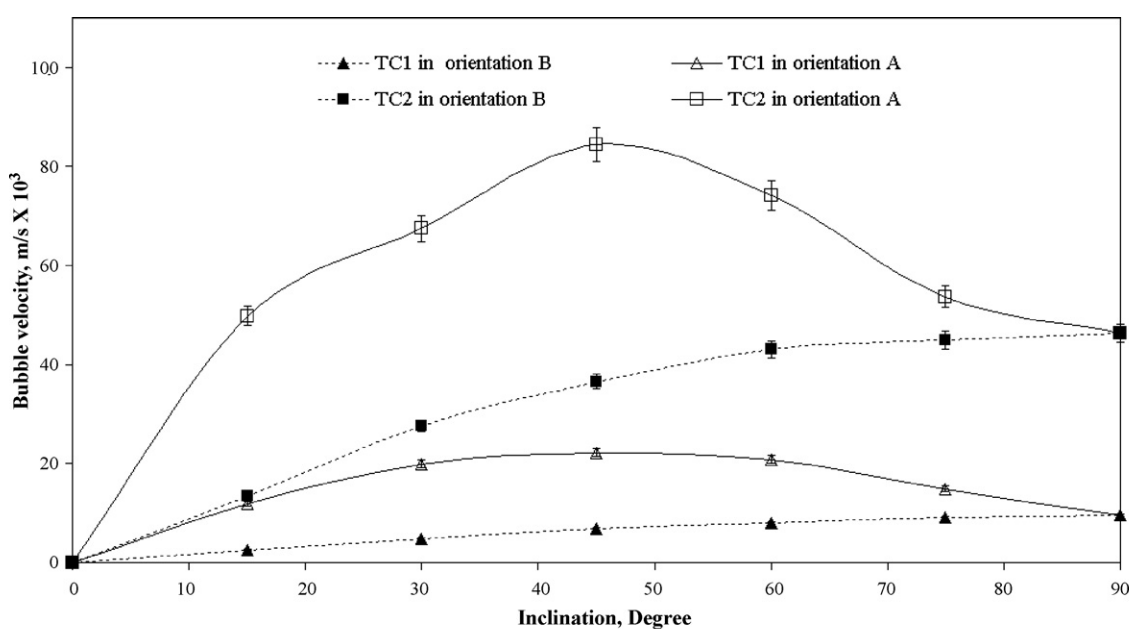

Fig. 3. Rise velocity of Taylor bubble for different inclination and orientation in stationary water.

3. Results and discussion

The experimental results are presented sequentially in the following section. Initially the results have been presented for Taylor bubbles rising through stationary water. The bubble dynamics in moving water has been discussed subsequently.

3.1. Bubble behavior in stationary water column

The rise velocities have been noted to be independent of bubble volume for both the channels in different orientation and inclinations. This is in agreement with the past observation that rise velocity is a function of channel characteristics and fluid properties and independent of the injected volume of air.

The velocity of propagation as noted for different inclinations is represented by the solid lines in Fig. 3 for the two channels in orientation A. The figure shows that the rise velocity initially increases till it reaches a maximum at an inclination of approximately 45° from the horizontal. Subsequently, it decreases as the channels become vertical. This is in agreement to the reported results in circular pipes (Cheng and Lin [12]). Even a recent investigation (Mandal et al. [24]) on the rise of liquid Taylor bubbles through an immiscible liquid have exhibited the same trend.

On the other hand, the curves indicated by dotted lines in Fig. 3 show an altogether different trend for orientation B of both the channels. In this case, the velocity increases continuously with inclination as the channel is rotated from the horizontal to the vertical position. However, the rate of increase is higher for small inclinations and the curve become more gradual as the channel approaches the vertical configuration. A comparison of the curves marked by solid and dotted lines in the figure further indicates that the rise velocity is always higher for orientation A as compared to orientation B of the inclined passage. It may be noted that hollow symbols indicate the data in orientation A, while the corresponding solid symbols denote data in orientation B for both the test rigs.

In order to explain this difference in behavior, investigations were made through extensive visualization and photographic recording. The photographs are taken from the wider side of the channel for ease of understanding and representation. The photographs in orientation A and B of channel TC1 have been depicted in Fig. 4a and b, respectively. From the figures it is evident that the bubble is asymmetric in the horizontal position. It has a rounded nose and a rounded tail in orientation A and propagates along the upper wall of the conduit. As a result, the bottom liquid film is thicker than the film at the upper wall. The nose becomes more and more pointed as the channel is rotated upward. The pointed nose increases the rise velocity of the bubble. This continues till the conduit is inclined at an angle of 45°. Subsequently the nose becomes blunt and finally the bubble assumes an axisymmetric shape in the vertical position. Gravity has an altogether different influence on the bubble as it rises through an inclined channel. Only a component of gravity ($g\sin\theta$ where θ is the angle of inclination of the channel with respect to the horizontal) acts along the channel axis. Due to the combined effect of nose shape and gravity, the bubble attains maximum velocity when the inclination is around 45°. The

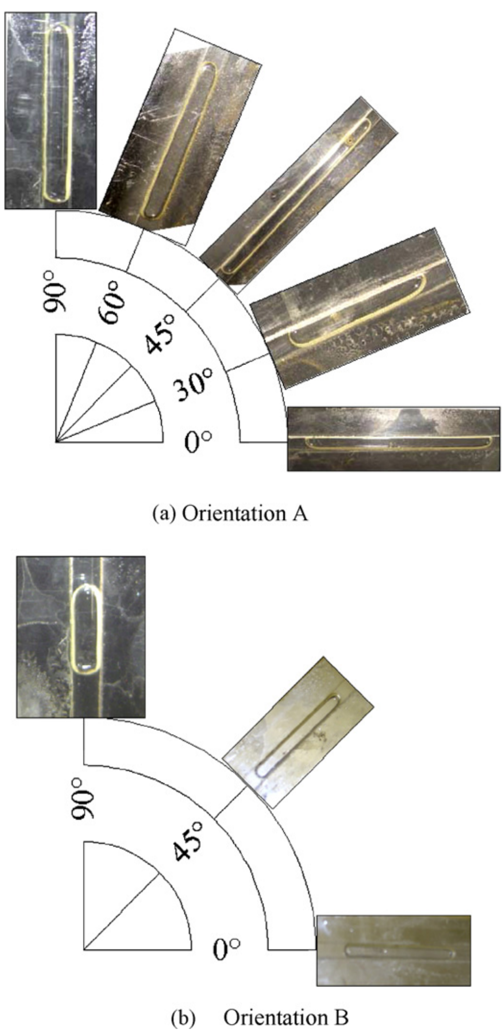

Fig. 4. Shape of Taylor bubble at different inclination of channel TC1. (a) Orientation A and (b) orientation B.

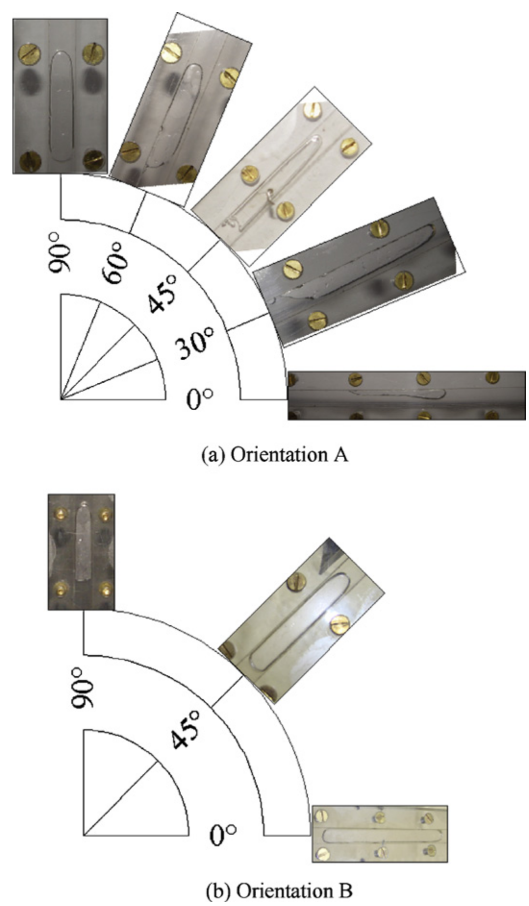

Fig. 5. Shape of Taylor bubble at different inclination of channel TC2. (a) Orientation A and (b) orientation B.

Table 1
Comparison of experimental rise velocity with corresponding theoretical values for Taylor bubbles rising in vertical channels.

Channel	Experimental u_b (m/s)	Characteristic dimension			Corresponding u_b (m/s)		
		D_h hydraulic	D_e Sadatomi et al. [15]	P Clanet et al. [19]	$0.35\sqrt{gD_h}$	$0.35\sqrt{gD_e}$	$0.2\sqrt{gP}$
TC1	0.0095	0.0035	0.00496	0.015	0.065	0.077	0.078
TC2	0.046	0.0042	0.00808	0.0254	0.098	0.098	0.1

counterbalancing effects of nose shape and gravity has been discussed in detail by Maneri and Zuber [14]. On the other hand, the bubble is axisymmetric at all inclinations in orientation B of the channel (Fig. 4b) and the thin liquid film is more or less uniform for all the cases. In this case as the bubble rises through a narrow gap, due to surface tension the nose shape always remain semi-circular for any inclination. However, the effect of gravity increases with increase in θ. As a result, a monotonic increase in rise velocity is observed when the channel is rotated from horizontal to vertical position.

Similar photographs for channel TC2 are presented in Fig. 5a and b. A comparison of the photographs of the two passages (TC1 and TC2) for the same orientation and inclination reveal the influence of channel dimension on bubble shape. The bubble has a rounded nose and a rounded tail for all the cases in TC1 (Fig. 4a and b) while a flattened tail characterizes the bubble in TC2, particularly in orientation A (Fig. 5a). The tail gets more and more distorted as the channel is rotated from 90° to 0° inclination and the gas phase assumes an irregular distorted shape at the horizontal position.

Over the years several attempts have been made to predict the rise velocity of Taylor bubbles theoretically. Both analytical (Liao and Zhao [18], Clanet et al. [19]) as well as computational fluid dynamic (Qian and Lawal [20]) approaches have been adopted. For inertia-dominated systems, the rise velocity through a circular tube can be expressed from a Froude number correlation ($u_b = 0.35\sqrt{gD}$), where the tube diameter is taken as the characteristic length.

In case of Taylor bubbles rising through non-circular conduits there is no unequivocally accepted characteristic length. Time to time several suggestions has been made. Sadatomi et al. [15] have proposed the equi-periphery diameter (D_e), which reduces to the

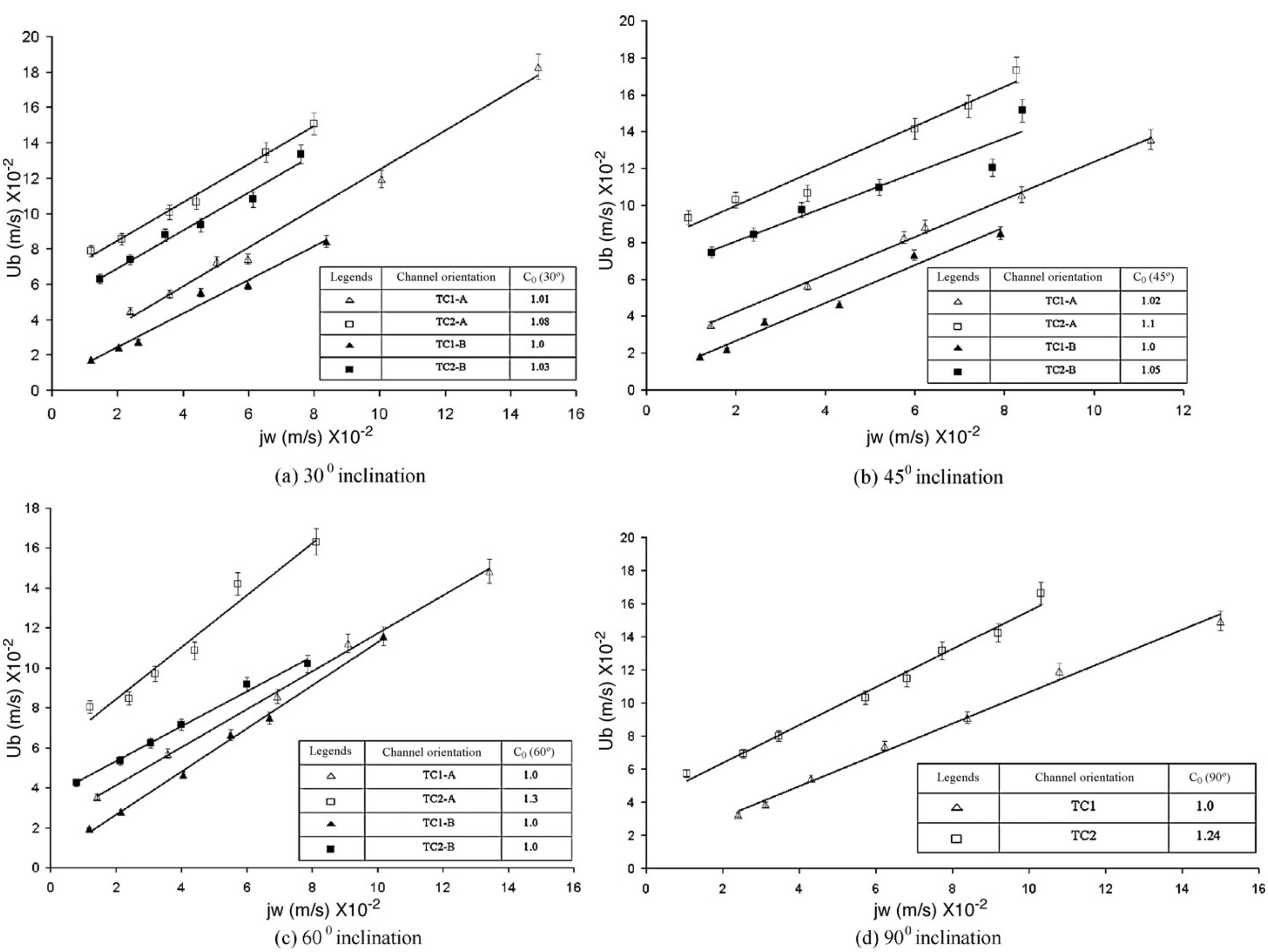

Fig. 6. Rise velocity of Taylor bubble in a co-current stream. (a) 30° inclination, (b) 45° inclination, (c) 60° inclination and (d) 90° inclination.

following expression for a rectangular channel:

$$D_e = \frac{2(a+b)}{\pi} \tag{5}$$

a and *b* are width and thickness of the rectangle.

The conventional hydraulic diameter is expressed as:

$$D_h = \frac{2ab}{(a+b)} \tag{6}$$

And from the expression of Clanet et al. [19], the characteristic dimension is the wetted perimeter expressed as:

$$P = 2(a+b) \tag{7}$$

The rise velocity obtained from the aforementioned characteristic dimensions is listed in Table 1 where the corresponding experimental values are also tabulated for a comparative study. It may be observed that none of the earlier theories/correlations can give a good prediction. The reason behind this can be attributed to the unsuitability of the existing expressions for the characteristic length of a rectangular conduit. In this case, the corners induce additional liquid drainage. This cannot be accounted for by the existing correlations and calls for an in-depth investigation of the rise of Taylor bubbles through narrow rectangular conduits. It may further be noted that for a narrow passage, the general practice is to correlate Froude number with Eotvos number. Such an exercise could not be performed in the present study since both the dimensionless groups require a proper definition of characteristic length.

3.2. Rise of bubbles in co-current stream

Attempts have next been made to study the rise of Taylor bubbles through moving water. Fig. 6a–d depict the rise velocity of Taylor bubbles (u_b) as a function of water velocity (j_w) for orientations A and B of channels TC1 and TC2 at different inclinations. All the curves show an increase in rise velocity with water velocity as expected. Moreover, the rise velocity is higher for orientation A as compared to orientation B. The rise velocity first increases with inclination from the horizontal position and then decreases in orientation A while it continuously increases with inclination in orientation B. These observations are in agreement with the results obtained in stationary water columns and can be attributed to the changing shape of the bubble in the two orientations.

The past researchers investigating the rise of Taylor bubbles in moving water columns had attempted to correlate bubble velocity with water velocity by the following:

$$u_b = C_0 j_w + u_\alpha \tag{8}$$

where u_b is the bubble rise velocity in moving water, u_∞ is the terminal rise velocity in stationary water, j_w is the water volumetric flux expressed as:

$$j_w = \frac{Q_w}{A} \tag{9}$$

Q_w is the volumetric flow rate of water as noted from measurements and A is the cross-sectional area of the pipe. C_0 the distribution parameter as defined by Zuber and Findlay [25] accounts for the velocity profile in the moving liquid. Most of the researchers have obtained the value of C_0 between 1.0 and 1.2 for circular tubes. Sadatomi et al. [15] have reported C_0 to be 1.2 for a 17 mm × 50 mm rectangular geometry and Mishima et al. [16] have reported C_0 to lie between 1 and 1.2 for rectangular channels with a gap of 1.07 mm, 2.45 mm and 5 mm. Jones and Zuber [26] have predicted C_0 as 1.2 for slug flow regime in a rectangular conduit while Ishii [27] has proposed the following equation of C_0 as a function of density ratio of gas and liquid (ρ_g/ρ_l):

$$C_0 = 1.35 - 0.35\sqrt{\frac{\rho_g}{\rho_l}} \tag{10}$$

In the present work the average values of C_0 obtained for the two channels in different orientation and inclination are presented in Fig. 6a–d. The figures depict that C_0 remains more or less constant at unity for different inclinations and orientations for the smaller channel. This probably implies that the presence of the bubble tends to flatten the velocity profile of the moving water in the narrow channel. As a result, the propagation velocity of the bubble simply increases by an amount equal to the average water velocity. In case of the wider channel in orientation A the value of C_0 increases with inclination, reaches a maximum at about 60° and then decreases. In orientation B the maximum C_0 occurs at 90°. It is also noted that for the same channel dimension C_0 is usually higher for orientation A as compared to orientation B. Nevertheless, the value lies between 1 and 1.3 in agreement to the results of Cheng and Lin [12] for circular tubes and Mishima et al. [16] for rectangular conduits.

4. Conclusion

The present work reports an experimental study on the motion of Taylor bubbles rising through narrow rectangular conduits of different dimensions, inclination and orientation. The important observations are:

- The rise velocity is a function of channel orientation apart from dimension and inclination. It is higher when the axis of rotation is parallel to the narrow face. The influence of inclination is similar to the observations reported in literature for circular passages. The rise velocity increases when the conduit is inclined from 0° to 45° (approximately) and then decreases as the conduit approaches the vertical alignment.
- Entirely different results are obtained when the axis of rotation is parallel to the broad face. In this case, the velocity continuously increases from the horizontal to the vertical alignment. This can be attributed to the axisymmetric shape of the bubble for all inclinations in the latter case.
- It is further noted that none of the existing theories can provide an accurate estimation of bubble rise velocity through rectangular mini-channels. A rigorous analysis which incorporates the local hydrodynamics of the channel is necessary for this purpose.
- It would be useful to predict the rise velocity of the bubble for different shape and dimension of the conduit irrespective of its inclination. However, such an attempt could not be made since none of the existing co-relations could propose a proper definition of characteristic dimension for a rectangular channel. Further the behavior of Taylor bubbles with inclinations was observed to be different when the axis of rotation parallel to the narrow and wide face of the channel.
- The rise velocity increases with water velocity and the value of distribution parameter lies between 1 and 1.3 for co-current flow of air and water.
- The value of distribution parameter appears to be insensitive to inclination and orientation for very narrow passages. The influence becomes more pronounced with increase in channel dimension. However, additional investigations are necessary to ascertain the nature of variation.

References

[1] V.E. Nakoryakov, O.N. Kashinsky, A.V. Petukhov, P.S. Gorelik, Study on local hydrodymanic characteristics of upward slug flow, Exp. Fluids 7 (1989) 560–566.

[2] D.T. Dumitrescu, Stromung an einer Luftblase im senkrechten Rohr, Z. Angew. Math. Mech. 23 (1943) 139–149.
[3] R.M. Davies, G. Taylor, The mechanics of large bubbles rising through extended liquids and through liquids in tubes, Proc. Roy. Soc. 200A (1949) 375–390.
[4] E.E. Zukoski, Influence of viscosity, surface tension and inclination angle onmotion of long bubbles in closed tubes, J. Fluid Mech. 25 (1966) 821–837.
[5] K.H. Bendiksen, An experimental investigation of the motion of long bubbles in inclined tubes, Int. J. Multiphase Flow 10 (1984) 467–483.
[6] G. Das, P.K. Das, N.K. Purohit, A.K. Mitra, Rise velocity of a Taylor bubble through concentric annulus, Chem. Eng. Sci. 53 (1998) 977–993.
[7] G.B. Wallis, One Dimensional Two-phase Flow, McGraw-Hill, New York, 1969.
[8] F.P. Bretherton, The motion of long bubbles in tubes, J. Fluid Mech. 10 (1961) 166–188.
[9] P.S. Carew, N.H. Thomas, A.B. Johnson, A physically based correlation for the effects of power law rheology and inclination on slug bubble rise velocity, Int. J. Multiphase Flow 21 (1995) 1091–1106.
[10] D. Barnea, Y. Luninski, Y. Taitel, Flow pattern in horizontal and vertical two phase flow in small diameter pipes, Can. J. Chem. Eng. 61 (1983) 617–620.
[11] K. Mishima, T. Hibiki, Some characteristics of air–water two-phase flow in small diameter vertical tubes, Int. J. Multiphase Flow 22 (1996) 703–712.
[12] T.W. Cheng, T.L. Lin, Characteristics of gas–liquid two-phase flow in small diameter inclined tubes, Chem. Eng. Sci. 56 (2001) 6393–6398.
[13] H. Liu, C.O. Vandu, R. Krishna, Hydrodynamics of Taylor flow in vertical capillaries: flow regimes, bubble rise velocity, liquid slug length and pressure drop, Ind. Eng. Chem. Res. 44 (2005) 4884–4897.
[14] C.C. Maneri, N. Zuber, An experimental study of plane bubbles rising at inclination, Int. J. Multiphase Flow 1 (1974) 623–645.
[15] M. Sadatomi, Y. Sato, S. Saruwatari, Two-phase flow in vertical noncircular channels, Int. J. Multiphase Flow 8 (1982) 641–655.
[16] K. Mishima, T. Hibiki, H. Nishihara, Some characteristics of gas–liquid flow in narrow rectangular ducts, Int. J. Multiphase Flow 19 (1993) 115–124.
[17] Q.C. Bi, T.S. Zhao, Taylor bubbles in miniaturized circular and non-circular channels, Int. J. Multiphase Flow 27 (2001) 561–570.
[18] Q. Liao, T.S. Zhao, Modeling of Taylor bubble rising in a vertical mini noncircular channel filled with a stagnant liquid, Int. J. Multiphase Flow 29 (2003) 411–434.
[19] C. Clanet, P. Heraud, G. Searby, On motion of bubbles in vertical tubes of arbitrary cross section: some complements to Dumitrescu-Taylor problem, J. Fluid Mech. 519 (2004) 359–376.
[20] D. Qian, A. Lawal, Numerical study on gas and liquid slugs for Taylor flow in a T junction microchannel, Chem. Eng. Sci. 61 (2006) 7609–7625.
[21] H. Ide, A. Kariyasaki, T. Fukano, Fundamental data on the gas–liquid two-phase flow in minichannels, Int. J. Thermal Sci. 46 (2007) 519–530.
[22] M.J.F. Warnier, E.V. Rebrov, M.H.J.M. de Croon, V. Hessel, J.C. Schouten, Gas holdup and liquid film thickness in Taylor flow in rectangular microchannels, Chem. Eng. J. 135S (2008) S153–S158.
[23] A.K. Jana, G. Das, P.K. Das, A novel technique to identify flow patterns during liquid–liquid upflow through a vertical pipe, Ind. Eng. Chem. Res. 45 (2006) 2381–2393.
[24] T.K. Mandal, G. Das, P. Das, Prediction of rise velocity of a liquid Taylor bubble in a vertical tube, Phys. Fluids 19 (2007) 128109.
[25] N. Zuber, J.A. Findlay, Average volumetric concentration in two-phase flow systems, ASME J. Heat Trans. 87 (1965) 453.
[26] O.C. Jones Jr., N. Zuber, Slug-annular transition with particular reference to narrow rectangular ducts, in: F. Durst, G.V. Tsiklauri, N.H. Afgan (Eds.), Two-phase Momentum, Heat and Mass Transfer in Chemical, Process, and Energy Engineering Systems, vol.1, Hemisphere, Washington DC, 1979, pp. 345–355.
[27] M. Ishii, One dimensional drift-flux model and consecutive equations for elative motion between phases in various two-phase flow regimes, ANAL report ANL, 1977, 47.